MOISTURE ACCUMULATION IN WALLS: COMPARISON OF FIELD AND COMPUTER-PREDICTED DATA

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ABSTRACT

Traditional methods for analyzing moisture accumulation in the exterior building envelope are one-dimensional, steady-state, and limited to water vapor diffusion. The computer-based model MOIST is transient and includes capillary and vapor transfer through materials but is limited to one-dimensional analysis. In this study, the authors compared field data on moisture conditions and airflow in walls typical for manufactured home construction with predictions generated by MOIST and by a steady-state analytical tool (a modified version of the Kieper method). The results indicate that MOIST can provide reliable average relative humidity estimates for airtight wood-frame walls during winter, but it is less reliable for walls with air leakage typical for standard wood-frame construction. MOIST may yield better results with more detailed airflow input, but the authors do not advocate revising MOIST in this way because such detailed airflow data are generally not available. One-dimensional models such as MOIST are inherently limited in the type of building moisture issues they can address, and they are not capable of providing a complete spatial distribution of moisture and humidity in a wall. Steady-state moisture analysis methods can give acceptable results for mid-winter and possibly mid-summer but are inappropriate for assessing mold growth risk and drying during spring.

INTRODUCTION

The traditional methods for moisture analysis and design of the exterior building envelope (exterior walls, roofs, or ceilings) are one-dimensional, steady-state, and limited to water vapor diffusion; the results are difficult to interpret. The two most widely used methods are the dew-point method (ASHRAE 1993) and the Glaser method (Glaser 1959). The Kieper method has occasionally also been used (Kieper et al. 1976; Trethowen 1979; TenWolde 1983). These methods are used by design professionals and have provided the basis for current codes dealing with moisture control, such as requirements for vapor retarders. Some people advocate abandoning these design tools. Perhaps their greatest limitation is that their focus is restricted to prevention of sustained surface condensation. Many building failures, such as mold and mildew, buckling of siding, or paint failure, can sometimes occur without surface condensation. Conversely, limited condensation can often be tolerated, depending on the materials involved, temperature conditions, and the speed at which the material dries out. Another weakness is that these methods usually exclude all moisture transfer mechanisms other than vapor diffusion and neglect moisture storage in the building materials. Whatever their weaknesses, there is considerable debate about their usefulness. The most recent edition of the *ASHRAE Handbook of Fundamentals* (ASHRAE 1993) still contains a description of the dew-point method and an example of its use.

Several more complex computer-based tools have recently been developed. An overview of these models can be found in Hens and Janssens (1992) and Ojanen et al. (1994). These models are believed to provide more accurate results and are capable of addressing a wider variety of issues compared to traditional analytical methods. To date, MOIST is the only public domain program and probably the most widely used in the United States. While MOIST includes capillary and vapor transfer through materials, it does not address spatial two- or three-dimensional distribution, and it makes broad, simplifying assumptions about air leakage.

In recent years a U.S. government laboratory has collected field data on moisture conditions and airflows in walls typical of manufactured home construction. These data provide an opportunity for a comparison with results obtained with MOIST and from a simple steady-state computer spreadsheet program developed at the laboratory. This comparison can indicate the accuracy and advantages of these analytical tools.

OBJECTIVES AND APPROACH

The first objective of this study was to estimate the accuracy of a dynamic hourly moisture computer model such as MOIST by comparing modeling results with measured data. The second objective was to identify the

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differences between those results and results obtained with a steady-state calculation method and to assess under what conditions use of such a simplified method may be justified. Finally, the measured airflow data gave us an opportunity to determine if the effect of air movement can be simulated with the current version of MOIST in a satisfactory manner.

As both MOIST and the steady-state spreadsheet program are one-dimensional, capable only of calculating spatial average conditions, we compared all the modeling results with the average of the measured relative humidity (RH) values on a material surface. The comparison was necessarily limited to those surfaces for which we collected measured data. We made the comparison primarily on the basis of weekly average values, although a limited number of calculations with the steady-state method were made on a monthly average basis.

DESCRIPTION OF MOISTURE ANALYSIS TOOLS

MOIST Computer Model

For this study we used MOIST version 2.1. MOIST predicts the combined one-dimensional transfer of heat and moisture in multilayered walls (Burch and Thomas 1991, 1993). It is a transient model that includes heat storage, moisture storage, and moisture transfer by diffusion and capillary flow. MOIST accounts for the hygroscopic behavior of many building materials, including the variation of vapor transfer coefficients with moisture content. The model uses hourly weather data and produces hourly output of average moisture contents or surface moisture contents and surface relative humidity for all material layers in the wall. The approximate effects of air convection are accounted for by the option of including an air cavity with air exchange with the indoor or outdoor air. The effect of air infiltration can be approximated with air exchange with the outside and that of air exfiltration with air exchange with the indoor air. The user of MOIST version 2.1 is able to define a constant airflow for the entire run only—not hourly, weekly, or monthly airflow values.

