A PARAMETRIC STUDY OF WALL MOISTURE CONTENTS USING A REVISED VARIABLE INDOOR RELATIVE HUMIDITY VERSION OF THE "MOIST" TRANSIENT HEAT AND MOISTURE TRANSFER MODEL

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ABSTRACT

The present 2.1 version of the "MOIST" software predicts wall moisture contents and associated parameters using an assumed indoor relative humidity input that is constant for the duration of the simulation period. The authors modified the model to calculate the hourly indoor relative humidity during the heating season as a function of outdoor weather conditions, indoor air temperature, building size and airtightness, and indoor moisture generation rate. These changes were accomplished by incorporating within MOIST an indoor moisture balance and a single-zone infiltration model. The modified version of MOIST allows the summer indoor relative humidity to either float to simulate open windows/doors or to be fixed to simulate air conditioning. The new version has the advantage of incorporating many more inputs that influence the indoor relative humidity and construction-layer moisture content results. The development and details of the revisions are described.

This enhanced version of MOIST was subsequently used to investigate moisture accumulation in a 5-cm by 15-cm (2-in. by 6-in.) wood-framed wall exposed to a number of different winter climates. Predictions with a constant indoor relative humidity were compared to those with a "floating" or variable indoor relative humidity. The results generally are different, with the results of the revised version agreeing closely with field measurements. In addition, the variable indoor relative humidity program was used to analyze the effect of building airtightness, the indoor moisture generation rate, and the existence of exfiltration. The need for an interior vapor retarder in walls exposed to cold climates also was examined. Moreover, the effects of exterior insulating sheathing and an exterior vapor retarder were modeled. Results and findings are presented along with pertinent conclusions regarding appropriate building construction techniques in winter heating climates.

INTRODUCTION

There is considerable interest in using computer models to predict the moisture performance of building components such as walls. This is a particularly valuable way of examining the performance of different types of wall constructions, be they new design or existing, to determine if they are prone to moisture accumulation or related problems such as wood decay or mold growth. The decay can lead to structural deterioration, while the mold growth can lead to occupant health problems (Olson et al. 1993). Obviously, the alternative to modeling is to field or laboratory test each and every construction of interest under a wide range of conditions. That typically is much more time consuming and expensive and is seldom done.

There are a number of models of varying sophistication that have been developed in a number of countries to estimate the moisture conditions in walls (Trechsel 1994). One such model developed in the United States is known as MOIST (Burch and Thomas 1992). It is a public domain personal computer program that has been widely used in the United States. The MOIST program analyzes the one-dimensional transfer of heat and moisture in a multilayer wall using hourly weather data. It accounts for moisture transfer by diffusion and capillary flow. The model also includes some approximate algorithms to calculate the effect of a constant airflow rate of indoor or outdoor air to an imbedded cavity (exfiltration or infiltration). The program predicts the average moisture content of each of the construction layers, as well as the relative humidity (RH) at the adjoining surfaces of the components as a function of the time of year.

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One of the features of the current version (2.1) of the model is that it assumes a fixed or constant indoor relative humidity throughout the analysis period. Yet indoor relative humidity typically varies substantially throughout the year and often from one day to the next. In a heating climate, relative humidities usually are high in the fall and spring and low in the cold winter months. The amount of variation often is surprising. One can input monthly average outdoor temperature and relative humidity data for a particular climate into a simple moisture balance model that neglects the storage of moisture at internal surfaces (Tsongas 1986) to get an idea of the degree of variation of monthly average indoor RH values.

For example, assume a 111-m^2 (1,200-ft^2) house with a constant infiltration rate of 0.5 air changes per hour (ACH), an indoor temperature of 18°C (65°F), and a moisture generation rate of 11 kg/day (24 lb/day). For Madison, Wis., the monthly average indoor RH varies from 62% in October to 30% in January. Summer values would be much higher without air conditioning. In the milder Portland, Oreg., climate, the indoor RH still varies from 76% in October to 54% in January. If diurnal or day-to-day or hourly swings of outdoor humidity are included, the variation in indoor humidity levels is even more extreme.

The fact that indoor RH values do vary considerably during nonsummer months motivated the modification of MOIST so that indoor relative humidity values would float or vary according to the outdoor conditions, the building tightness, and the occupant use characteristics. Variable indoor relative humidity should give much more accurate predictions. Thus, the model was modified so that the indoor relative humidity was first calculated for each hour during the non-summer months and then the hygrothermal performance of the walls was analyzed. During the summer, when space cooling was provided, the indoor relative humidity was held constant. If space cooling was not provided, then it was assumed that the windows and doors were open and the indoor relative humidity was equal to the outdoor relative humidity. This modified version is referred to as the "variable indoor relative humidity (or variable indoor RH)" version, whereas the original version is referred to as the "constant indoor relative humidity (or constant indoor RH)" version.

The revisions to version 2.1 noted herein will officially be released at a later date along with other modifications and enhancements. That release will be called version 3.0.

DESCRIPTION OF THE "MOIST" COMPUTER MODEL

As noted above, MOIST predicts the one-dimensional heat and moisture transfer in building envelopes. The model includes moisture transfer by diffusion, capillary flow, and air convection; the important couplings between heat and moisture transfer; and the incident solar radiation onto surfaces having different azimuth, orientation, and tilt. Other MOIST features include graphics that display the average moisture content of the construction layers vs. time and a catalog of heat and moisture properties for common building materials. The mathematical algorithms for MOIST are described in Burch and Thomas (1992), and have recently been verified in the hygroscopic regime by way of comparison to a comprehensive laboratory experiment (Zarr et al. 1995).

MOIST permits users to easily define a wall or flat roof and predict the moisture content of the various construction materials as a function of time. The type and placement of building materials also can be varied. MOIST can help the user determine whether a vapor retarder is needed and, if so, where it should be placed. It also can be used to evaluate the effect of various paints and wall coverings on moisture accumulation. In addition, MOIST allows users to "move" a wall or ceiling to different United States and Canadian cities to investigate the effect of climate on moisture accumulation. The program inputs hourly weather year for energy calculations (WYEC) weather data, which are available for 46 United States cities and five Canadian cities (Crow 1981).

In the latest release of MOIST (release 2.1), a constant indoor relative humidity must be specified for each simulation. In the present paper, algorithms of MOIST are described that permit the indoor relative humidity to float and be calculated from a moisture balance of the whole building. Details regarding this revision are given below.

MOIST Revision Details

Space Heating Condition When the daily average outdoor temperature is less than or equal to the balance-point temperature for space heating, the building operates in a space-heating mode. The natural ventilation rate (Q_n) is predicted by the single-zone infiltration model developed by Sherman and Grimsrud (1980) and described by ASHRAE (1993), which is given by

$$Q_n = L\,(C_{\Delta T}\Delta T + C_v v^2)^{0.5} . \qquad (1)$$

In this equation, the natural ventilation rate is related to the effective leakage area (L), the indoor-to-outdoor temperature difference (ΔT), and the average wind speed (v) measured at the local weather station for the time interval of interest (hourly in this case). The effective leakage area can be determined from a whole-building fan depressurization measurement (see ASTM [1994]). Definitions of other terms are presented in the Nomenclature.

