A MATHEMATICAL ANALYSIS OF MOISTURE AND HEAT TRANSFER IN THE ROOF CAVITIES OF MANUFACTURED HOUSING

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A mathematical model is presented that predicts moisture and heat transfer in ventilated cavities such as attics, roof cavities and cathedral ceilings. The model performs a transient moisture and heat balance as a function of time of year and includes the storage of moisture and heat at the construction layers. The model includes both molecular diffusion and capillary transfer within the materials. Radiation exchange among the ventilated cavity surfaces is predicted using a mean-radiant-temperature-network model. Airflow from the house into the ventilated cavity is predicted using a stack effect model with aggregated effective leakage areas. Air exchange between the ventilated cavity and outdoor environment is predicted by a semi-empirical model. The relative humidity in the house is permitted to vary during the winter and is calculated from a moisture balance of the whole building.

This mathematical model was used to simulate the performance of a double-wide manufactured house constructed in compliance with the latest HUD Standards. For the simulations, an interior vapor retarder was included in the ceiling construction and ventilation openings were included in the roof cavity consistent with the 1/300 rule given in the HUD Standards. The effect of passive and mechanical ventilation, as well as a wide range of other factors on the roof sheathing moisture content, was investigated as a function of time. The weekly average moisture content of the lower surface of the plywood sheathing was analyzed in several cold climates, while the relative humidity at the lower surface of the ceiling insulation was analyzed in a hot and humid climate. The analysis revealed that airflow from the house into the roof cavity, as opposed to water-vapor diffusion, is the dominant moisture transport mechanism into the roof cavity during the winter.

KEYWORDS

Airflow, attic ventilation, attics, building technology, HUD standards, manufactured housing, mathematical analysis, moisture, moisture analysis, moisture control, moisture modeling, roof cavities, roof ventilation.

INTRODUCTION

During the winter, moisture released by occupant activities causes the absolute humidity (or water vapor pressure) inside a house to be higher than that of the outdoor air. This vapor pressure potential causes water vapor to diffuse through the ceiling construction into the roof cavity. In addition, a buoyant force (i.e., the stack effect) causes airflow from the house into the roof cavity through cracks and penetrations (e.g., ceiling light fixtures, plumbing and HVAC penetrations, and cracks above interior partition walls). A portion of this moisture is removed by attic ventilation. The remainder becomes absorbed or condenses at the cold interior surfaces of the roof cavity (most important of which is the plywood roof sheathing).

It is possible for the moisture content of the roof sheathing to rise above fiber saturation (e.g., 28 percent moisture content for plywood). Above fiber saturation, wood decay can occur. However, the wood must be warm (above 10°C [50°F] and optimally between 24°C [75°F] and 32°C [90°F]) before decay takes place.[1] The possibility of decay tends to be higher in manufactured houses because they tend to have higher indoor relative humidity compared to site-built houses. This is because they are usually tighter[2] and usually have smaller interior volumes than site-built houses.

In an effort to prevent roof cavity moisture problems, the Department of Housing and Urban Development (HUD) issued rules in their Manufactured Home Construction and Safety Standards.[3] Henceforth in this report, these standards will be referred to as the HUD Standards. The rules require manufactured houses to have an interior ceiling vapor retarder, except for houses constructed in the southeastern part of the United States where a ceiling vapor retarder is optional. In addition, houses constructed with moisture absorbing roof sheathing are required to be provided with either passive or mechanical attic ventilation for removing moisture from their roof cavities. Passive attic ventilation systems shall have a net free ventilation opening of 1/300 of the attic floor area. Mechanical attic ventilation systems shall provide a minimum air change rate of 0.00010 m^3/s per m^2 (0.02 ft^3/min per ft^2) of attic floor area. Single-wide houses constructed with metal roof coverings are not required to have attic ventilation.

