A COMPUTER ANALYSIS OF MOISTURE ACCUMULATION IN THE WALLS OF MANUFACTURED HOUSING

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ABSTRACT

A detailed computer analysis was conducted to investigate the effectiveness of three alternative practices for controlling moisture accumulation in the walls of manufactured housing during the winter. The three practices included (1) providing an interior vapor retarder, (2) using permeable sheathing and siding, and (3) providing an outdoor ventilated cavity. The current HUD Manufactured Home Construction and Safety Standards do not require a vapor retarder for practices 2 and 3. The analysis was carried out for a cold winter climate (Madison, WI), an intermediate winter climate (Boston, MA), a mild winter climate (Atlanta, GA), and a Pacific Northwest climate (Portland, OR).

The practice of providing a vapor retarder was found to be effective in all four climates. The moisture content of the siding was always considerably below fiber saturation. On the other hand, the practice of using permeable sheathing and siding and the practice of providing an outdoor ventilated cavity were not always effective in colder climates. Moisture accumulated above fiber saturation, and free liquid water existed within the pore structure, providing a potential for material degradation.

A detailed computer analysis was also conducted of moisture accumulation in manufactured housing walls in a hot and humid climate (Lake Charles, LA). During the summer, moisture from the outdoor environment is transferred into manufactured housing by diffusion and, more importantly, infiltration. As a result, moisture accumulates at interior layers of the construction cooled by air conditioning. When an interior vapor retarder is used in the instruction, the relative humidity at the outside surface of the vapor retarder can approach saturation, thereby providing an environment conducive to mold and mildew growth.

INTRODUCTION

During cold weather, the absolute humidity of the air within a residence is considerably higher than that of the outdoor air. In this situation, moisture from the indoor environment permeates walls by way of diffusion and air exfiltration through openings and cracks in the construction. This moisture is partially adsorbed and accumulates at exterior layers of the construction. Duff (1968) observed that the moisture content in outer layers of the wall increases during cold winter periods and subsequently decreases during warm summer periods. Relative to the above discussion, the maximum amount of moisture that can be absorbed by wood-based materials during the winter without material degradation is fiber saturation. At this condition, the liquid water exists within the pore space of a material.

During the winter, more moisture may accumulate in the walls of manufactured housing than in those of site-built houses. This is because manufactured houses tend to have higher indoor relative humidity compared to conventional houses due to their smaller volumes and their lower infiltration rates (Burch 1991).

The American Hotel and Motel Association (1991) has reported that mold and mildew growth behind interior vapor retarders (e.g., vinyl wallpaper) is a serious problem in hot and humid climates. During the summer, outdoor moisture permeates into a building and adsorbs (or condensates) at interior wall surfaces cooled by air conditioning. When the exterior construction is permeable to water vapor or outdoor air infiltrates into the construction, the relative humidity at the outside surface of an interior vapor retarder (e.g., vinyl wallpaper) can approach a saturated state. Such a condition is conducive to mold and mildew growth. Fungal spores from this mold and mildew subsequently can enter the living space and cause an indoor air quality problem (i.e., musty odor).

All manufactured homes constructed and sold in the United States must meet the requirements specified in Section 3280.504 of the HUD Manufactured Home Construction and Safety Standards (HUD 1987). These standards require manufacturers to use one of the following practices to control moisture accumulation in walls during cold winter periods: (1) install an interior vapor retarder of 1 perm or less, (2) use permeable sheathing and siding that has a combined permeance higher than $2.9 \times 10^{-10}$ kg/Pa·s·m$^2$ (5 perm), or (3) provide an outdoor ventilated cavity between the siding and wall insulation. For practices 2 and 3, the HUD standards do not require an interior vapor retarder. The same practices apply to homes sold in hot and humid climates.

Henceforth, in this report, these standards will be referred to as the HUD standards.