If mechanical ventilation (Q_m) is present (assumed to be the measured or actual in situ flow rate of the exhaust fan *system* [including ductwork and exhaust vent, as well as the fan] rather than the nominal or rated flow rate of the fan alone), then the total ventilation rate (Q_t) is determined by (Palmiter and Bond 1991):

$$\text{If } Q_m < 2Q_n,\ \ Q_t = Q_n + 0.5Q_m \qquad (2)$$

$$\text{If } Q_m \geq 2Q_n,\ Q_t = Q_m. \tag{3}$$

Often the nominal or rated flow rate of the exhaust fan is known rather than the actual measured flow rate of the system. If that is the case, the above two equations can be used knowing that the actual in situ performance of an exhaust fan system is typically about 50% of its rated performance (Tsongas 1990). The 0.5 factor in Equation 2 accounts for the fact that when an exhaust fan is turned on, the actual *net* ventilation of the house is about half of the measured exhaust flow because some of the exhausted air previously was exfiltrating out of the house before the fan was turned on (Palmiter and Bond 1991).

The instantaneous hourly indoor relative humidity (ϕ_i) is determined from the TenWolde (1994) moisture balance equation:

$$\phi_i = \frac{\eta + k \cdot A \cdot \phi_{i,\tau} + Q_t \cdot P_{v,o}/C_1}{k \cdot A + P_{s,i}[Q_t/100C_1]} \tag{4}$$

where C_1 is the physical constant 1.3557×10^5 Pa·m^3/kg (641.33 in. Hg·ft^3/lb). This equation may be derived by equating the indoor moisture generation rate (η) to the loss of moisture by ventilation and storage within building surfaces and furnishings. The hygric memory ($\phi_{i,\tau}$) is computed from the relation:

$$\phi_{i,\tau} = \frac{\sum_{n=N-4\tau}^{N-1} W(n) \cdot \phi_i(n)}{\sum_{n=N-4\tau}^{N-1} W(n)} \tag{5}$$

where n is the hourly time index.

The exponential weighting factors, $W(n)$, are defined as

$$W(n) = e^{-(N-n)/\tau}. \tag{6}$$

When the sorption constant per unit floor area (k) is set equal to zero, then indoor storage of moisture is neglected and the relative humidity (ϕ) is calculated from an instantaneous moisture balance of the whole building.

Initially, window condensation was not included in our indoor air moisture balance model as a moisture-removal mechanism. However, without window condensation, the results of computer runs indicated unrealistically high indoor RH values for high moisture production and tight home conditions. Those results indicated the need to include the effects of window condensation, and the approach taken by TenWolde (1994) was used. In the hourly calculations, the dew-point temperature of the indoor air is compared with the temperature of the inside surface of the window glass to determine if condensation occurs. When it does occur, the vapor pressure of the indoor air is taken to be equal to the saturation pressure of the air at the inside glass surface. The indoor relative humidity is calculated from the indoor temperature and vapor pressure using psychrometric relationships.

Space-Cooling Condition When the daily average outdoor temperature is greater than or equal to the balance-point temperature for space cooling, then the building operates in a space-cooling mode. The indoor temperature and relative humidity are maintained at constant specified values.

No Space Heating or Cooling Condition When the daily average outdoor temperature is greater than the balance point for space heating and less than the balance point for space cooling, then neither space heating nor space cooling is required, and the indoor condition is assumed to float. It is assumed that the windows are opened, and the indoor temperature and relative humidity are assumed to equal the outdoor values. This floating mode also is assumed to occur during space cooling when a simulation is carried out in which the space-cooling equipment is turned off.

Moisture Properties

A concerted effort was made to obtain accurate moisture property data for wall construction materials used in the computer analysis. For sugar pine, gypsum board, and exterior-grade plywood, sorption isotherms (curves of moisture content vs. relative humidity) were obtained from Richards et al. (1992) and permeability measurements (curves of permeability vs. relative humidity) were obtained from Burch et al. (1992). For polyisocyanurate, the sorption isotherm and the permeability were based on unpublished measurements.

In the computer analysis, the storage of moisture was small and, therefore, neglected in several of the construction materials either because they were thin layers or because, in the case of the fiberglass insulation, the material does not absorb much moisture (i.e., it is only weakly hygroscopic). Permeances of these relatively nonhygroscopic materials are given in Table 1. ASHRAE values were used whenever possible because they typically are based on three or more independent measurements.

TABLE 1 **Permeances of Relatively Nonhygroscopic Materials**

Material	Permeance ng/s·m^2·Pa	perm	Reference
Air barrier (Spin-bonded polyolefin)	23,100	402	Unpublished NIST measurements
Interior latex paint	690	12	Assorted NIST measurements
Exterior latex paint	320	5.5	ASHRAE (1993)
Kraft paper	17	0.3	ASHRAE (1993)
Polyethylene (0.152 mm (0.006 in.))	3.4	0.06	ASHRAE (1993)
Fiberglass insulation (140 mm (5.5 in.))	1,200	21	ASHRAE (1993)

DISCUSSION OF PARAMETERS USED IN THE ANALYSIS

Base-Case Prototype Wall and House Conditions

The base case was assumed to be representative of typical new construction and typical operating conditions in northern heating climates. The wall construction for the base case is shown in Table 2. There was no interior vapor retarder, and the wall was considered to be airtight without any air convection through it for the base case. All the wall air leakage was assumed to occur through cracks associated with the windows and doors. Because high moisture levels in wall wood members are associated with high indoor RH values (Tsongas 1990), a fairly high nonsummer value of 50% was chosen for runs with fixed indoor relative humidity (RH). That value is approximately the average of the annual average indoor relative humidities for a base-case house in the four cities considered in this study.

For runs with variable relative humidity, a 139-m^2 (1,500-ft^2) single-story site-built home with an average room height of 2.4 m (8 ft) was assumed. The winter heating thermostat setpoint was 20°C (68°F), the summer cooling thermostat setpoint was 24°C (76°F) (summer air conditioning was assumed for all cases in this paper), the space-heating balance-point temperature was 13°C (56°F), and the space-cooling balance-point temperature was 17°C (62°F). The summer cooling season indoor RH was 56%, there was no mechanical ventilation (only natural infiltration), the effective leakage area was 710 cm^2 (110 in.^{2}) (Nelson 1994) (or ACH50 = 10 [CFM50 = 2,000], corresponding to an average natural infiltration rate of about 0.5 ACH), and the indoor moisture generation rate was 11 kg/day (24 lb/day). The indoor moisture generation rate assumed for a typical family of three to four people was within the range given by a number of references (Anderson 1972; ASHRAE 1993; Lee 1987; Trechsel 1994). The sorption constant per unit floor area, k, and the corresponding thermal time constant, τ, were taken as 4.5×10^{-8} kg/s·m^2 (0.33×10^{-4} lb/h·ft^2) and 72 hours (TenWolde 1994), respectively. Wind and stack coefficients for the infiltration model were obtained from ASHRAE (1993) for a single-story home. Only north-facing walls were analyzed.