FPL/Kieper Method

The steady-state analysis tool used in this study is described by TenWolde (1985) and its application is further described in a later paper (TenWolde and Carll 1992). The method is based on one-dimensional vapor diffusion and heat flow by conduction. It is an extension of the Kieper method, described by Trethowen (1979) and TenWolde (1983), with the addition of the effects of one-dimensional uniform airflow through the wall. In this paper it is referred to as the FPL/Kieper method. Moisture sorption and heat storage are ignored, as well as liquid moisture flow. The basic equations are given below, without the derivation. The derivation of the equation can be found in TenWolde (1985).

The equation for the steady-state moisture accumulation rate at the surface of interest can be derived from a mass balance analysis for that surface:

$$w = \frac{B}{Z}\left[\frac{(p_i - p_s)\,e^{By}}{e^{By} - 1} - \frac{(p_s - p_o)}{e^{B(1-y)} - 1}\right] \tag{7}$$

where

w = moisture accumulation rate, grain/h·ft^2 (kg/s·m^2)
p = vapor pressure, in. Hg (Pa);
p_i = indoor vapor pressure, in. Hg (Pa);
p_o = outdoor vapor pressure, in. Hg (Pa);
p_s = saturation vapor pressure at surface, in. Hg (Pa);
B = $\rho c v Z$;
c = $\omega/p \approx 145$ grain/lb·in. Hg ($6.14 \cdot 10^{-6}$ Pa^{-1});
v = air flux, ft/h (m/s);
Z = water vapor diffusion resistance of wall, perm^{-1} (m/s);*
ρ = density of air, lb/ft^3 (kg/m^3);
ω = humidity ratio, lb/lb (kg/kg).

Other elements of Equation 1 are explained below. The value for parameter y can be determined from

$$y = \frac{1}{Z}\int_0^L \frac{a}{\mu}\,dl \tag{8}$$

where

a = 12 for U.S. units and 1 for SI units;
L = distance of surface from the interior wall surface, ft (m);
l = distance from interior wall surface, ft (m); and
μ = water vapor permeability, perm-in. (s).

For practical purposes, Equation 2 can be reduced to the sum of the permeances of all material layers to the interior of the surface of interest, divided by the total vapor diffusion resistance of the wall. The temperature at the surface can be determined from

$$t = t_i - (t_i - t_o)\,\frac{e^{Ax} - 1}{e^{A} - 1} \tag{9}$$

where

t = temperature at surface, °F (°C);
t_i = indoor temperature, °F (°C);
t_o = outdoor temperature, °F (°C);
A = $\rho c_p v R$;
c_p = specific heat of air, Btu/lb·°F (kJ/kg·°C); and
R = thermal resistance of wall, h·ft^2·°F/Btu (m^2·K/W).

*1 perm = 1 grain/h·ft^2·in. Hg = 5.745 10^{-11} s/m (or kg/Pa·s·m^2). 1 lb = 7,000 grain.

The value of parameter x can be calculated in a manner very similar to that of y:

$$x = \frac{1}{R}\int_0^L \frac{1}{k} dl \tag{10}$$

where

k = thermal conductivity, Btu·in./h·ft²·°F (W/m·K).

Equations 3 and 4 allow the calculation of the surface temperature, which, in turn, allows calculation of the saturation vapor pressure at the surface, which is needed for Equation 1. Finally, the surface vapor pressure, p, and the surface relative humidity, ϕ, can be calculated:

$$\phi = \frac{p}{p_s} = \frac{1}{p_s}\left[p_i - (p_i - p_o)\frac{e^{By} - 1}{e^{B} - 1}\right]. \tag{11}$$

Equations 1 through 5 were incorporated in a computer spreadsheet program, allowing quick determination of the steady-state surface condensation (evaporation) rate and surface RH.

DESCRIPTION OF MEASURED DATA

Moisture conditions and air pressure differentials were monitored in 20 test walls in a test building constructed west of Madison, Wisconsin (TenWolde et al. 1995). The test building was 50 by 8 ft (15.2 by 2.4 m) and was partitioned into three rooms. In each of the two end rooms, the authors installed 10 test walls of various designs, all facing north. The two sets of 10 test walls were of identical design. Installation of the walls took place in December 1989. The middle room served as an instrumentation room. The building was heated and humidified for roughly half the 1989/90 heating season and the entire 1990/91 heating season prior to monitoring in the 1991/92 winter. During the heating season both test rooms were maintained at 70°F (21°C), but the relative humidity in the east room (low-humidity room) was 35% and in the west room (high-humidity room) it was around 45%. The building was left unconditioned during the spring, summer, and early fall.

Air pressurization tests were conducted on all but two walls during the summer of 1990, after installation of the walls in the building. From November 1991 through May 1992, the authors collected hourly relative humidities and temperatures inside the walls.