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The National Institute of Standards and Technology (NIST) recently has developed a detailed model, called MOIST, that predicts the combined transfer of heat and moisture in a multilayer wall under isothermal conditions (see Burch and Thomas [1991]). This model includes moisture transfer by diffusion and capillary flow. The moisture-transfer resistance offered by vapor retarders and paint layers is readily included in simulations. The model accounts for convective moisture transfer by including sir cavities that may be coupled to indoor and outdoor air. In this report, the model MOIST is used to investigate the viability of the three above moisture-control practices in cold climates and hot and humid climates.

DISCUSSION OF MODEL

Theory

Within each layer of a wall construction, moisture transfer is governed by the following one-dimensional conservation of mass equation:

$$\frac{\partial}{\partial y} \left[ D_y(\gamma, T) \frac{\partial \gamma}{\partial y} \right] + \frac{\partial}{\partial y} (D_T(\gamma, T) \frac{\partial T}{\partial y}) = \frac{\partial \gamma}{\partial t}. \quad (1)$$

The selection of moisture content ($\gamma$) and temperature ($T$) as potentials has the advantage that the same mathematical formulation represents both diffusion transfer and capillary transfer. This formulation is equivalent to using water-vapor pressure as the moisture-transfer potential in the diffusion regime and suction pressure in the capillary flow regime with a single required diffusivity.

Heat transfer is governed by the one-dimensional conservation of energy equation:

$$\frac{\partial}{\partial y} \left[ k(\gamma, T) \frac{\partial T}{\partial y} \right] - \rho (C_d + \gamma C_w) \frac{\partial T}{\partial t} = 0. \quad (2)$$

Latent transport of heat is included at the boundaries of the layers (see Burch and Thomas [1991]). The other components of enthalpy transport by moisture movement are generally small and are therefore neglected in the analysis. The term $(C_d + \gamma C_w)$ includes the effect of energy storage in both the dry material and accumulated moisture.

In the above two governing equations, strong couplings exist between heat and moisture transfer. Both the diffusivity for the moisture gradient ($D_y$) and the diffusivity for the temperature gradient ($D_T$) are strong functions of moisture content and temperature. The thermal conductivity ($k$) can also be a function of moisture content and temperature, but for the present analysis it is assumed to be constant.

When the moisture content of a material is below fiber saturation, the diffusivity for the moisture gradient ($D_y$) and the diffusivity for the temperature gradient ($D_T$) are calculated by the relations

$$D_y = \frac{\mu(\phi) \rho_v(T)}{D_v}$$

and

$$D_T = \frac{\mu(\phi) \rho_P(T)}{D_p} \quad (3)$$

The above equations may be derived by introducing the sorption isotherm function $f(\phi)$ and applying the chain rule to Fick's steady-state diffusion equation with the gradient of the water-vapor pressure as the driving-force potential.

When the moisture content of a material is above fiber saturation, a liquid diffusivity $D_L$ is used in Equation 1. It is calculated using procedures given in Burch and Thomas (1991). The diffusivity for the temperature gradient ($D_T$) is calculated using the second relation of Equation 3.

The model also has a provision for including nonstorage layers (e.g., an air space, glass-fiber insulation, a vapor retarder, etc.) that may be sandwiched between two storage layers. In a nonstorage layer, the storage of heat and moisture is neglected, and the transfer of heat and moisture is assumed to be steady-state. A nonstorage layer may be connectively coupled to indoor and outdoor air.

A more detailed description of the model is given in Burch and Thomas (1991). When MOIST is released into the public domain in the near future, the program and documentation can be obtained at no cost from Doug Burch at the National Institute of Standards and Technology.

Solution Procedure

Equations 1 and 2 were recast into finite-difference equations using a uniform nodal spacing within each layer. An implicit solution technique with coupling between the two conservation equations was used to solve the equations. A Fortran 77 computer program, called MOIST, with a tridiagonal-matrix solution algorithm was prepared. At each time step, the calculation proceeds by first solving for the temperature distribution, after which a set of moisture contents is calculated.