TABLE 2 **Base Case (Typical) Wood-Framed Wall Construction**

Wall Component
13 mm (0.5 in) gypsum board with interior latex paint (primer and finish coat)
R_{SI} – 3.3^a (R_{IP} – 19^b) fiberglass batt insulation
13 mm (0.5 in) exterior grade plywood sheathing
an air barrier (spin bonded polyolefin)
13 mm (0.5 in) sugar pine siding with exterior latex paint (primer and finish coat)

[a] R_{SI} is expressed in m^2·°C/W
[b] R_{IP} is expressed in h·ft^2·°F/Btu

Parameters Varied

Initially, base-case runs were made with different indoor moisture storage characteristics (k and τ) to examine the sensitivity of the wall moisture content results. Then fixed and variable indoor RH runs were executed for four heating climates: Madison, Wis., Boston, Mass., Portland, Oreg. and Atlanta, Ga. Envelope tightness was varied using the assumed effective leakage area (ELA) for typical (base-case) construction, twice that value for loose construction, and half that value for tight construction. The building floor area was not varied; because the ELA essentially is proportional to the envelope surface area, varying the ELA by a factor of two gives roughly the same results as varying the floor area by that factor. Indoor moisture generation rates included the base-case value (assumed for a typical family of three to four people), twice that, and half that. Further runs were made to examine the effect of an interior vapor retarder, exterior insulating sheathing, and an exterior vapor retarder. Worst-case runs assumed tight construction with high moisture generation.

To examine what might be an adverse wall moisture accumulation situation, runs with exfiltration through the wall cavity also were made using a constant airflow rate of 1.54×10^{-4} m^3/s per m^2 (1.67 ft^3·h/ft^2)^3 for the base case (typical house) and half that for the tight house. MOIST is a one-dimensional model, so the assumed air convection is of necessity simple uniform flow. Of course, air convection through a wall cavity typically occurs through small isolated leakage sites (Tsongas and Nelson 1991), and the resultant moisture accumulation at those sites should be considerably greater than that with uniform flow. Nonetheless, this admittedly simplified analysis should indicate some of the impact of exfiltration. A better approach to more accurately analyze the impact of exfiltration would be to use a two- or three-dimensional model such as that developed by Ojanen and Kumaran (1992).

Each simulation was run hourly over a year and a half starting on January 1. The actual moisture content results presented herein were for the one-year period of July 1 to the following July 1. Almost 300 runs were completed for this paper. On average, each took about 15 minutes using a 66-Mhz 486 personal computer with 8M bytes of RAM. The major focus of the modeling runs was on the weekly average moisture content (hereafter referred to simply as the moisture content) of the plywood sheathing. It was calculated for each week of the year. In all cases the plywood's moisture content was considerably higher than that of the siding or any other component. By comparison, the gypsum board was always extremely dry. Thus, its moisture content results have not been presented.

RESULTS AND DISCUSSION

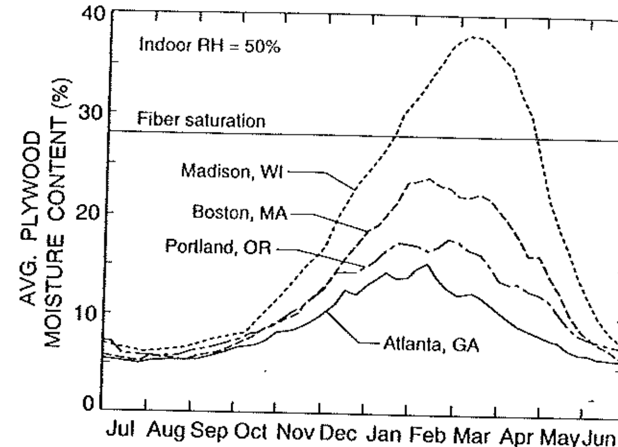
Effect of Indoor Moisture Storage

The annual variation of the plywood moisture content was found to be fairly insensitive to the indoor moisture storage parameters k and τ. The values cited by TenWolde (1994) for site-built and manufactured homes gave almost identical results. Moreover, those results were about the same as those with no storage. Only when the parameters were considerably larger than those determined by TenWolde (1994) were the moisture contents higher; then the sheathing moisture content increased by as much as about 5% at the time of the winter peak. Summer values essentially never were affected because the indoor RH was fixed during the cooling season.

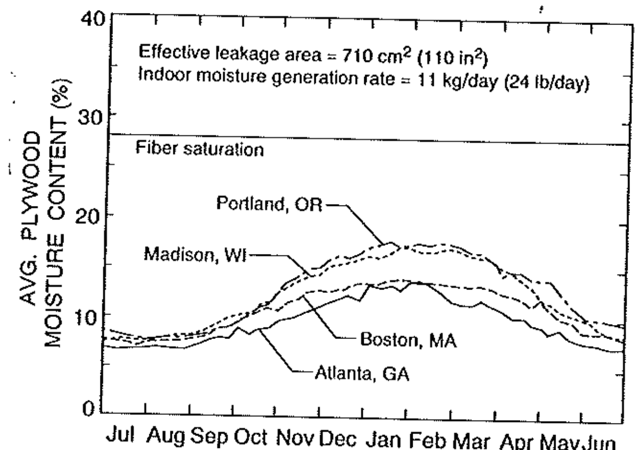
Constant vs. Variable Indoor RH Runs

The sheathing moisture content was calculated using both the constant and variable indoor RH versions for the base-case wall in the four different heating climates. The constant and variable indoor RH results are shown in Figures 1a and 1b, respectively. In all cases the sheathing moisture content values are lowest in the summer and peak in the winter as moisture migrates outward through the wall. For the constant indoor RH runs, the colder the climate, the greater the peak winter values, which is in general agreement with the trend of the results from a two-dimensional model (Ojanen and Kumaran 1992). With 50% indoor RH year-round, moisture contents peak at 38%, 24%, 18%, and 15% for Madison, Boston, Portland, and Atlanta, respectively. Those peak values are to be compared to peaks of 17%, 13%, 16%, and 13% when indoor RH varies. For the variable RH version of the model and the base case, or assumed typical, situation, the peak values for all the climates are well below the 27.9% fiber saturation level for plywood.