Providing an interior vapor retarder in the ceiling construction and ventilating the roof cavity may be counter-productive and actually cause a summer moisture problem in manufactured houses located in hot and humid climates. This is because the attic ventilation airflow transports a large amount of moisture into the roof cavity from the outdoors. This moisture subsequently diffuses downward through the insulation to the upper surface of the vapor retarder which may be cooled by the indoor air conditioning equipment below the dew point temperature of the roof cavity air. In this situation, condensation occurs and the relative humidity at the upper surface of the vapor retarder approaches a saturated state, thereby providing a conducive environment for mold and mildew growth. A monthly mean surface relative humidity greater than 80 percent is conducive to mold and mildew growth.[4] Once mold and mildew exists, fungal spores may enter the living space and cause indoor air quality and health-related problems.[5]

A motivation for conducting this research was to address several of the limitations of a previous attic modeling study.[6] The limitations of the previous study included: constant indoor relative humidity, constant airflow from the house into the attic, and constant air exchange between the attic and outdoor environment. A new and more sophisticated model without these limitations is presented herein. The model is subsequently used to simulate the performance of a current practice double-wide manufactured house. Various factors that affect the moisture content of the roof sheathing were analyzed. The effectiveness of the current moisture control practices specified within the HUD Standards are investigated in several cold climates and in a hot and humid climate.

The same model is used to analyze heat and moisture in the attics of site built homes in a companion paper.[7]

THEORY

A brief synopsis of the MOIST Attic Model is presented below. A more detailed description is given in Burch, Tsongas, and Walton.[8]

Assumptions

Some of the more important assumptions of the new attic model are given below: moisture and heat transfer are one-dimensional; air within the ventilated cavity is well mixed; and the wetting of exterior surfaces by rain is neglected, and the insulating effect and changes in roof absorptance from a snow load are neglected. Other assumptions are discussed in the model presentation below.

Basic transport equations

The basic transport equations are taken from Pedersen[9] and are briefly presented below. Within each material of the construction, the moisture distribution is governed by the following conservation of mass equation:

$$\frac{\partial}{\partial y}\left(\mu \frac{\partial p_v}{\partial y}\right) - \frac{\partial}{\partial y}\left(K \frac{\partial p_l}{\partial y}\right) = \rho_d \frac{\partial \gamma}{\partial t} \qquad [1]$$

Symbols are defined in the Nomenclature at the end of the report. The first term on the left side of Equation 1 represents water-vapor diffusion, whereas the second term represents capillary transfer. The right side of Equation 1 represents moisture storage within the material. The minus sign accounts for the fact that liquid flows in a porous material in the same direction as the gradient in capillary pressure. The sorption isotherm (i.e., the relationship between equilibrium moisture content and relative humidity) and the capillary pressure curve (i.e., the relationship between capillary pressure and moisture content) were used as constitutive relations in solving Equation 1.

The temperature distribution is calculated from the following conservation of energy equation:

$$\frac{\partial}{\partial y}\left(k \frac{\partial T}{\partial y}\right) + h_{lv} \frac{\partial}{\partial y}\left(\mu \frac{\partial p_v}{\partial y}\right) = \rho_d c \frac{\partial T}{\partial t} \qquad [2]$$

The first term on the left side of Equation 2 represents conduction, whereas the second term is the latent heat transfer derived from any phase change associated with the movement of moisture. The right side of Equation 2 represents the storage of heat within a material.

In Equation 1, the water vapor permeability (μ) and the hydraulic conductivity (K) are strong functions of moisture content. In Equation 2, the thermal conductivity (k) is also a function of moisture content, but for the present analysis it is assumed to be constant.

Ventilated cavity moisture and heat balance

Placing a control volume around the roof cavity, the principal of conservation of mass may be applied (i.e., sum of mass fluxes must equal to zero). The sum of the evaporation rates from the ventilated cavity surfaces plus the rate of moisture transfer by airflow from the house into the cavity is equal to the rate of moisture removed by outdoor ventilation, or:

$$\sum_{n=1}^{N} A_n m_n (p_{v,n} - p_{v,c}) + \rho_a \dot{V}_{h\to c}(\omega_i - \omega_c) = \rho_a \dot{V}_c(\omega_c - \omega_o) \qquad [3]$$