We used MOIST to analyze the moisture accumulation in a wall subjected to both a cold climate and a hot and humid climate. For the baseline wall construction (see Figure 1), 2 nodes were used for the gypsum board, 2 for the Kraft paper, and 14 for the waferboard siding. The insulation was treated as a nonstorage layer. When the computer program was run on a 386-level microcomputer with a 33-MHz clock speed, equipped with a math coproces-
about 30 minutes of computer time was required to simulate one year of real time.

**DESCRIPTION OF BASELINE WALL**

Unless otherwise indicated, the wall construction given in Figure 1 was analyzed. The 89-mm (3.5-in.) wall cavity was filled with glass-fiber insulation with a thermal resistance of R-1.9 m²·K/W (11 h·ft²·°F/Btu). The wall faced north, and the solar absorptance of the exterior surface was 0.7. The effect of wood-framing members was neglected.

**PARAMETERS USED IN ANALYSIS**

The following diffusion properties and boundary conditions were used as input for the model.

**Boundary Conditions**

For the cold-climate analysis, the indoor temperature and relative humidity were assumed to be 21°C (70°F) and 50%, respectively. For the analysis of hot and humid climate, the indoor temperature and relative humidity were taken to be 24°C (76°F) and 50%, respectively. The use of an indoor relative humidity of 50% is warranted because mobile homes are tighter and have lower infiltration rates and therefore tend to have higher indoor relative humidities than site-built homes. In fact, Zieman and Waldman (1984) report mobile homes having indoor relative humidities in excess of 50%.

The outdoor temperature, relative humidity, and solar radiation were based on weather year for energy calculations (WYEC) hourly weather data for each of the five locations (Crow 1981).

**Diffusion Properties**

A plot of the equilibrium moisture content versus relative humidity (called a sorption isotherm) for the construction materials is given in Figure 2a. The sorption isotherm data were measured by Richards et al. (1992). The water vapor permeance of the materials was measured by Burch et al. (1992). A plot of the permeance of the materials versus relative humidity is given in Figure 2b.

In the analysis, the vinyl wallpaper, glass-fiber insulation, and latex paint layers were treated as nonstorage layers. The permeance of vinyl wallpaper was taken to be $2.9 \times 10^{-11}$ kg/Pa·s·m² (0.5 perms), based on measurements by Burch et al. (1992). The permeance of glass-fiber insulation was taken to be $3.8 \times 10^{-9}$ kg/Pa·s·m² (33.1 perms), based on Table 7 of ASHRAE (1989). The permeance of latex paint layers was taken to be $5.7 \times 10^{-10}$ kg/Pa·s·m² (10 perms).

**COLD CLIMATE ANALYSIS**

In the results below, the wall construction is considered to be airtight, unless otherwise indicated.

**Effectiveness of a Vapor Retarder**

First, the model was used to investigate the effectiveness of an interior vapor retarder in controlling moisture accumulation in the baseline wall construction. Asphalt-coated kraft paper is used for the vapor retarder. The following four winter climates were analyzed: a cold winter...
climate (Madison, WI), an intermediate winter climate (Boston, MA), a mild winter climate (Atlanta, GA), and a Pacific Northwest climate (Portland, OR). The heating degree-days for these locations are 4,294°C days (7,730°F days), 3,123°C days (5,621°F days), 1,719°C days (3,095°F days), and 2,662°C days (4,792°F days), respectively.

Results with Vapor Retarder The moisture content of the layers of the construction are plotted versus time of year in Figure 3 for the four winter climates. The moisture content of the waferboard siding is seen to rise during the winter and decrease during summer periods. Higher moisture contents occur at the surface of the waferboard siding that faces the wall insulation, due to its high moisture-transfer resistance. For this reason, separate curves are given for a thin surface layer (facing the wall insulation) and a remaining bulk interior layer. The thickness of the thin surface layer was 2 mm (0.079 in.). Comparing the four plots, higher peak moisture contents occur in colder climates. The vapor retarder maintains the peak moisture content of the waferboard siding substantially below fiber saturation (i.e., 25%) in all four climates. This means that free liquid water is not present within its pore structure. It should be pointed out that a vapor retarder is only effective if air leakage is effectively eliminated, as will be shown later.