For comparison with model predictions, only the results from six walls for which we had the most complete data for RH and airflow were used. Of these, four walls (1HA, 1HB, 5HA, and 5HB) were located in the high-humidity room and two (1LA and 1LB) in the low-humidity room. The construction of 1LA was identical to that of 1HA and the construction of 1LB was identical to that of 1HB and represented construction typical for manufactured homes. The walls were constructed with nominal 2-in. by 6-in. (38-mm by 140-mm) lumber, with the studs 16 in. (40.6 cm) on center. The walls were 7 ft (2.13 m) high. The interior of all walls was 5/16-in. (8 mm) thick gypsum board with vinyl wall paper. The exterior of walls 1LA, 1LB, 1HA, and 1HB was covered with 3/8-in. (10-mm) thick waferboard siding finished with an exterior latex paint. The exterior of wall 5HA consisted of 0.47-in. (12-mm) fiberboard sheathing and the painted waferboard siding, with a 1/4-in. (6-mm) ventilated air space between the sheathing and siding. Wall 5HB was constructed as wall 5HA but with a 0.2-in. (5-mm) thick foamcore weather barrier replacing the fiberboard sheathing. All wall cavities were insulated with fiberglass batt insulation with kraftpaper facing. In walls 1LB, 1HB, 5HA, and 5HB we installed standard electrical outlet boxes in the interior gypsum board. These four walls were tested for air leakage; walls 1LA and 1HA were considered to be airtight. Special measures were taken to prevent lateral air and moisture flow between test walls.

The construction and measured airtightness of the walls are summarized in Table 1. The airtightness data translate to a range in effective leakage area (ELA) of 0.0027 to 0.0080 in.²/ft² (19 to 56 mm²/m²) of wall area, close to the range of values for framed exterior walls listed in chapter 23 of the *ASHRAE Handbook of Fundamentals* (ASHRAE 1993).

The authors monitored hourly relative humidities and temperatures on the back surface of the siding and sheathing (when present) and exterior surface temperatures. Figure 1 shows the location of each sensor. Temperatures were measured with thermocouples. For RH measurements, small wood electric resistance (DC) sensors, as described by Duff (1966), were used. This type of sensor clearly registers periods of condensation, but used as an RH sensor, it has an estimated error of approximately ±10% RH. However, it is not believed that

TABLE 9 **Summary of Wall Construction.**

Wall	Interior	Electrical Outlet	Cavity Insulation	Sheathing	Siding	ELA[a] in² (mm²)
1LA	gypsum board	no	glass fiber	—	waferboard	no data
1HA	gypsum board	no	glass fiber	—	waferboard	no data
1LB	gypsum board	yes	glass fiber	—	waferboard	0.054 (35)
1HB	gypsum board	yes	glass fiber	—	waferboard	0.023 (15)
5HA	gypsum board	yes	glass fiber	fiberboard[b]	waferboard	0.068 (44)
5HB	gypsum board	yes	glass fiber	foamcore[b]	waferboard	0.025 (16)

[a]ELA is the effective leakage area of the wall at an air pressure difference of 0.016 in of water (4 Pa), averaged over exfiltration and infiltration measurements.
[b]Ventilated air space between sheathing and siding, with openings at top and bottom.

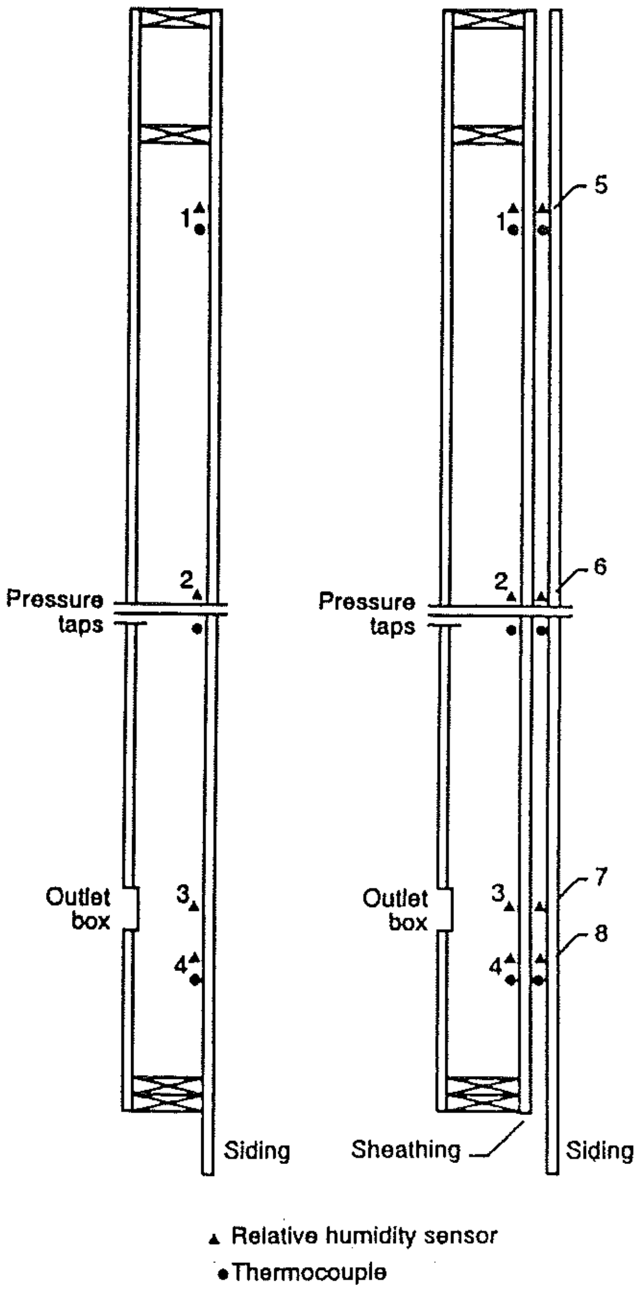

Figure 10 Locations of pressure taps and sensors in walls 1LA, 1LB, 1HA, and 1HB (left) and walls 5HA and 5HB (right).