In a similar fashion, the principal of conservation of energy may be applied to the cavity air volume. The net rate of convective heat transfer from the cavity surfaces plus the rate of energy transfer by airflow from the house into the cavity is equal to the rate of energy removed by outdoor ventilation, or:

$$\sum_{n=1}^{N} A_n h_{c,n}(T_{s,n} - T_c) + \rho_a c \dot{V}_{h\to c}(T_i - T_c) = \rho_a c \dot{V}_c(T_c - T_o) \qquad [4]$$

Radiation exchange among the ventilated cavity surfaces is handled using the mean-radiant-temperature network method described by Carrol.[10]

Airflow from house into attic

The airflow rate from the house into the roof cavity is predicted using the equation.[11]

$$\dot{V}_{h\to c} = L_c \sqrt{\frac{(2\Delta p_r)}{\rho_a}} \left(\frac{\Delta p_l}{\Delta p_r}\right)^{0.65} \qquad [5]$$

Airflow passes through the following three leakage areas: the ceiling, the roof and the exterior walls of the house below. The effective leakage area of the series combination of the three areas is given by the relation:

$$L_e = \left[\left(\frac{1}{L_w}\right)^{1/0.65} + \left(\frac{1}{L_c}\right)^{1/0.65} + \left(\frac{1}{L_r}\right)^{1/0.65}\right]^{-0.65} \qquad [6]$$

Here the effective leakage area for each of the house parts has been aggregated at a single location placed at the mid-height level of each part. The total stack-effect pressure head

(Δp_t) is equal to the sum of the pressures for the house and the roof cavity, or:

$$\Delta p_t = \rho_a H_h \left(\frac{T_i - T_o}{T_o}\right) + \rho_a H_c \left(\frac{T_c - T_o}{T_o}\right) \qquad [7]$$

The first and second terms are the house and roof cavity stack effect pressures, respectively.

The NIST Contaminant Air Flow Model[12] was used to investigate the validity of the assumption of aggregating the wall effective leakage area (ELA) at a single location at the mid-height level. For the investigation, the stack-effect airflow from the house into the roof cavity was predicted for two cases. In the first case, the wall ELA was equally distributed into eight separate ELA's spaced at equal intervals from the floor to the ceiling. In the second case, the wall ELA was aggregated at a single location at the mid-height level. The two simulations agreed within 9 percent, thereby supporting the validity of the simplifying assumption.

Roof cavity ventilation rate

The single-zone infiltration model developed by Sherman and Grimsrud[13] was applied to estimate the air exchange rate between a roof cavity and the outdoor environment, or:

$$\dot{V}_c = L_r \left[C_{\Delta T} \left| T_c - T_o \right| + C_v V^2 \right]^{0.5} \qquad [8]$$

The coefficients $C_{\Delta T}$ and C_v were evaluated by fitting the above equation to a set of measured data, as described in a later section.

Indoor and outdoor boundary conditions

At the indoor and outdoor boundaries of the construction, the convective-radiative heat transfer across the boundary layer was equated to the rate of heat conduction into the surface. In a similar fashion, the mass transfer across the boundary layer was equated to the rate of diffusion into the surface. The model has a provision for including the water vapor transfer resistance of paint layers.

The outdoor boundary of the construction included incident solar radiation and sky radiation. The solar radiation incident onto exterior surfaces having arbitrary tilt and orientation was predicted using algorithms given in Duffie and Beckman.[14] The sky temperature was calculated using an equation developed by Bliss.[15]

Indoor temperature and humidity conditions

During periods when space heating was required, the indoor temperature was maintained at a constant specified value. The indoor relative humidity was permitted to vary and was calculated from a moisture balance of the whole building with the house effective leakage area (ELA) and the indoor moisture production rate serving as inputs.[8] The natural infiltration rate for the house was predicted by the single-zone Lawrence Berkeley Laboratory (LBL) model developed by Sherman and Grimsrud[13] and described by ASHRAE.[11]

During periods when space cooling was required, the indoor temperature and relative humidity were maintained at constant specified values. When neither space heating nor space cooling were required, it was assumed that the windows were opened, and the indoor temperature and relative humidity were equal to the outdoor values.