Results without a Vapor Retarder Similar results for the baseline wall without a vapor retarder and no air leakage are given in Figure 4. The solid horizontal line depicts the moisture content at which fiber saturation occurs within the waferboard siding. A moisture content above fiber saturation means that free liquid water exists within the pore structure, thereby posing a risk of material degradation. In Madison (Figure 4a), the moisture content of the waferboard siding rises above fiber saturation during a three-month winter period. In Boston (Figure 4b), Atlanta

Based on Richards et al. (1992).
(Figure 4c), and Portland (Figure 4d), the peak moisture content approaches, but does not exceed, fiber saturation. The sharp rises and falls seen in the results of Figure 4 are due to intermittent high moisture accumulation at the inside surface of the waferboard siding. The permeability of the wafer board siding is low at low moisture contents but rises markedly as the moisture content approaches a saturated state (see Figure 2b). As moisture accumulates at the surface, the moisture content approaches a saturated state. This causes the material to become very permeable. Moisture is absorbed into the bulk of the material, thereby reducing the surface moisture content.

Fungus deterioration of the waferboard siding is unlikely, even though the moisture content reaches fiber saturation for several results of Figure 4. This is because the waferboard siding is cold when the moisture content is high. The wall is seen to dry rapidly in the spring. Decay fungi grow very slowly when exposed to cold temperatures.

Sensitivity of Results to Resistance of Wall Insulation In northern climates, some manufactured homes are built with 150-mm (6-in.) nominal studs with thermal insulation having a resistance of R-3.3 m²·K/W (19 h·ft²·°F/Btu) instead of R-1.9 m²·K/W (11 h·ft²·°F/Btu). Separate computer runs were conducted for these two levels of insulation. The climate of Madison, WI, was used in the analysis.

The moisture contents of the waferboard siding for these two computer simulations are compared in Figure 5. The difference in moisture content for these two computer simulations is small. The amount of moisture transfer and subsequent accumulation depends on two factors: the temperature difference between the indoors and the waferboard siding and the water-vapor permeance of the interior portion of the wall. Since these two factors do not differ appreciably between the two insulation levels, little difference in moisture content of the waferboard is predicted.

Effect of Indoor Air Exfiltration In this section and sections that follow, we used the model to investigate the effect of air leakage on the moisture accumulation. Since the model is one dimensional, we assumed that the air

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**Figure 4**  Moisture content of layers plotted versus time of year for baseline wall without a vapor retarder (airtight construction).
exfiltrates uniformly at all locations of the construction. The authors would like to acknowledge that it is more likely that exfiltration does not occur uniformly but is concentrated at specific air leakage sites where the moisture accumulation is likely to be higher (see Tsongas and Nelson [1991]).

The ventilation equipment used in manufactured housing may inadvertently positively pressurize the interior of the home. This positive pressure can cause indoor air to exfiltrate outwardly through cracks in the construction. Here it should be recognized that an interior vapor retarder often does not provide a perfect air seal. When exfiltrating air impinges on the exterior parts of the construction, moisture adsorbs (or condenses) and accumulates at this location during winter. In this section, the effect of indoor air exfiltration on the moisture accumulation in the baseline wall with a vapor retarder is investigated.

In the analysis, it was assumed that indoor air exfiltrated through the building envelope at a rate of $2.2 \times 10^{-5} \text{ m}^3/\text{s per m}^2$ ($0.26 \text{ ft}^3/\text{h per ft}^2$). We assumed that a single-width home had a ventilation rate of $1.2 \times 10^{2} \text{ m}^3/\text{s}$ (25 cfm). This corresponds to a moderate ventilation rate of about 0.2 air changes per hour for a typical single-width home with a floor area of 93 m$^2$ (1,000 ft$^2$). Furthermore, we assumed that one-half of the exfiltration occurred through cracks associated with windows and doors, while the other half occurred through penetrations in opaque portions of the building envelope (e.g., electrical outlets, baseboard cracks, etc.).