that level of accuracy was attained in these measurements because the monitoring took place more than 20 months after calibration and installation of the sensors. In addition, in all the walls the authors found a large spatial variation in RH measurements between different locations on a particular surface. For the purposes of this study, the average RH for a surface was determined from all the readings on that surface, and the error was estimated from the standard deviation of the individual readings. This estimate should include random errors originating from calibration and measurement, as well as errors in the average RH caused by spatial variations in moisture distribution. Table 2 lists the estimated standard deviation of the average RH for each surface. The standard deviations were quite high for all surfaces of walls 5HA and the sheathing of 5HB, which made it difficult to use those measurements for model verification.

TABLE 10 **Estimated Standard Deviations of Relative Humidity Measurements.**

Wall Surface		Number of Sensors[a]	Standard Deviation of RH Readings (% RH)	Standard Deviation of Average of Measured RH (% rh)
1LA	back of siding	3	12	7
1HA	back of siding	2	14	10
1LB	back of siding	4	11	6
1HB	back of siding	4	13	7
5HA	back of sheathing	4	21	11
	back of siding	3	22	13
5HB	back of sheathing	4	29	15
	back of siding	3	10	6

[a]Excludes sensors that obviously malfunctioned.

In addition, the authors measured differential pressure across the siding (and sheathing) and the gypsum board every half-hour in walls with an electrical outlet. Pressures were measured at half-height at the locations indicated in Figure 1. The half-hour readings were taken with a single differential pressure transducer, using a computer-controlled switching valve. These readings were converted into hourly average airflows using pressurization calibration data obtained from the pressurization tests performed during the summer of 1990.

During the monitoring period, short periods of condensation were recorded in walls 1LA and 1LB on the back of the siding, but later inspection showed no mold in those walls. The authors recorded sustained condensation in walls 1HA and 1HB, and these walls had traces of mold. The location of the mold was different in each wall and did not reveal any obvious systematic patterns related to the construction of the wall or the location of the electrical outlet. Walls 5HA and 5HB showed no evidence of condensation or mold. More details on the data-acquisition system and the measurement results are described by TenWolde et al. (1995).

SIMULATION RUNS AND CALCULATIONS

Simulation Runs with MOIST

The authors used MOIST version 2.1 to generate weekly average data for surface RH and moisture contents, using our own weather data and hourly boundary conditions. For boundary conditions, hourly measured exterior surface temperature and outdoor RH were used, as were hourly measured indoor RH and indoor air temperature. The authors used the exterior surface temperature rather than the measured outdoor air temperature because more confidence was placed in the surface temperature data. The difference between the measured air and surface temperatures was too small to warrant a correction in the outdoor RH values. Moreover, because of the limited confidence in the air temperature measurements, the authors felt that a correction using those temperature data might increase the error in the RH values. To compensate for the effect of using surface temperatures, a large value was used for the exterior surface convection coefficient.

Burch and TenWolde (1993) simulated walls similar to the walls in this study, thus many selected run parameters were the same. The authors specified 2 nodes in the gypsum board, 2 in the kraft paper, 10 in the foamcore, and 14 in the fiberboard sheathing and waferboard siding.

The thermal insulation was entered as a nonstorage layer, represented only by its thermal resistance and water vapor permeance. In walls with airflow (1LB, 1HB, 5HA, and 5HB), the insulation layer was coupled to the exterior air for infiltration and to the interior air for exfiltration. Because MOIST does not allow entering hourly values for airflow, airflows were entered as seasonal averages: 0.621 $ft^3/h \cdot ft^2$ (0.0796 $m^3/h \cdot m^2$) (exfiltration) for wall 1LB, 0.00863 $ft^3/h \cdot ft^2$ (0.0263 $m^3/h \cdot m^2$) (exfiltration) for 1HB, 0.0057 $ft^3/h \cdot ft^2$ (0.0018 $m^3/h \cdot m^2$) (infiltration) for 5HA, and 0.00044 $ft^3/h \cdot ft^2$ (0.00014 $m^3/h \cdot m^2$) (infiltration) for 5HB. The ventilation air space behind the siding in walls 5HA and 5HB was represented by another non-storage layer, with air coupling to the outside. Because the authors did not measure the actual ventilation rate in this air space, MOIST was run with two assumptions: 1 air change per hour (ACH) and 100 ACH. The air space was assumed to have a thermal resistance of R-1 (0.18 $m^2 \cdot K/W$) and a large permeance.