Using the model with variable indoor RH, the peak values for the colder Madison and Boston climates are significantly lower, whereas the peaks for the milder Portland and Atlanta climates are about the same. With the variable indoor RH model the differences in the peak values between the four climates are relatively small. In fact, the results for the different climates are all generally about the same. Surprisingly, the results for Madison, with its cold, but dry winter are almost identical to the results for Portland with its mild, wet winter (the same is true of Boston and Atlanta). This is because in Madison the winter indoor relative humidity values are much lower than in Portland so that there is less moisture migration into the Madison wall. On the other hand, the colder Madison winter leads to more opportunities for condensation. The two factors appear to offset each other. When assuming equal constant indoor RH values for the two climates, the differences are substantial because of the outdoor weather differences (i.e., more condensation opportunities in the colder climate).



a. Constant indoor relative humidity model



b. Variable indoor relative humidity model

Figure 1 *Effect of climate on plywood moisture content.*

The sheathing moisture content results for each of the four climates determined using the variable indoor RH model version and shown together in Figure 1b also are shown for the Madison and Portland climates in Figures 2a and 2b. On each graph the results of using the constant indoor RH version with indoor RH values of 20%, 30%, 40%, 50%, and 60% also are shown. The effect of increasing indoor relative humidity on the results is in agreement with the results of Ojanen and Kumaran (1992), who varied the constant indoor RH in their two-dimensional model. From Figures 2a and 2b it is clear that one cannot use a single constant value of indoor RH in the MOIST model that will reproduce the results of the variable RH version. Furthermore, from these graphs one can clearly infer that the indoor RH values do vary significantly throughout the year, as discussed below.

To verify that point, the variable indoor RH model was used to investigate the annual variation of the weekly average indoor relative humidity in Madison and Portland for base-case (typical) conditions. The results are plotted in Figures 3a and 3b. The plots for worst and best

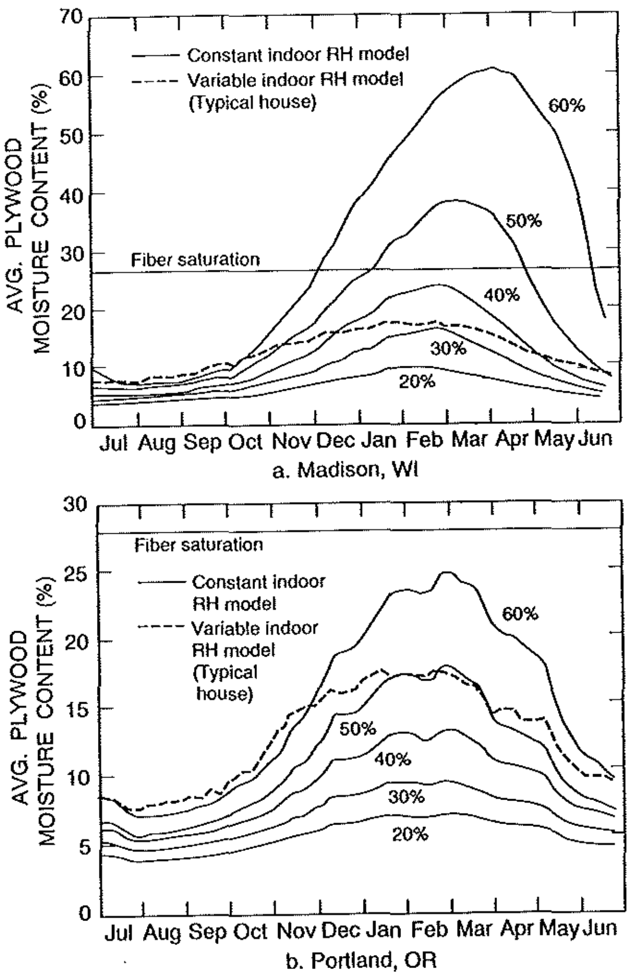


Figure 2 *Comparison of constant and variable indoor RH model results.*

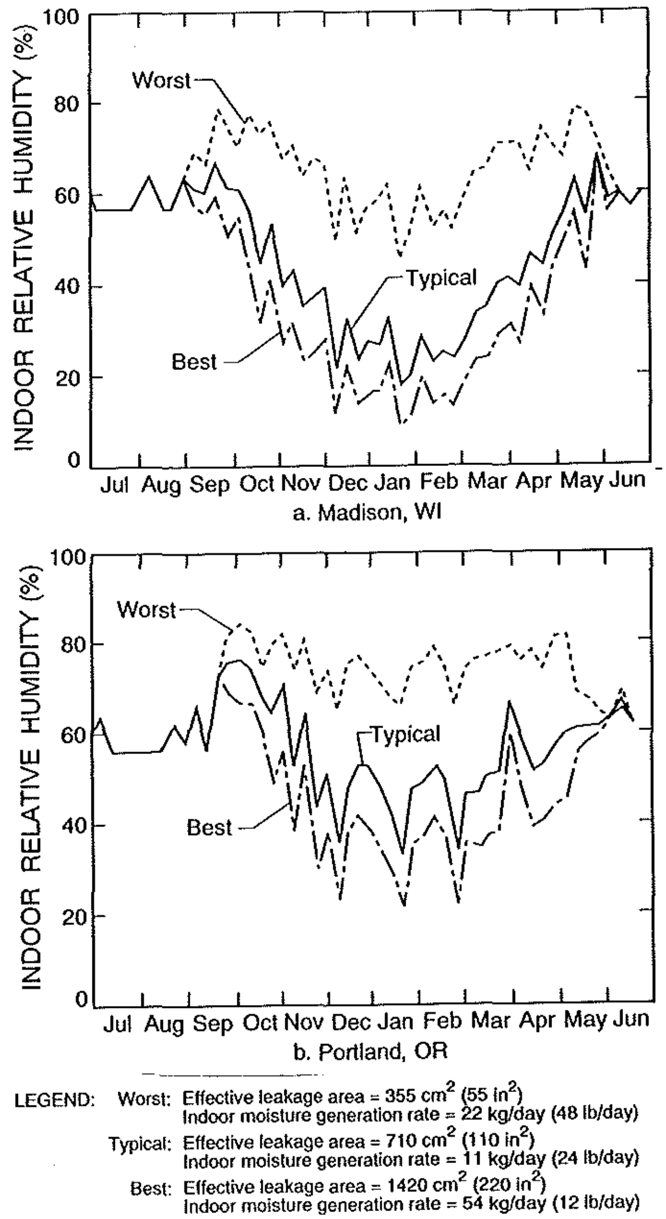


Figure 3 *Annual variation of indoor RH for worst, typical (base) and best case.*

cases will be described in a later section. However, worst case refers to a tight house with high moisture generation, while the best case refers to a loose house with low moisture generation. The plotted lines shown in Figures 3a and 3b are averages of the individual weekly data points. Clearly there is substantial seasonal variation of the indoor RH for Madison about the 45% annual mean; it ranges from a fall maximum of 67% to a winter minimum of 18%. Had there been no summer air conditioning, then the range would have been significantly greater because of the high summer outdoor humidities. The variation in Portland around its annual mean of 56% is about the same, ranging from 76% to 33%. In both cities the highest RH values occur in the fall and the spring.

Using the constant indoor RH version of the model can clearly give substantially different results than with the variable indoor RH version. Note that even when using the annual mean indoor RH values with the constant indoor RH model, the sheathing moisture content values are still quite different from the predictions of the variable indoor RH model. It has always been difficult, if not impossible, to know what indoor RH values to use with the constant indoor RH model.