The results given in Figure 6 show that the air exfiltration causes the moisture content of the waferboard siding to approach fiber saturation in Madison, WI. However, as in the case of the previous results, the wall dries rapidly in the spring.

It should be pointed out that indoor air exfiltration into wall construction can largely be prevented by the use of an air barrier in the construction.

**Effectiveness of Permeable Sheathing and Siding**

Next, we consider the effectiveness of permeable sheathing and siding. In the baseline wall construction (see Figure 1), the waferboard siding is replaced with 13-m (0.5-in.) fiberboard sheathing and lapped vinyl siding, and the vapor retarder is removed. Cracks between the lapped pieces of the vinyl siding were assumed to exchange air with the outdoor environment, giving it an effective permeance of $5.7 \times 10^{-9} \text{ kg/Pa·s·m}^2$ (10 perm). The combined permeance of the sheathing and vinyl siding is $4.8 \times 10^{-10} \text{ kg/Pa·s·m}^2$ (8 perm). This value is higher than the minimum of $2.9 \times 10^{-10} \text{ kg/Pa·s·m}^2$ (5.0 perm) required by the HUD standards. The interior vapor retarder was removed.

The moisture content of the fiberboard sheathing is plotted versus time of year in Figure 7 for the four climates. Since there is only a very small gradient in moisture content across the fiberboard sheathing, a single curve for its average moisture content is given. In Madison, the moisture content rises considerably above fiber saturation during a four-month winter period, thereby posing a potential risk of material degradation. Moreover, the peak moisture content approaches fiber saturation in Boston, MA.

The above results show that the practice of providing permeable sheathing and siding is not, by itself, an effective moisture-control practice for cold winter and intermediate winter climates.

**Effectiveness of Outdoor Cavity Ventilation**

Next, we consider the effectiveness of an outdoor ventilated cavity. In the baseline wall construction, the waferboard siding is furred out from the insulation, forming a 19-mm (0.75-in.) cavity we assume to be ventilated with outdoor air at a rate of 6 ach. The interior vapor retarder is removed.

**Without Indoor Air Exfiltration** The moisture content of the waferboard siding is plotted versus time of year in Figure 8 for the four winter climates. Comparison with Figure 4 reveals that the ventilation reduces moisture levels in the wall, but in Madison the moisture content is still above fiber saturation for a one-month winter period. In addition, the peak moisture content still approaches fiber saturation in Boston, MA, and Portland, OR.

These results indicate the practice of providing outdoor air ventilation to the cavity may not be effective in preventing moisture accumulation in the siding in cold and intermediate winter climates or the Pacific Northwest climate. Outdoor ventilation has limited effectiveness because the temperature-difference driving force for transferring moisture between the cavity and the outdoors is small. In addition, the outdoor air is cold during the winter and therefore has reduced capacity to hold water vapor.

These results are based on an assumed cavity ventilation rate of 6 ach. The results might have been more
positive with higher ventilation rates. However, it is impossible in practice to ensure that the ventilation rate will always be sufficiently high to prevent moisture problems. 

**With indoor Air Exfiltration** Providing an outdoor ventilated cavity increases the air permeability of the exterior wall construction and thereby increases the air permeability for the whole wall system. This provides a potential for increased air exfiltration of indoor air and moisture into the construction (TenWolde and Carll 1992). A separate computer simulation was carried out to investigate this potential side effect.