Material properties of samples from the actual materials used in these test walls had previously been measured at a national laboratory and were reported by Richards et al. (1992) and Burch et al. (1992). These property data have been incorporated into the MOIST database; therefore, the data from this database were used. Figure 2 shows the permeance values of the materials. For the permeance of the vinyl wall cover, the authors used 0.5 perm (29×10^{-12} s/m), based on measurements conducted at the laboratory (Burch et al. 1992). Permeance of the exterior latex paint was assumed to be 10 perm (570×10^{-12} s/m). Based on the MOIST database, the fiberglass insulation was assumed to have an R-value of 18.4 (3.24 $m^2 \cdot K/W$) and a permeance of 8.6 perm (490×10^{-12} s/m). The permeance value is the value for fiberglass insulation in the MOIST database at 25% RH, representing an approximate dry-cup value. The authors' value is about half the value reported for fiberglass in Table 9 in chapter 22 of the *ASHRAE Handbook of Fundamentals* (ASHRAE 1993), which is a wet-cup, rather than a dry-cup value. In any case, the precise choice of permeance for the insulation is unlikely to have a significant effect on the results because the lower permeances of the vinyl wall paper, the kraft paper, and the waferboard siding controlled the rate of moisture entry and release.

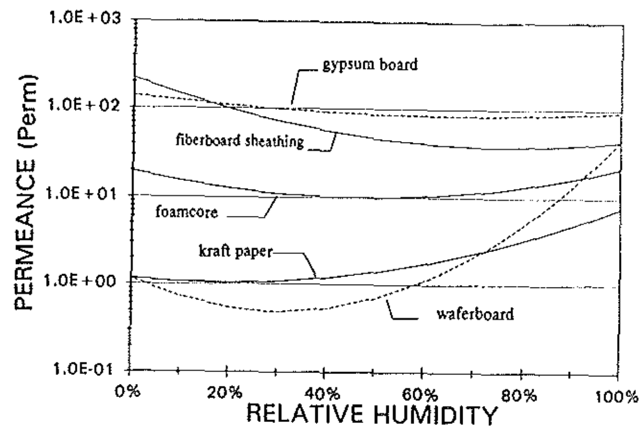

Figure 11 *Permeance of building materials as a function of relative humidity.*

Calculations with FPL/Kieper Method

Steady-state calculations were performed with the FPL/Kieper equations, using weekly average and monthly average input data for outdoor conditions, indoor conditions, and airflows. Figure 3 shows weekly average outdoor (surface) temperature and RH, and Figure 4 shows the measured weekly average airflows for walls 1LB, 1HB, 5HA, and 5HB. Input data were selected as close as possible to the material property data in the MOIST database. Thermal resistance and permeance values

TABLE 11 **Material Property Values Used for FPL/Kieper Calculations**

Material	Thickness, Inch	(mm)	R-Value	($m^2 \cdot K/W$)	Permeance, Perm	(10^{-12} s/m)
inside air film	—		0.68	(0.12)	1000	(57000)
vinyl wall paper	—		—		0.5	(29)
gypsum board	5/16	(8)	0.29	(0.05)	103	(5900)[a]
kraft paper	0.006	(0.15)	0.005	(0.0009)	1	(57)[a]
glass fiber insulation	5.5	(140)	18.4	(3.24)	8.58	(490)[a]
waferboard siding	3/8	(10)	0.625	(0.11)	3	(180)[b]
latex paint	—		—		10	(570)
foamcore	0.21	(5.3)	0.62	(0.11)	12.2	(700)[b]
fiberboard sheathing	0.47	(12)	1.25	(0.22)	37	(2200)[b]
ventilated air space	1/4	(6)	1	(0.18)	1000	(57000)

[a] This value represents a dry-cup value and equals the MOIST permeance data base value at 25% RH.
[b] This value represents a wet-cup value and equals the MOIST permeance data base value at 75% RH.