Solution procedure

A FORTRAN 77 computer program, called the MOIST Attic Model, was prepared to solve the above system of equations. Finite-difference equations were developed to represent the basic moisture and heat transport equations (Equations 1 and 2).

The solution of the complete system of equations proceeds by first solving for all the material temperatures and the cavity air temperature. Since the material temperatures and the cavity air temperature are dependent upon one another, it is necessary to iteratively solve at each time step the material temperatures and cavity air temperature until convergence is achieved. The model next solves for the water vapor pressure distribution within the materials and the cavity water vapor pressure. Since the material vapor pressures and the cavity vapor pressure are dependent on one another, it is necessary also to iteratively solve at each time step the material vapor pressures and cavity vapor pressure until convergence is attained. The model next solves for the distribution of capillary pressures within the materials. From the predicted gradients in vapor pressure and capillary pressure and the transport coefficients for vapor and liquid flows, a new set of material moisture contents is calculated. The model is now ready to proceed to the next time step.

Before making the final computer runs for the present study, a series of special computer runs were carried out to establish that the finite-difference representation of the transport equations was indeed converging. In a sequence of simulations, the number of the finite-difference nodes in each material was doubled until no further change in the solution occurred. In another set of simulations, the convergence criteria for the thermal solution and the convergence criteria for the moisture solution were decreased until no further change in the solution occurred. A value of 1.0×10^{-4} for both the convergence criteria provided convergence of the mathematical solution.

DESCRIPTION OF CURRENT PRACTICE HOUSE

In selecting the construction of the current practice house, the authors contacted manufacturers and other persons knowledgeable of manufactured home construction. An effort was made to select construction characteristics representative of current construction practice. The house simulated in this study was a double-wide manufactured house having a floor area of 130.3 m² (1402 ft²) and a 2.44 m (8 ft)

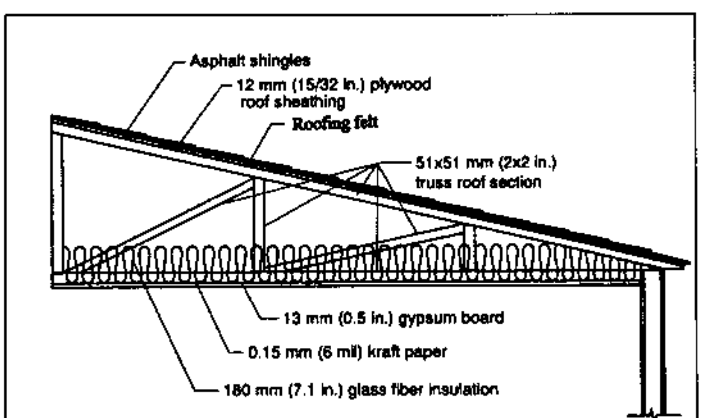

Figure 1. Half cross-section of roof cavity of double-wide manufactured house.

ceiling height. The size of the house was based on a control group of 29 manufactured houses studied by Palmiter, Bond, Brown, and Baylon.[16]

A cross section of the roof construction is shown in Figure 1. The sloping roofs faced north and south; the gable end walls faced east and west. The slope of the roof was 14°. The roof construction was comprised of 12 mm (15/32 in.) exterior-grade plywood, roofing felt and asphalt shingles. The shingles were medium-dark colored and had a solar absorptance of 0.8. The gable end walls were constructed of 9.5 mm (3/8 in.) asphalt-impregnated fiberboard and vinyl siding. The ceiling construction (or floor of the roof cavity) consisted of 180 mm (7.1 in.) [R-3.9 $m^2 \cdot K/W$ (R-22 $h \cdot ft^2 \cdot F/Btu$)] glass-fiber insulation, 0.15 mm (6 mil) kraft paper vapor retarder, and 13 mm (0.5 in.) gypsum board with 575 $ng/s \cdot m^2 \cdot Pa$ (10.0 perm) latex paint applied to its interior surface. In the roof and ceiling construction, the framing members (including trusses) were spaced 0.41 m (16 in.) on center.