In the analysis, we assumed that providing an outdoor ventilated cavity gives rise to an air exfiltration rate of $2.5 \times 10^{-5} \text{ m}^3/\text{s} \text{ per m}^2 (0.29 \text{ ft}^3/\text{h per ft}^2)$. This exfiltration rate corresponds to a cavity air exchange rate of 1 ach with the indoors. Weather data for Madison, WI, were used. The results are given in Figure 9. Comparing Figures 8a and 9, it is seen that the exfiltration of indoor air into the wall construction increases the moisture content of the waferboard siding. With air exfiltration (Figure 9), the moisture content rises above fiber saturation for a three-
month winter period. On the other hand, without exfiltration (Figure 8a), the moisture content rises above fiber saturation for a only one-month winter period.

Similar simulation results with an outdoor ventilated cavity but with a vapor retarder are given in Figure 10. When the wall is airtight (Figure 10a), the peak moisture content rises to only 12%. On the other hand, when indoor air exfiltrates into the construction at $2.5 \times 10^{-5} \text{ m}^3/\text{s per m}^2$ ($0.29 \text{ ft}^3/\text{h per ft}^2$), indoor moisture is transported through penetrations in the interior vapor retarder and the peak moisture content approaches fiber saturation (Figure 10b).

It should be pointed out that the exfiltration of indoor air into wall construction can largely be eliminated by providing a continuous air barrier at interior layers of the construction. An air barrier may be a separate component of the construction, or the function of an air barrier may be incorporated into another layer of the construction. For example, a continuous sheet of polyethylene may serve both as a vapor retarder and an air barrier. Still another ap-

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**Figure 8** The effectiveness of outdoor ventilation on controlling moisture buildup in the baseline wall without a vapor retarder (without indoor air exfiltration).

**Figure 9** The effectiveness of outdoor ventilation in controlling moisture accumulation in the baseline wall without a vapor retarder (with indoor air exfiltration).
preach is to seal the drywall into the wall construction (i.e., airtight drywall approach). All these approaches have been shown to work well.

In the present analysis, we did not consider control of indoor relative humidity as a practice for controlling moisture accumulation. The authors would like to acknowledge that reducing indoor relative humidity is very effective in reducing moisture accumulation in walls (see Burch and Thomas [1991]).

HOT AND HUMID CLIMATE ANALYSIS

Homes constructed with an interior vapor retarder are also used in hot and humid climates. We used the model to investigate the performance of a wall with an interior vapor retarder subjected to hot and humid climates. Hourly outdoor temperature, relative humidity, and solar radiation for Lake Charles, LA, were used in the analysis. Two types of interior vapor retarders were considered: kraft paper installed directly behind the gypsum board (see Figure 1) and vinyl wallpaper.

Kraft Paper Vapor Retarder

Baseline Wall The weekly average relative humidity at opposite surfaces of the kraft paper are plotted versus time of year in Figure 11. The relative humidity at the outside surface of the kraft paper is seen to rise to a maximum during summer and decreases to a minimum during winter. This is where the moisture accumulation was observed to be the highest. It is interesting to observed that the relative humidity at the inside surface of the kraft paper is close to that of the indoor environment.

The horizontal line in Figure 11 and subsequent figures depicts the critical relative humidity believed to be the threshold for mold and mildew growth. The International Energy Agency (1990) recently published Guidelines and Practices (Volume 2) for preventing mold and mildew growth at building surfaces. The consensus was that a monthly mean surface relative humidity above 80% is conducive to mold and mildew growth. Note that the peak relative humidity at the outside surface of the kraft paper is well below the critical 80% level. The permeance of the waferboard siding is low (see Figure 2b) and limits outdoor moisture permeating the wall construction.

Baseline Wall with Permeable Exterior Construction A computer simulation was also conducted for the baseline wall construction with permeable exterior construction. Here the low-permeability waferboard siding was replaced with permeable fiberboard sheathing and vinyl siding with a combined permeance of $4.6 \times 10^{-6}$ kg/Pa·s·m² (8.0 perms). Weekly average relative humidity at the outside surface of the kraft paper is plotted versus time of year in
Figure 12a. The weekly average relative humidity is seen to approach the critical 80% level.