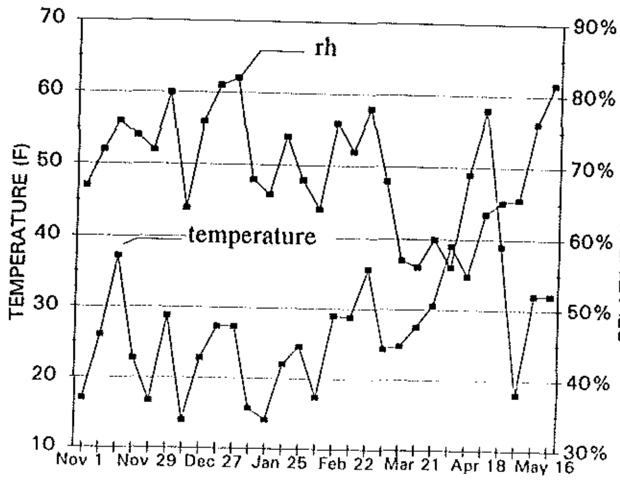

***Figure 12** Weekly average outdoor temperature and humidity during the monitoring period.*

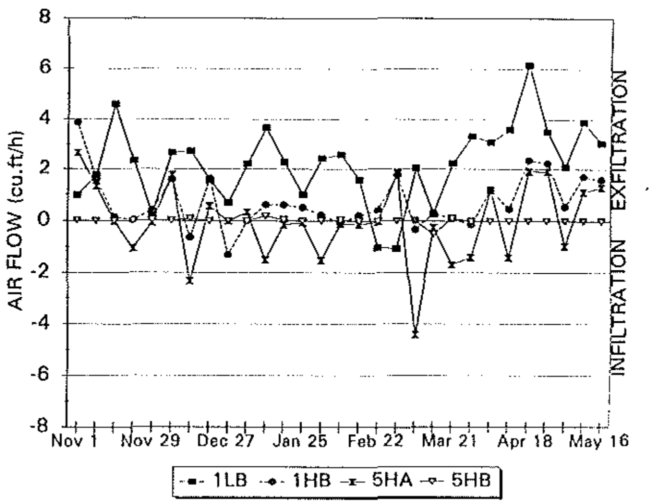

***Figure 13** Weekly average air leakage through walls 1LB, 1HB, 5HA, and 5HB during the monitoring period*

were taken from the MOIST database, as listed in Table 3. Because steady-state methods require constant values for permeance, the authors chose the MOIST value at 25% RH, representing approximate dry-cup values; however, for the exterior siding and sheathing materials, we used values at 75% RH, representing approximate wet-cup values.

The vented air space in walls 5HA and 5HB was handled by vapor flow and thermal resistances parallel to the resistances of the siding, as described in detail previously (TenWolde and Carll 1992). The thermal parallel resistance is given by

$$R_{par} = \frac{S}{Q\rho c_p} \tag{12}$$

where

R_{par} = parallel thermal resistance, h·ft²·°F/Btu (m²·K/W);

Q = ventilation airflow, ft³/h (m³/s); and

S = wall surface area, ft² (m²).

The parallel vapor flow resistance is defined by

$$Z_{par} = \frac{S}{Q\rho c}. \tag{13}$$

The authors did not measure the ventilation rate in the air space behind the siding. To obtain an indication of the sensitivity of the results to this ventilation rate, very low (1 ACH) and very high rates (100 ACH) were used. It was assumed that ventilation air was delivered to the center of the air space, dividing the air space and its resistances into halves.

RESULTS AND DISCUSSION

Standard deviations for the average of the measured RH for each wall (Table 2) were used as a yardstick for the uncertainty in the measured average. For this paper, the authors will refer to twice the standard deviation as the *measurement error.* In addition to focusing on the overall coincidence of measured and predicted values, special attention was paid to the early spring values, when temperatures became high enough to support mold growth on the surface. This occurred in the week of April 18.

Airtight Walls

Walls 1LA and 1HA were built very airtight and therefore it was assumed they had no air leakage. Figure 5 shows the relative humidity at the back surface of the siding in wall 1LA (which was exposed to 35% average indoor RH) as calculated by MOIST, as determined with the FPL/Kieper method, and as measured. The MOIST results show good agreement with the measured data—the MOIST results are always within the measurement

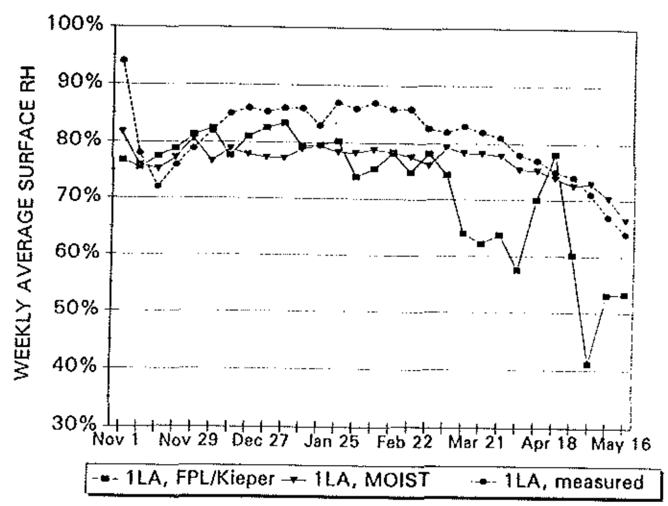

***Figure 14** Weekly average RH at the back of the siding of wall 1LA, as measured and as calculated with FPL/Kieper and MOIST.*

error band (±14% RH), and 66% of the results fall within 7% RH (one standard deviation). MOIST also accurately predicted the drying behavior in early spring and accurately predicted that conditions were not conducive to mold growth on the back of the siding.

As expected, the weekly results from the FPL/Kieper method are not as close to the measured data as the MOIST results but are generally close during the peak of the winter season. The results are within the measurement error 79% of the time, with the most serious deviations occurring in the spring. This should come as no surprise because the FPL/Kieper method calculates steady-state relative humidity and therefore does not account for any drying of moisture accumulated during winter. However, the results accurately indicate that wall 1LA had a low potential for condensation or mold growth.

Using FPL/Kieper with monthly averages did not significantly change the reliability of the results. Results during winter were acceptable, but were substantially below the measured values during spring.