Based on the control group of 29 houses studied by Palmiter, Bond, Brown, and Baylon,[16] the whole house was assumed to have an effective leakage area (ELA) of 594 cm^2(92 in^2). Based on airtightness test results of 20 site-built houses,[17] the authors assumed that the ceiling ELA was 35 percent of the whole house total or 206 cm^2 (32 in^2). The ELA for the house below (excluding the ceiling and roof construction) was 65 percent of the whole house total or 387 cm^2 (60 in^2). Consistent with the current HUD Standards for manufactured housing, the gable end walls and the roof construction were fitted with roof cavity vents having a net free open area of 1/300 of the ceiling area or 4,340 cm^2 (673 in^2). When computer simulations were conducted in a current practice house without roof cavity vents, the authors assumed that unintentional air leakage sites in the construction provided a leakage area of one-tenth that provided by the roof cavity vents themselves or 434 cm^2 (67.3 in^2).

Consistent with the HUD Standards, the current practice house was provided with indoor (whole house) mechanical ventilation having an average air change rate of 0.00018 m^3/s per m^2 (0.035 ft^3/min per ft^2) of floor area or 0.023 m^3/s (49 ft^3/min).

PARAMETERS USED IN ANALYSIS

Water vapor diffusion properties

The sorption isotherm (i.e., the relationship between equilibrium moisture content and ambient relative humidity) of the materials were based on measurements conducted at the National Institute of Standards and Technology (NIST).[18] The permeability (i.e., the relationship between water vapor permeability and relative humidity) of the materials were also based on measurements conducted at NIST.[19] The liquid diffusivity (i.e., the relationship between liquid diffusivity and moisture content) of the materials were based on measurements by Richards.[20] The thermal conductivity, density and specific heat of the materials were taken from ASHRAE.[11]

The long-wave emittance of the materials was taken to be 0.9. The solar absorptances of the asphalt shingles and the vinyl siding applied to the gable end walls were taken to be 0.8 and 0.6, respectively.

Roof cavity ventilation rate

Buchan, Lawton, Parent Ltd[17] measured 60 attic ventilation rates in 20 site-built houses in several Canadian climates. The houses had different types of attic ventilation with a wide range of ELA's measured using a pressurization technique. For each of the measurements, they also measured the wind speed, wind direction, and temperature difference between the roof cavity and the outdoor environment. The authors applied Equation 8 to this set of data and used regression analysis to determine the empirical coefficients. The stack coefficient ($C_{\Delta T}$) was determined to be a very small value and was taken to be zero. The wind coefficient (C_v) was found to be 6.94×10^{-5} $[L/s]^2 \cdot [cm]^{-4} \cdot [m/s]^{-2}$ (0.00259 $cfm^2 \cdot in^{-4} \cdot mph^{-2}$).

A plot of the volumetric attic ventilation rate per unit roof effective leakage area as a function of wind speed is given in Figure 2. Each point represents one of the measurements of Buchan, Lawton, Parent Ltd.[17] The least-squares-fit correlation is also given in the plot of Figure 2. It should be noted that a great deal of scatter exists between the least-squares-fit correlation and the measurement points. A contributing factor is that the least-squares-fit correlation does not include wind direction and attic ventilation type. Upper and lower bounds for the measured data are also shown on the plot. With the exception of a few points deemed to be outliers, most of individual measurements fall between the upper and lower bounds.

Indoor and outdoor conditions

In the computer analysis, the hourly outdoor boundary conditions (i.e., ambient temperature, relative humidity, wind speed, and incident solar radiation) were obtained from ASHRAE WYEC weather data.[21] During the winter when space heating was required, the set-point temperature was 20°C (68°F). The occupant activities produced moisture at a rate of 10.9 kg/day (24.0 lb/day) unless stated otherwise, and the indoor relative humidity during the winter was predicted from a moisture balance of the whole building. During the summer when space cooling was required, the set-point temperature and indoor relative humidity were 24°C (75°F) and 56 percent, respectively.