It is worth noting that when using the variable indoor RH model, the predicted winter sheathing moisture content values for Madison and Portland of about 16% to 18% (see Figure 1b) agree closely with values measured in the field in similar cold and mild climates (Montana and Seattle-Olympia). In that field study the average sheathing moisture content for measurements during winter months was 16% for 30 wall openings in Montana and 18% for 101 wall openings in the Seattle-Olympia area (Tsongas 1990). It is presumed that, on average, the conditions in the field-test homes were similar to those of the base-case prototype assumed for the modeling. Thus, the revised one-dimensional model appears to be making reasonable predictions. As noted in Figures 2a and 2b, depending on the choice of the constant indoor relative humidity, the predictions of the unrevised model may or may not agree well with those field measurements. The average daytime indoor relative humidity for the 20 Montana homes was 40%, whereas for the 50 Seattle-Olympia homes it was 47% (Tsongas 1990). Even knowing the relative humidity, the agreement is not as good as with the variable indoor RH model, and it is typically difficult to know what constant indoor relative humidity to use in the unrevised model.

Effect of Building Tightness and Moisture Generation Rate

Because the constant indoor RH version of the model did not include building- and occupant-related parameters, we investigated some of their effects with the variable indoor RH version. In Figure 4a the moisture content results using the variable indoor RH version with the base-case conditions (including a typical moisture generation rate of 11 kg/day [24 lb/day]) are shown for the Madison climate and three building tightness (effective leakage area) levels. The results are the same as those for the base case (including typical tightness of 710 cm^2 [110 $in.^2$]) with the three different moisture generation rates (see Figure 5a). The tighter the building or the higher the moisture generation rate, the greater the moisture content. Clearly, varying either tightness or moisture generation strongly affects the sheathing moisture content.

In Figure 4b the results are shown for the three tightness levels and a high moisture generation rate (22 kg/day [48 lb/day]). While for the typical moisture generation case shown in Figure 4a the plywood never gets above 32%, it rises almost twice as high (approaching 50%) when the moisture generation rate is doubled for the tight house (355 cm^2 [55 $in.^2$]) (as in Figure 4b). That is quite high, but so is the moisture generation rate. This case amounts to a worst-case scenario. For that scenario, the relative humidity values shown in Figure 3a also are high, especially in the fall and spring.

It should be recalled that we did include in the model revisions limits to the indoor RH due to window condensation at high indoor relative humidities, as did TenWolde

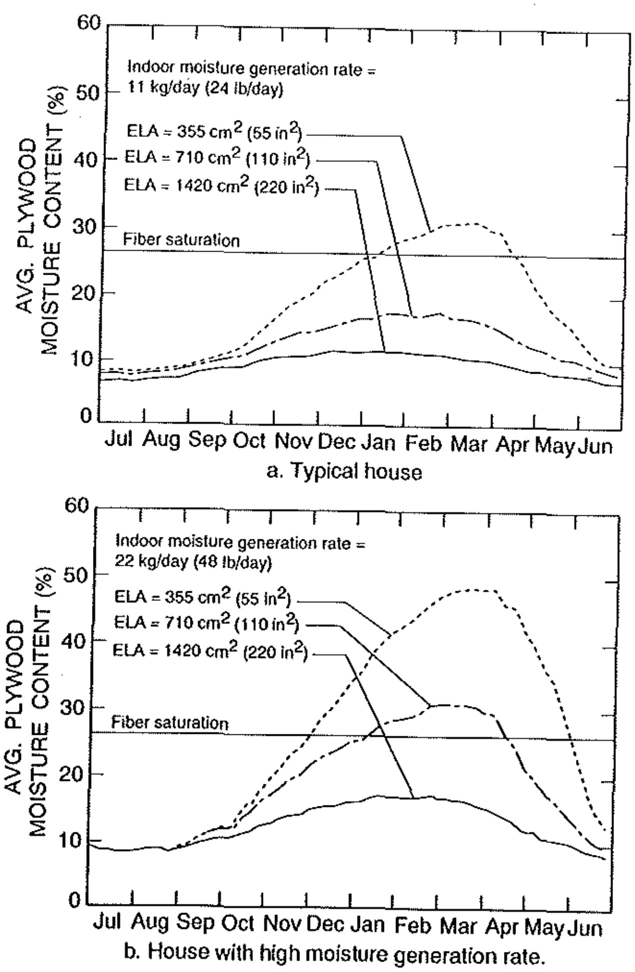


Figure 4 *Effect of effective leakage area (ELA) in Madison, Wis.*

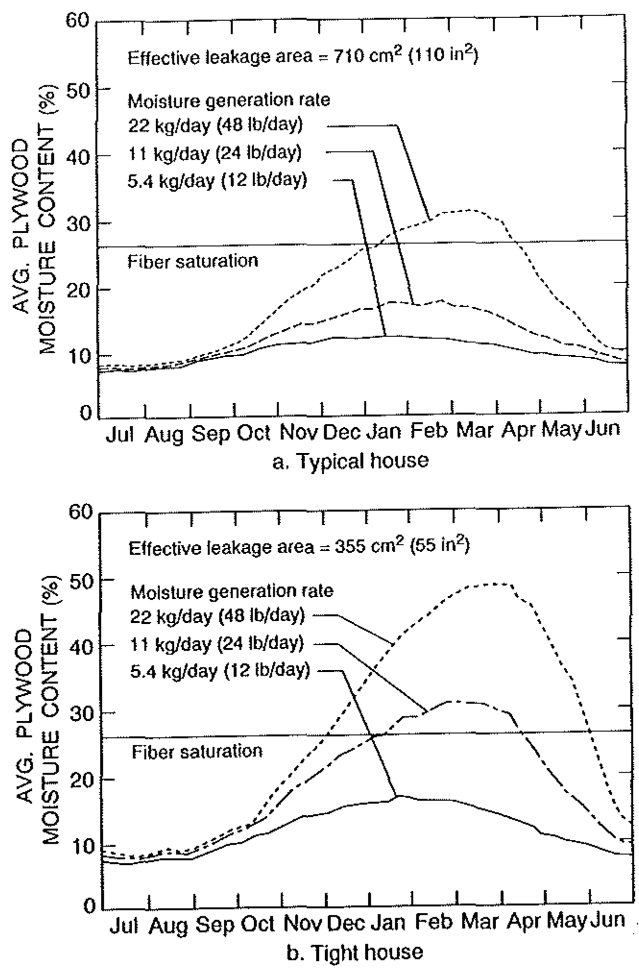


Figure 5 *Effect of moisture generation rate in Madison, Wis.*

(1994). Had we not done that, our indoor RH values and consequently our moisture content predictions would have been about 10% higher for the worst-case scenario (about 60% rather than about 50% moisture content). However, there was essentially no impact of window condensation for typical conditions. Thus, window condensation is an important moisture-removal mechanism that must be included in any indoor moisture model, especially for high moisture generation rates in tight houses.

What is most important is that for the worst-case condition the moisture levels are above the fiber saturation point in the warm late spring and early summer months such that decay could occur. Recall that decay can only occur when the wood is warm (typically above 10°C [50°F] and below 32°C [90°F]) and its moisture content is above the fiber saturation point (Trechsel 1994).