Figure 6 shows the results for wall 1HA, which was exposed to an average indoor humidity of 45% RH. Although MOIST results do not appear to be as close to measured average values as with wall 1LA, the measurement error for 1HA (20% RH) was substantially greater than that for wall 1LA. MOIST results always fall within this error band, and 86% of the results are within 10% RH (one standard deviation). As with wall 1LA, there is fairly good agreement between MOIST and measurements during the crucial early spring period, but neither indicates a great potential for mold. Two sensors on the sheathing indicated periods of sustained condensation during the winter months, and inspection of wall 1HA revealed small patches of light, localized mold growth on the sheathing. However, it is possible that the mold was already present at the start of monitoring because the walls had been exposed to roughly 1½ heating seasons, with the same indoor conditions, before monitoring began. In any event, MOIST results accurately indicate high relative humidity during winter but no serious moisture problems in wall 1HA.

The FPL/Kieper results for wall 1HA show much the same character as those for wall 1LA. Results are good for the middle of winter, when outdoor conditions were relatively constant, but the method's steady-state approach led to substantial underprediction of relative humidity during early spring. The results are within the measurement error band 83% of the time, and 72% of the results are within 10% RH of the measured average. Despite the errors, the results lead to the correct conclusion that wall 1HA did not experience serious moisture problems. Again, using monthly averages in the analysis did not improve the results.

Walls with Air Leakage

Figure 7 shows all relative humidity results for the back of the siding of wall 1LB, which had the same construction as 1LA and 1HA but included an electrical outlet through which some air leakage occurred (see Figure 4). The MOIST results are within the measurement error band (±12% RH) 54% of the time, a considerably poorer agreement than for the airtight walls. With an ELA of 0.054 in.^{2} (35 mm^2), the airtightness of wall 1LB is typical for standard frame construction.

Steady-state (FPL/Kieper) calculations, using weekly average airflow data, indicated sustained condensation on the sheathing. The results are within the measurement error band (±12% RH) only 29% of the time. Although three sensors recorded short periods of condensation on the siding during midwinter, steady-state methods

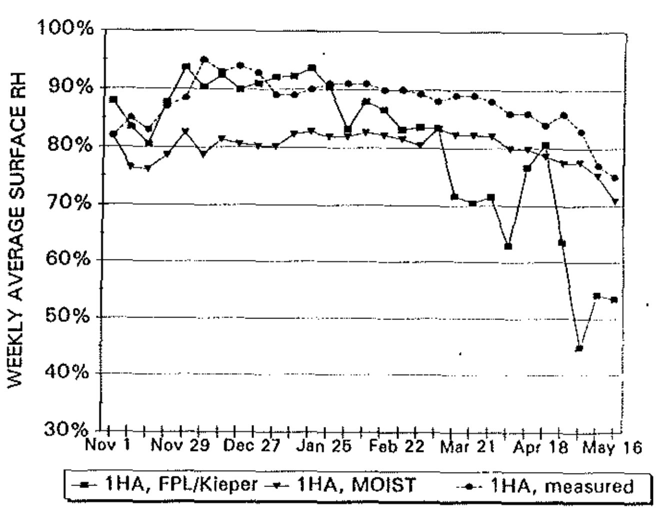

Figure 15 *Weekly average RH at the back of the siding of wall 1HA, as measured and as calculated with FPL/Kieper and MOIST.*

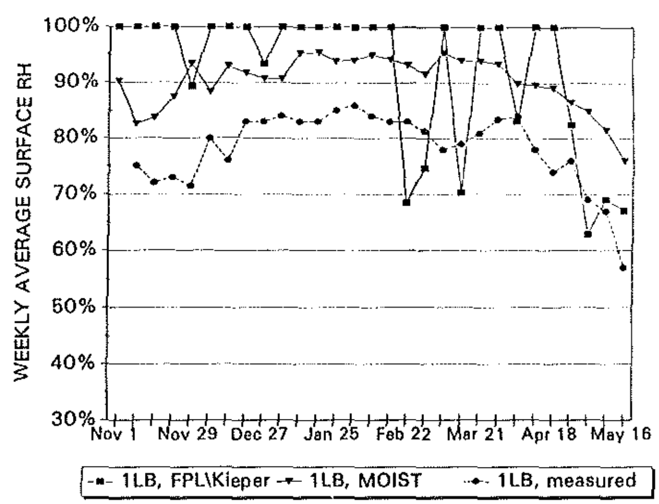

Figure 16 *Weekly average RH at the back of the siding of wall 1LB, as measured and as calculated with FPL/Kieper and MOIST.*

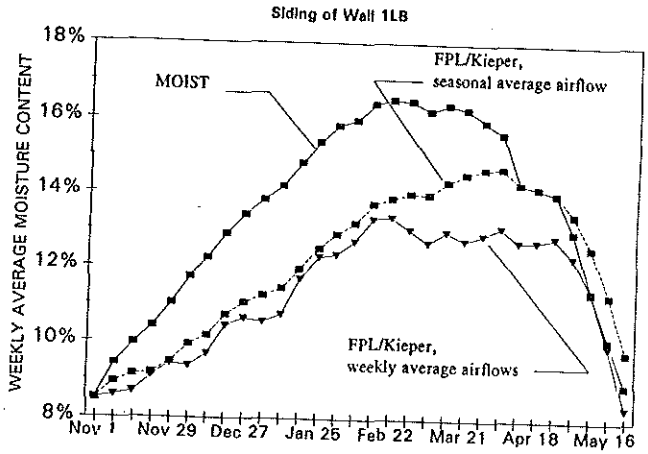

***Figure 17** Weekly average moisture content of the siding of wall 1LB as determined with MOIST and FPL/Kieper, using weekly average and seasonal average airflow data.*