Six months of weather data were used to initialize the reported one-year simulation results in order to reduce the effect of assumed initial construction layer moisture content and temperature. The moisture performance of the prototype roof was analyzed for the cold climates of Madison, WI (most simulations); Boston, MA; Portland, OR; and Atlanta, GA; as well as the hot and humid climate of Miami, FL.

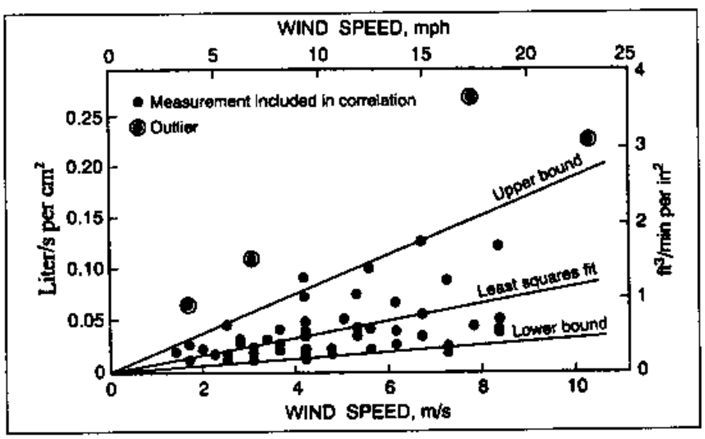

Figure 2. Volumetric attic ventilation rate per unit roof effective leakage area plotted as a function of wind speed (measurements taken from Buchan, Lawton, Parent Ltd. [1991]).

COLD CLIMATE RESULTS

Performance of current-practice house in Madison

The new attic model was first used to predict the weekly average moisture content of the roof cavity surfaces for the current-practice house located in Madison, WI. In this plot and the plots that follow, an interior vapor retarder was included in the ceiling construction and roof vents were included consistent with the 1/300 rule, unless stated otherwise. The surface moisture contents are plotted versus time of year in Figure 3. The moisture content of the roof rafters (not shown) tended to track the plywood roof sheathing but were slightly lower. The surface moisture contents were lowest during summer and rose to a maximum during fall and winter. The construction component having the highest surface moisture content was the north sloping plywood roof. The peak plywood moisture content is seen to be 16 percent (dry mass basis), and is well below fiber saturation (i.e., a moisture content of 28 percent). The volumetric attic ventilation rate was predicted using the least-squares-fit correlation (see Figure 2).

The model was next used to investigate the relative importance of various parameters on the roof cavity performance. The approach was to vary one parameter at a time and investigate its effect on the moisture content of the north sloping plywood roof. Henceforth in this report, the winter analysis will focus on the moisture content of the north sloping plywood roof, since this construction component always had the highest moisture content. Unless stated otherwise, the climate is Madison, WI.

Effect of roof cavity ventilation

Passive roof cavity ventilation

The model was next used to investigate the consequences of not providing roof cavity vents. When the ventilation openings were not present, it was assumed that unintentional air leakage sites in other parts of the construction provided an ELA of 434 cm² (67.3 in.²) which was 1/10 of that provided by the passive ventilation openings themselves. Figure 4 compares the north sloping roof moisture content of two identical current practice houses, one with and the other without roof cavity vents. When roof cavity vents were provided, their ELA was set equal to the net free open area specified by the 1/300 rule. In the house without roof cavity vents (upper curve), the moisture content rose almost to fiber saturation (depicted by the horizontal line at 28 percent moisture content). On the other hand, in the house with roof cavity vents (lower curve), the moisture content was maintained well below fiber saturation. These results demonstrate that appropriately sized roof cavity vents are very effective in removing moisture and maintaining the roof sheathing moisture content at acceptable levels.