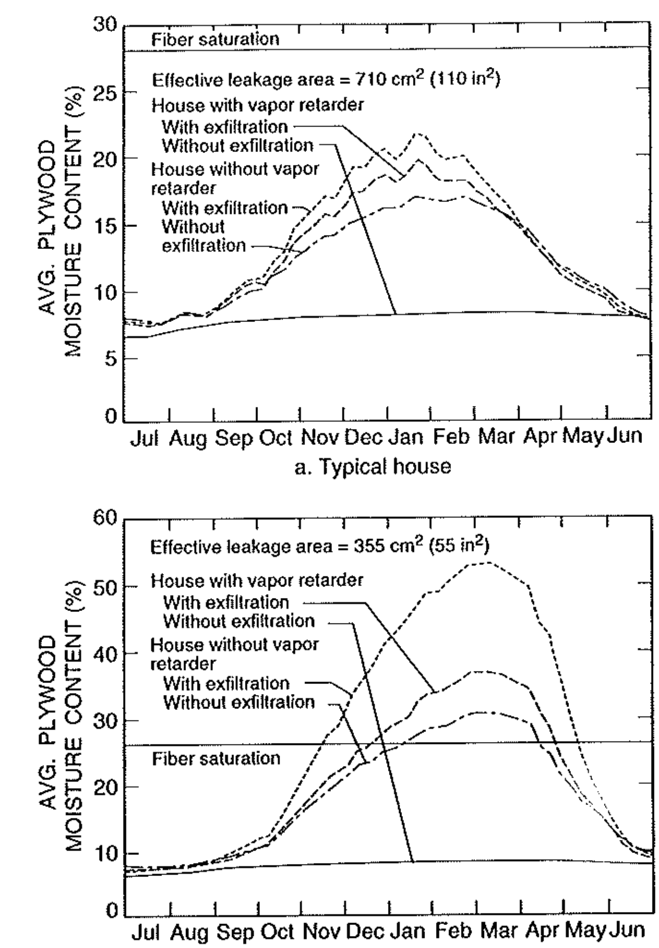
Houses of the tightness assumed for the tight building case (about 0.2 to 0.3 ACH) are not uncommon. In fact, many houses are much tighter. Furthermore, it is not unusual to have high moisture generation rates. They can occur for a variety of reasons, either individually or collectively, such as having a large number of occupants, cooking or boiling liquids for long periods, not having or not using a bathroom exhaust fan when showering or bathing, not installing a crawl space ground cover, not venting a clothes dryer, doing many loads of laundry and/or drying the clothes indoors, storing firewood indoors, having poor drainage around a foundation, and/or using a kerosene heater or an oven for space heating. A kerosene heater or an oven can produce as much as four to five times the amount of moisture as all the activities of a family of three or four. In fact, it is fairly easy to have a high moisture generation rate. Clearly, some fraction of the housing stock has high moisture generation levels. Those houses, if they also are tight, have the most potential for wall moisture damage. Thus, these results point out the need to do everything possible to reduce moisture generation, including source control, and to consider using mechanical ventilation or dehumidification (Tsongas 1993a). They also point out the need to consider using building construction practices that help mitigate adverse moisture conditions; some of these will be discussed in the following sections.

Effect of Exfiltration and an Interior Vapor Retarder

The authors also used the model to investigate the effects of exfiltration and the installation of an interior vapor retarder. The vapor retarder was assumed to be a 6-mil polyethylene sheet directly behind the gypsum board. The sheathing moisture content results are shown in Figures 6a and 6b. Figure 6a is for Madison and the base case (typical conditions), while Figure 6b is for Madison and a tight house (355 cm^2 [55 in.^{2}]). For each graph, four cases are plotted: without exfiltration and without a vapor retarder, with exfiltration and without a vapor retarder, with exfiltration and with a vapor retarder, and without exfiltration and with a vapor retarder.

Both figures show that with no exfiltration the polyethylene vapor retarder substantially reduces the plywood moisture content. The MOIST simulations also showed that similar reductions occurred in the moisture content of the wood siding. In addition, the modeling results showed that even installing a one-perm kraft paper vapor retarder significantly reduced sheathing moisture levels without exfiltration present. In fact, with either a kraft paper or a polyethylene vapor retarder in a wall without exfiltration, the plywood moisture content remained essentially constant throughout the year.

Both plots also show that exfiltration essentially diminishes the effectiveness of the vapor retarder. When exfiltration is present it is much more important than diffusion as a moisture migration mechanism. It substantially increases the plywood's moisture content because the vapor diffusion retarder is not an air barrier; it is assumed that even if a vapor retarder is present, exfiltration still can occur. A discussion on the difference



a. Typical house

b. Tight house

Figure 6 *Effect of exfiltration on houses with and without an interior vapor retarder in Madison, Wis.*

between a vapor retarder and an air barrier is given by Quirouette (1985).

It is also seen that with exfiltration present, the polyethylene does relatively little good under the typical base-case conditions (see Figure 6a). But then it is not really needed since the sheathing moisture levels are below the fiber saturation point most of the time. However, when the house is tighter (Figure 6b) the polyethylene is extremely important. Then it dramatically reduces peak winter moisture contents and, more important, reduces the time during warm weather when the plywood is above the fiber saturation point such that decay could occur. These modeling results are in agreement with the findings of field measurements in tight homes where 2-by-6 walls with an interior vapor retarder were drier, on average, than those walls without one (Tsongas 1990).

Under all conditions a vapor retarder reduces the extremes of moisture content variation both in the plywood and in the siding. That reduction in the moisture content variation of the siding is extremely valuable in reducing moisture-related expansion and contraction and swelling and related damage. That is one reason why many hardboard siding manufacturers require a continuous vapor retarder in place.