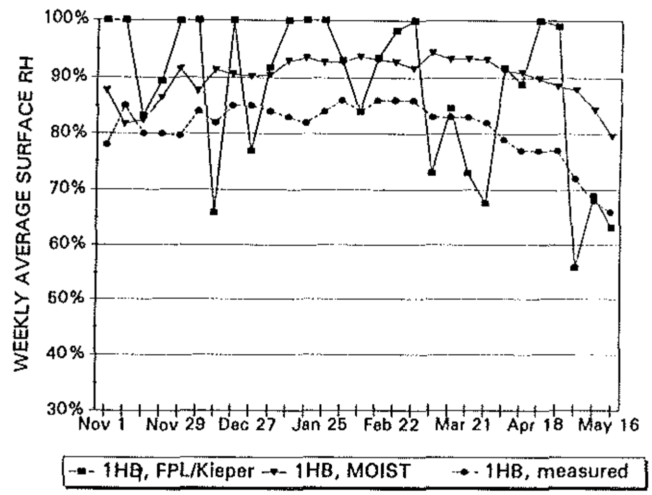

***Figure 18** Weekly average RH at the back of the siding of wall 1HB, as measured and as calculated with FPL/Kieper and MOIST.*

appear to overstate the condensation problem. However, when the change in moisture content of the siding was estimated from the weekly rates of condensation (evaporation), using Equation 1, FPL/Kieper actually predicted a lower siding moisture content than MOIST (Figure 8). This occurred because MOIST accounts for moisture sorption, which increases the rate of moisture uptake, and the FPL/Kieper method does not.

The FPL/Kieper method predicted lower moisture contents when weekly average airflow values were used than with a seasonal average value, as was used in the MOIST run (Figure 8). The reason for this is that the most severe air exfiltration occurred during November and April, when outdoor temperatures were relatively mild (see Figures 3 and 4). It is likely that the MOIST results also would have been lower if the authors had been able to use weekly average airflow data rather than a seasonal average. In MOIST, moisture content and surface RH are closely coupled, so the MOIST RH predictions likely would have been closer to measured RH with weekly average airflow input. It is also possible that the difference between MOIST results and measurements is primarily caused by errors in the airflow values or by the fact that MOIST is only one-dimensional.

Inspection of wall 1LB did not reveal any mold growth and the sensors signaled only sporadic localized condensation during midwinter. The FPL/Kieper method appears to overstate the condensation potential but also indicates a potential for rapid drying. MOIST indicates a moderate risk of mold growth in the spring, which was not borne out by the inspection, indicating that MOIST RH predictions are somewhat high.

The modeling results for wall 1HB, shown in Figure 9, are slightly closer to the measured values than is the case with wall 1LB, probably because 1HB was considerably more airtight than 1LB. The MOIST results are within the 14% RH measurement error 93% of the time and the FPL/Kieper results 55% of the time. Again, MOIST seems to somewhat overestimate RH conditions, perhaps because weekly average airflow data could not be used. Inspection of wall 1HB did reveal traces of mold, and the MOIST predictions of more than 80% RH for early spring therefore appear credible. The sporadic condensation, indicated by the FPL/Kieper results, also agrees with the measurements.

Measurement errors for walls 5HA and 5HB were too large to provide a useful comparison with calculated results, with the exception of relative humidity on the back of the siding of 5HB. In addition, it was found that the choice of ventilation rate of the air space behind the siding greatly affected the results. Poor correlations were found for the low (1-ACH) ventilation rate. With the 100-ACH rate, 83% of the MOIST results for the back of the siding of 5HB are within the ±12% RH error band.

CONCLUSIONS AND RECOMMENDATIONS

The results lead to the following conclusions, recommendations, and observations.

- MOIST is capable of providing reliable and useful average surface relative humidity estimates for airtight wood frame walls during winter, under the indoor conditions tested, but it is less reliable for walls with air leakage typical for standard wood frame construction.
- For insulated wood frame wall construction, steady-state methods can give acceptable results for midwinter, and possibly midsummer, but they are inappropriate for assessing mold growth risk and drying during spring.
- MOIST may yield better results with more detailed airflow input, but the authors do not advocate

revising MOIST in this way because such detailed airflow data are generally not available.

- One-dimensional moisture analysis tools are not capable of predicting the spatial moisture distribution. Although two- or three-dimensional models would theoretically be able to estimate spatial moisture variations, the apparent randomness of spatial patterns in the measured RH and observed mold suggest that it would be difficult to predict these actual patterns with any mathematical model. However, two- or three-dimensional models do allow investigation of additional issues relating to moisture performance, such as rising damp, wood siding performance, or corner effects.

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