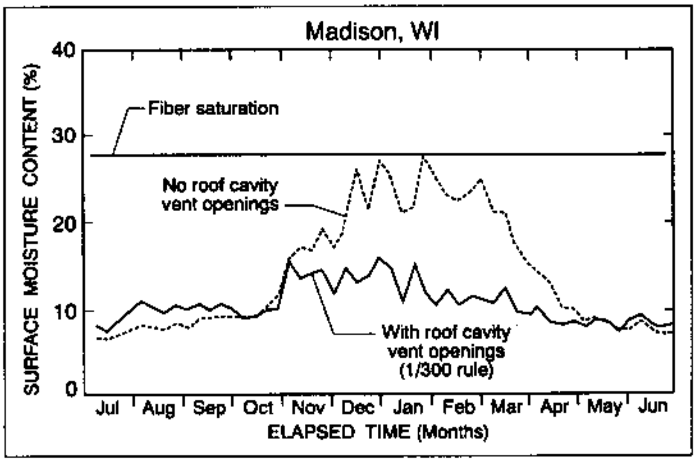

Figure 4. Effect of passive roof cavity ventilation on the moisture content of north-sloping plywood roof sheathing for current practice house.

Mechanical roof cavity ventilation

The model was subsequently used to investigate the effectiveness of the specified mechanical ventilation rate in the HUD Standards that permits mechanical ventilation to be substituted for passive roof cavity vents. The HUD Standards specify that the mechanical ventilation rate shall be at least 0.00010 m³/s per m² (0.02 ft³/min per ft²) of attic floor. The current practice house has a floor area of 130 m² (1402 ft²), and the mechanical ventilation rate was calculated to be 0.013 m³/s (28 ft³/min). The results of a computer simulation with the roof cavity ventilated at this constant rate are shown in Figure 5. The predicted moisture content of the plywood roof sheathing (upper curve) rose to fiber saturation during the winter. These results indicate that the mechanical attic ventilation rate specified in the HUD Standards is too low under some conditions and needs to be increased to achieve acceptable performance. This is especially critical since some houses will have greater moisture flow into the attic than assumed in this analysis due to leakier

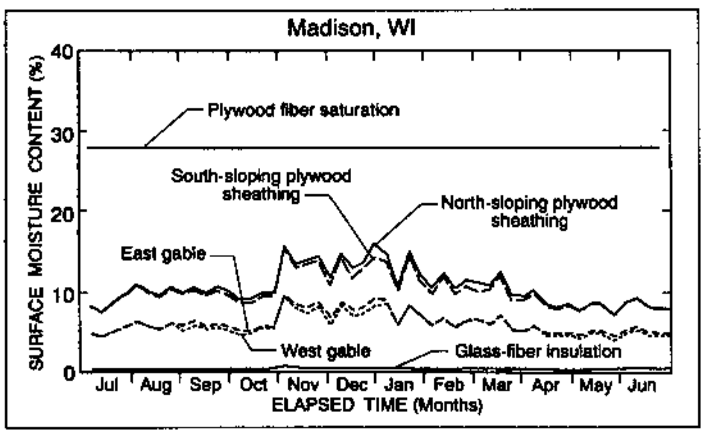

Figure 3. Surface moisture content of roof cavity construction materials for the current practice house.

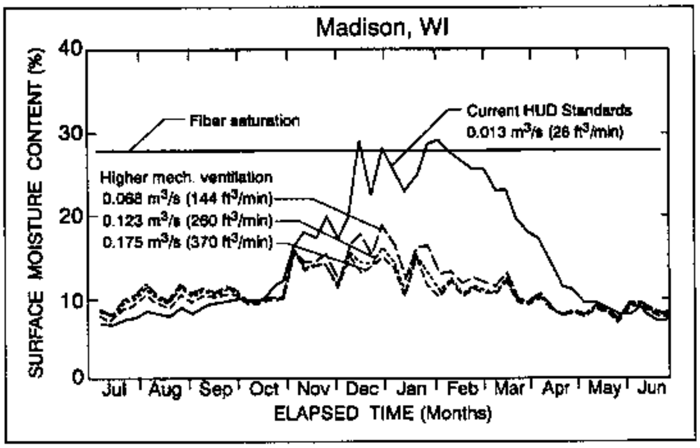

Figure 5. Effect of mechanical roof cavity ventilation on the moisture content of north-sloping plywood roof sheathing for current practice house.

ceiling construction and higher indoor relative humidity.