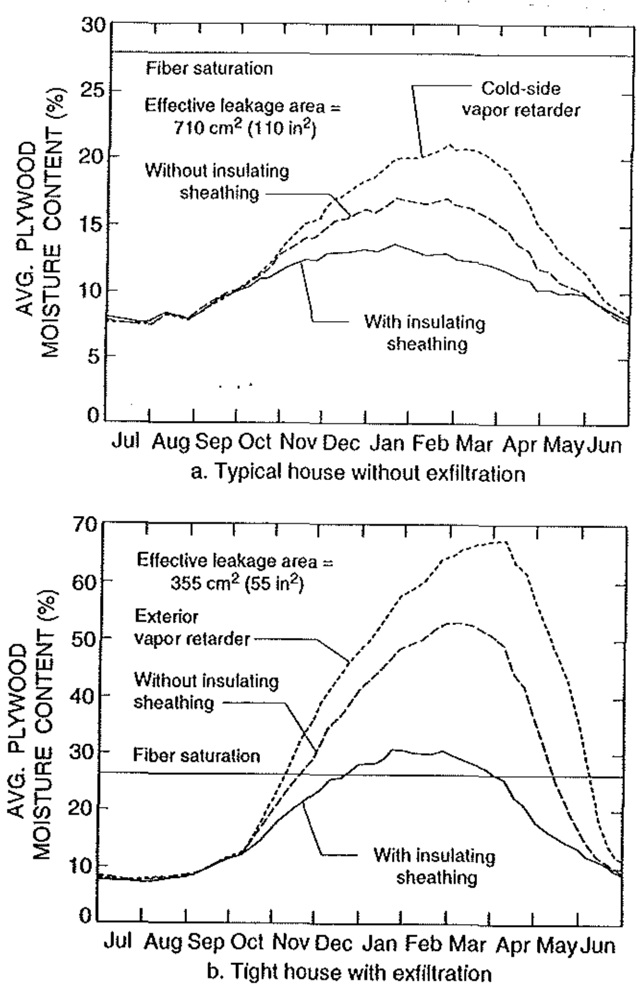
It is important to emphasize that the exfiltration assumed in this analysis is that due to the stack effect alone. The amount of exfiltration could be significantly greater if rooms such as bedrooms are pressurized during the operation of a forced-air heating system with supply registers only and doors closed. Ojanen and Kumaran (1992) modeled the impact of exfiltration assuming a 10-Pa (0.21 lbf/ft^2) room overpressurization. That corresponds to an exfiltration rate of about five times the value used in this analysis for the typical house; in their analysis, that caused moisture storage within the wall cavity of about three times the amount found in this analysis. Thus, overpressurization of rooms could make the situation much worse than shown here. Interestingly, a statistical analysis of field wall moisture data (Tsongas 1990) found that wall wood member moisture contents were highest in bedroom walls compared with all other rooms. That could be because bedrooms are typically kept cooler and hence the relative humidity is higher. Alternatively, it could be the effect of pressurization by the operation of forced-air heating systems.

Effect of Exterior Insulating Sheathing and an Exterior Vapor Retarder

The authors also used the model to study the impact on wall moisture accumulation of the use of exterior insulating sheathing or an exterior vapor retarder. We analyzed three separate cases. The first case was the base-case wall with plywood sheathing and a breathable, or highly permeable (402 perm), spin-bonded polyolefin building paper. For the next case, the building paper was removed and a low-permeability, 2.54 cm (1.0 in.) thick polyisocyanurate exterior insulating sheathing with foil facings (R_{SI}-1.2 [R_{IP}-7]) was put in its location. The last case was for the base-case wall without exterior insulating sheathing but with low-permeability (0.96 perm) building paper acting as an exterior vapor retarder. In all cases there was plywood sheathing and no interior vapor retarder.

In Figure 7a the impact of the addition of exterior insulating sheathing to the base-case wall in Madison (just outside the plywood sheathing) is shown. It is assumed there is no exfiltration. Figure 7b is for the same conditions except the house is tighter and exfiltration is included.

For the cases with and without exfiltration, the addition of exterior insulating sheathing significantly reduces the winter peak sheathing moisture levels, whereas the presence of a low-permeability exterior building paper substantially increases the peak moisture content. Without exfiltration, the sheathing never comes close to the fiber saturation point. So, in a sense, the wall construction does not matter.



a. Typical house without exfiltration

b. Tight house with exfiltration

Figure 7 Effect of exterior insulating sheathing and exterior vapor retarder in Madison, Wis.

However, as conditions become more adverse, such as in a tighter house with exfiltration, the addition of the insulating sheathing reduces the peak moisture content of the sheathing significantly, but also reduces the time during the warm late spring and early summer months when the sheathing is above the fiber saturation point. These results are in agreement with the finding (from field tests of a large number of relatively tight homes in climates similar to those used in the modeling) that walls with exterior insulating sheathing were significantly drier than those without (Tsongas 1991). The modeling also showed that adding an interior vapor retarder to the insulating sheathing made the wall even drier in worst-case conditions. That finding also is in agreement with those field test results.

Figures 7a and 7b also show the effect of an exterior low-permeability building paper in comparison to a highly breathable building paper at the same location. For the case of a tight house with wall exfiltration, the effect of the exterior vapor retarder is alarming. The low-permeability building paper increases the peak moisture levels relative to the wall with breathable building paper and keeps the wall wet (above the fiber saturation point) well into warm weather when decay can occur. In essence, the wetting potential is increased and the drying potential is reduced. Such poor moisture performance also can occur with low-permeability siding. Both low-permeability exterior-type products trap moisture within walls and slow the normal drying process such that deterioration can occur. Widespread plywood sheathing decay has been seen to occur as a result of using a relatively impermeable building paper (average perm rating of 0.65) between the plywood and the wood siding (Tsongas and Olson 1995). Other low-permeability products on the market, installed on the exterior of walls, may have similar effects.

It is worth noting that a low-permeability exterior insulating sheathing reduces moisture levels, while a low-permeability building paper that has no insulating quality does just the opposite. The insulating sheathing increases the plywood temperature to a level such that it remains above the dew-point temperature enough to substantially reduce the amount of condensation. Because the plywood remains so much drier, the relatively impermeable nature of the exterior insulating sheathing is not a detriment. Moreover, it has been shown to keep the wall relatively free from the adverse wicking effects associated with splashback (Tsongas 1993b).

Not only does the use of exterior insulating sheathing reduce the plywood sheathing moisture content (and presumably that of the studs) when exfiltration is present, it also decreases the moisture content of the wood siding during the winter months compared to a wall without exterior insulating sheathing. The effect of the presence of exterior insulating sheathing on the weekly average siding moisture content is shown in Figure 8. The same three

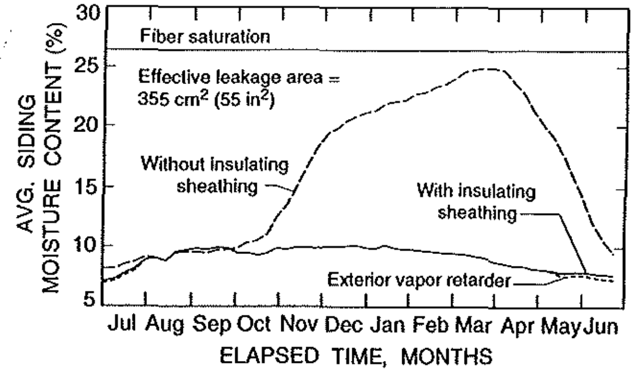


Figure 8 *Effect of exterior insulating sheathing on wood siding moisture content for a tight house with exfiltration in Madison, Wis.*

cases for a tight house with exfiltration in Madison, Wis., are presented as were shown in Figure 7b. With either the exterior vapor retarder or with insulating sheathing, the siding remains quite dry and its moisture content varies little throughout the year. However, with the insulating sheathing not in place, the siding gets much more moist in the winter and shows more variation throughout the year.

The presence of a low-permeability layer near the exterior surface in the cases with exterior insulating sheathing or an exterior vapor retarder dramatically reduces the amount of moisture migrating to the siding. In a sense, the siding is decoupled from the rest of the wall and, thus, stays relatively dry.