Hourly variation in surface relative humidity for the first week in July is plotted in Figure 12b. The outside surface of the kraft paper intermittently gets wet during warm day periods and dries during cool night periods. The inside surface remains comparatively dry, thereby indicating that the intermittent liquid wetting is not transferred through the kraft paper. Intermittent wetting of vapor retarders in hot and humid climates has been observed by TenWolde and Mei (1985).

Baseline Wall with Outdoor Air Exfiltration

Next, we consider the effect of the infiltration of outdoor air into the construction on the performance of the baseline wall with kraft paper and without permeable exterior construction. The operation of a ventilation exhaust fan in a manufactured home can induce outdoor air and moisture to infiltrate inwardly through clogs and penetrations of construction. In this simulation, we used an infiltration rate of $8.5 \times 10^{-5} \text{m}^3/\text{s per m}^2$ (1.0 ft$^3$/h per ft$^2$). This rate is based on the continuous operation of a 0.047 m$^3$/s (100 cfm) ventilation exhaust fan with half the make-up air provided through cracks associated with the windows and doors and the other half through air leakage sites in opaque portions of the building envelope (e.g., electrical outlets, baseboard cracks, etc.).

The results are given in Figure 13. The weekly average relative humidity at the outside surface of the kraft paper is seen to rise above the critical 80% level during a two-month summer period. This environment is conducive to mold and mildew growth. The operation of an indoor ventilation exhaust fan may draw some make-up air with mold and mildew spores from the wall cavity through cracks and penetrations in the wall, thereby causing an indoor air quality problem (e.g., musty odors or respiratory problems).

Vinyl Wallpaper Vapor Retarder

In the next series of computer simulations, we consider the performance of the baseline wall with a vinyl wallpaper vapor retarder instead of a kraft paper vapor retarder. The latex paint, of course, is not present on the interior surface.

Baseline Wall The weekly average relative humidity at the inside and outside surfaces of the gypsum board is plotted versus time of year in Figure 14. Note that very little difference in relative humidity occurs across the gypsum board. In August, the peak relative humidity approaches, but does not reach, the critical 80% level. The low permeability of the waferboard siding limits outdoor moisture permeating inwardly toward the vinyl wallpaper.

Baseline Wall with Permeable Exterior Construction

Next, we considered the effect of replacing the waferboard
siding with a permeable exterior construction (fiberboard sheathing and vinyl siding) with a combined permeance of $4.6 \times 10^{-10} \text{kg/Pa·s·m}^2$ (8 perms). The results are given in Figure 15. The weekly average relative humidity at the gypsum board exceeds the critical 80% level during a four-month summer period. This situation is very conducive to mold and mildew growth.

Mold and mildew colonies cause characteristic pink and chartreuse splotches to develop behind vinyl wallpaper. As previously noted, mold and mildew colonies emit fungal spores, which often cause an indoor air quality problem. Mold and mildew growth behind vinyl wallpaper has been documented in field studies by the American Hotel and Motel Association (1991) and Lstiburek (1992a, 1992b).

Baseline Wall with Outdoor Air Infiltration Next, we considered the effect of imposing an outdoor infiltration rate of $8.5 \times 10^{-5} \text{m}^3/s \text{per m}^2$ (1 ft$^3$/h per ft$^2$) on the baseline wall construction. The results are given in Figure 16. Here the weekly average relative humidity rises above the critical 80% level during a three-month summer period. This situation is also very conducive to mold and mildew growth.

Baseline Wall with Exterior Kraft Paper Vapor Retarder Next, we considered the merit of relocating the interior kraft paper vapor retarder in the baseline wall construction to the exterior (i.e., between the wall insulation and the waferboard siding). If the wall is airtight, the results are as given in Figure 17. When vinyl wallpaper is

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Figure 14  Relative humidity at surfaces of gypsum board plotted versus time of year for baseline with vinyl wallpaper.

Figure 15  Relative humidity at surfaces of gypsum board plotted versus time of year for baseline wall with vinyl wallpaper and permeable exterior construction.

Figure 16  Relative humidity at surfaces of gypsum board plotted versus time of year for baseline wall with vinyl wallpaper and outdoor infiltration.

Figure 17  Relative humidity at surfaces of gypsum board plotted versus time of year for baseline wall with permeable exterior construction and with exterior vapor retarder.
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applied to the interior surface, the weekly average relative humidity at the gypsum board surface nearly reaches the critical 80% level. On the other hand, when permeable latex paint is applied to the interior surface, the weekly average relative humidity tends to coincide closely with the indoor relative humidity (50%).

**Recommended Practices for Hot and Humid Climates**

Based on the above analysis for hot and humid climates, the following recommended practices will minimize mold and mildew growth at the interior wall construction layers: (1) avoid interior vapor retarders, (2) install an exterior vapor retarder and air barrier, and (3) avoid negative pressurization of the indoor space by providing adequate air intake openings for ventilation exhaust systems.

**SUMMARY AND CONCLUSIONS**

The current HUD standards require manufacturers to comply with one of the following practices to control winter moisture accumulation in walls of manufactured housing: (1) install a vapor retarder at the interior wall surface, (2) use permeable sheathing and siding having a combined permeance larger than $2.9 \times 10^{-10}$ kg/Pa·s·m² (5 perms), or (3) provide an outdoor ventilated cavity between the siding and the wall insulation. For practices 2 and 3, the HUD standards do not require a vapor retarder. In this study, a detailed computer analysis was conducted to investigate the effectiveness of each of these practices.

A vapor retarder was found to effectively reduce winter moisture accumulation in exterior construction layers, providing that air intrusion is minimized by the use of an air barrier. In all of the climates analyzed, the moisture content of the exterior siding always remained well below fiber saturation.

The practice of providing permeable sheathing and siding and omitting the interior vapor retarder does not prevent the moisture content of the sheathing from rising to fiber saturation in cold winter and intermediate winter climates. However, the exterior parts of the construction dry out rapidly in the spring.

The practice of providing an outdoor ventilated cavity and omitting the interior vapor retarder cannot be relied upon to be effective in preventing moisture accumulation in siding exposed to cold and intermediate winter climates or the Pacific Northwest climate. The siding did, however, dry out quickly in the spring. Moreover, an outdoor ventilated cavity may increase the total air permeability of a wall system, thereby making it possible for more indoor air and moisture to exfiltrate into the wall construction.

In hot and humid climates, when an interior vapor retarder is used in the construction, the weekly average relative humidity at its outside surface may rise above a critical 80% level, which is believed to be conducive to mold and mildew growth. This problem becomes particularly acute when vinyl wallpaper is used as the interior vapor retarder. Practices recommended to control this problem include (1) avoiding interior vapor retarders, (2) installing an exterior vapor retarder and air barrier, and (3) avoiding negative pressurization of the interior of the home by providing adequate air intake openings for ventilation exhaust systems.

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**NOMENCLATURE**

- $C$ = specific heat, J/kg·°C
- $D_T$ = diffusivity for temperature gradient, m²/°C·s
- $D_{\gamma}$ = diffusivity for moisture gradient, m²/s
- $f(\phi)$ = sorption isotherm function
- $k$ = thermal conductivity of porous material, W/m·°C
- $p$ = water-vapor pressure, Pa
- $t$ = time, s
- $T$ = temperature, °C
- $y$ = distance from inside surface of wall, m
- $\gamma$ = moisture content on dry basis, kg/kg
- $\mu$ = water-vapor permeability, kg/s·m·Pa
- $\rho$ = density, kg/m³
- $\phi$ = relative humidity

**Subscripts**

- $d$ = dry property
- $s$ = saturated state
- $T$ = temperature gradient
- $v$ = vapor property
- $w$ = moist or water property
- $\gamma$ = moisture content gradient

**REFERENCES**