Fortunately, the siding moisture content does not reach the fiber saturation level in any of the three cases. Moreover, even in the worst case without insulating sheathing, the siding dries out substantially during the late spring and early summer. Thus, siding decay is not likely and that agrees with the field results of Tsongas (1990). In that field study of 86 homes in the Pacific Northwest there were no cases of siding or other wall component decay. Moreover, the homes essentially were devoid of any evidence of any other type of siding problems.

Based upon these results it would appear that siding in a home with exterior insulating sheathing in place should undergo far less seasonal expansion and contraction induced because of moisture changes than similar walls without the insulating sheathing. That could dramatically affect the service life of the siding or the paint. There is some field evidence of moisture accumulating between exterior insulating sheathing and siding at isolated locations near the joints of the sheathing in homes with forced-air heating. That could be the result of localized exfiltration of moist indoor air, especially if the rooms were pressurized. Thus, taping all the seams of exterior insulating sheathing is strongly recommended to help keep the local exfiltration levels to a minimum. That would likely be a prudent approach to avoiding any such potential siding problems.

CONCLUSIONS

Release 2.1 of the MOIST personal computer program for predicting moisture accumulation in the components of building walls has been revised to calculate indoor relative humidity hourly during the heating season rather than using a constant value for the duration of the analysis period. The variable RH version of the software provides sheathing moisture content results that are much lower than with the constant RH version for cold winter heating climates such as Madison, Wis., but about the same results for mild winter heating climates such as Portland, Oreg. Surprisingly, the variable RH model predicts almost the same moisture contents for the same home and conditions in the milder Portland, Oreg., climate as in Madison. In fact, the variable RH model predictions are quite insensitive to heating climate differences.

Importantly, the predicted results using the variable RH version agree closely with measured field results, suggesting that the one-dimensional model is making fairly accurate predictions. The authors recommend that the variable indoor relative humidity version of the model be used once it is available.

It should be noted that the variable RH version of the MOIST model includes a number of building constructions and operations, as well as occupant life-style parameters that were not previously accounted for in the constant RH version. Thus, the variable RH version is much more versatile in that it allows one to examine the effect of a number of important house and occupant lifestyle parameters, including building tightness, moisture generation rate, summer space cooling, setpoint temperatures for space heating and cooling, and hygric storage capacity.

The effect of building tightness and moisture generation rate was found to be substantial. A worst case for moisture accumulation in conventional walls is for tight homes with high moisture generation rates. Exfiltration of moist indoor air through the wall cavity makes matters even worse. Given that factors such as house tightness and moisture generation rate generally cannot be easily controlled, it was found that certain building practices could provide a considerable margin of safety relative to moisture problems in walls.

For example, the results point out the need to focus on air sealing of walls, as well as minimizing room pressurization due to the operation of forced-air distribution systems to reduce the adverse effects of exfiltration. Furthermore, while the need for vapor retarders has received considerable attention recently (Nisson 1994), the results point out the unmistakable value of incorporating an interior vapor retarder. In essence, the interior vapor retarder is like an insurance policy that provides protection when necessary. Under typical conditions it really is not needed for the conditions and cities examined. But under adverse conditions that are more common with new tight construction, it is essential. Without it, decay could occur. Now that new homes, for the most part, are being built relatively tighter, we may begin to see more cases of decay under worst-case or similar conditions if builders forego installing an interior vapor retarder in winter heating climates.

In addition, the modeling predictions show the clear value of incorporating exterior insulating sheathing in cold winter climates. Its presence keeps all the wall wood members drier, including the siding. In fact, the combination of such sheathing and an interior vapor retarder provides one of the safest wall designs in cold climates. On the other hand, use of noninsulating building products on the exterior side of a wall that incorporate a relatively impermeable layer or material that acts like a vapor retarder is not recommended because they can create conditions conducive to decay and structural deterioration.

RECOMMENDATIONS FOR FURTHER STUDY

The analysis undertaken in this paper using the variable indoor RH MOIST model only examined cases with summer air conditioning. Yet conditions are likely to be worse from a moisture point of view for homes without air conditioning because summer indoor humidities typically will be higher than those with air conditioning. Thus, the results of this study may be conservative and should be re-examined.

In addition, it is recommended that the type of analysis contained herein for northern heating climates be extended to southern hot and humid cooling climates. Previous MOIST analyses for these climates have only considered constant indoor relative humidities throughout the year.

This paper has focused on controlling excess moisture in walls under adverse (worst-case or similar) conditions using building construction techniques such as air sealing, using an interior vapor retarder, and using exterior insulating sheathing in cold climates. Those approaches clearly provide a factor of safety against deterioration of wall components because of high wall moisture levels occurring in warm weather. However, another approach is to control indoor relative humidity levels using dehumidification or mechanical ventilation. The new variable indoor RH model will allow one to analyze the effectiveness of mechanical ventilation in reducing wall moisture levels under adverse conditions. Natural ventilation rates of 0.2 to 0.3 ACH, such as assumed for the tight house in this study, can have the ventilation augmented mechanically to 0.35 ACH or higher. A study of the effects of mechanical ventilation in tight houses should be undertaken. If ventilation were effective, it would have the added benefit of reducing health problems associated with high indoor relative humidities. However, ventilation may not be particularly effective for indoor moisture control in mild and humid winter climates such as that in Portland; dehumidification may be needed as a complement to ventilation (Tsongas 1993a).

Finally, it is strongly recommended that MOIST be further modified to include plotting routines that plot out results directly, as well as built-in batch analysis capabilities to allow multiple runs to be made at one time. Both would make MOIST much easier to use and extend its usefulness. A workshop to train potential users how to properly use the fully revised software also is a good idea.

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NOMENCLATURE

A = floor area, m^2 (ft^2)

$C_{\Delta T}$ = stack (buoyant force) coefficient, $(L/s)^2 \cdot (cm)^{-4} \cdot (°C)^{-1}$ $(cfm^2 \cdot in.^{-4} \cdot °F^{-1})$

C_v = wind coefficient, $(L/s)^2 \cdot (cm)^{-4} \cdot (m/s)^{-2}$ $(cfm^2 \cdot in.^{-4} \cdot mph^{-2})$

k = sorption constant per unit floor area, $kg \cdot s^{-1} \cdot m^{-2}$ $(lb \cdot h^{-1} \cdot ft^{-2})$

L = effective leakage area, cm^2 ($in.^2$)

n = time index

N = current hour

P_s = saturated water-vapor pressure, Pa (in. Hg)

R = thermal resistance, $m^2 \cdot °C/W$ $(h \cdot ft^2 \cdot °F/Btu)$

P_v = water vapor pressure, Pa (in. Hg)

Q = ventilation rate, L/s (cfm)

v = wind speed, m/s (mph)

W = weighting factor

ΔT = indoor-to-outdoor temperature difference, °C (°F)

η = indoor moisture generation rate, kg/s (lb/h)

ϕ = relative humidity or hygric storage, %

τ = moisture time constant, h

Subscripts

i = indoor

m = mechanical

n = natural

o = outdoor

t = total

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