The previous results with passive roof cavity vents provided satisfactory performance (see Figure 4). An effort was made to find a mechanical ventilation rate that would provide the same amount of attic ventilation as the passive ventilation openings operated under prevailing outdoor wind speeds. From the *Climatic Atlas of the United States*,[22] the mean January wind speed for many parts of the United States is approximately 4.9 m/s (11 mph). Using Equation 8, an equivalent mechanical ventilation rate of 0.175 m^3/s (370 ft^3/min) was determined.

A computer simulation was carried out using the above equivalent mechanical ventilation rate of 0.175 m^3/s (370 ft^3/min). In addition, simulations were conducted at attic mechanical ventilation rates of 0.123 m^3/s (260 ft^3/min) and 0.068 m^3/s (144 ft^3/min). The results are included in Figure 5. All of the above revised mechanical ventilation rates had roof sheathing moisture contents that were well below fiber saturation. Based on these results, it is recommended that the prescribed mechanical attic ventilation rate be the lower of the revised rates or 0.068 m^3/s (144 ft^3/min). Expressing this figure on a per unit attic floor area, the specified mechanical attic ventilation rate should be 0.0005 m^3/s per m^2 (0.1 ft^3/min per ft^2).

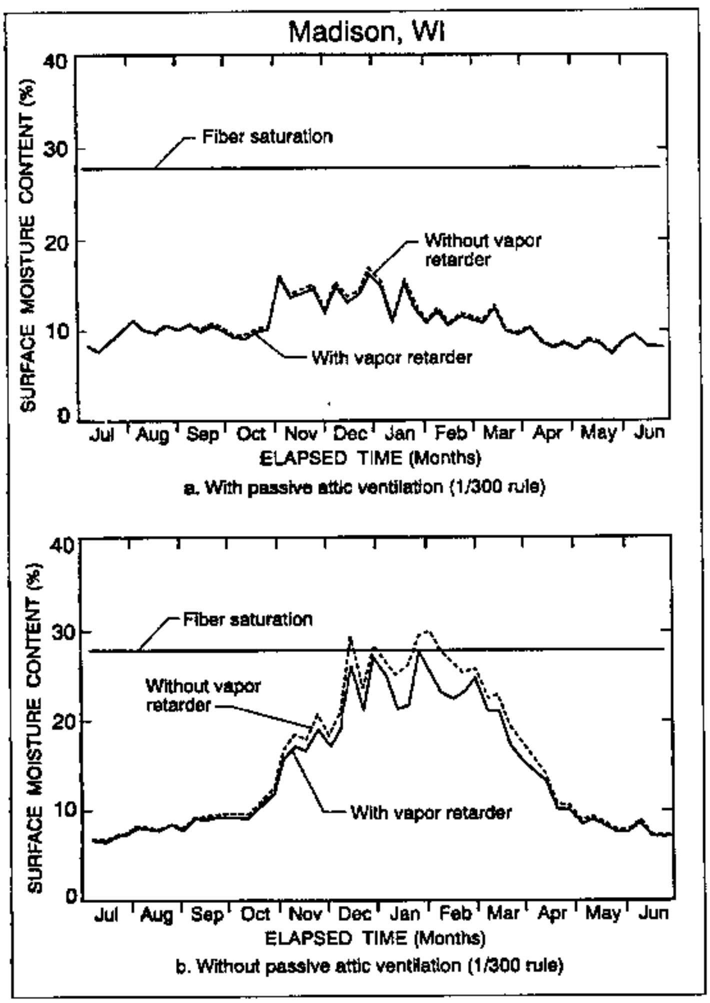

Figure 6. Effect of an interior ceiling vapor retarder on the moisture content of north-sloping plywood roof sheathing for current practice house.

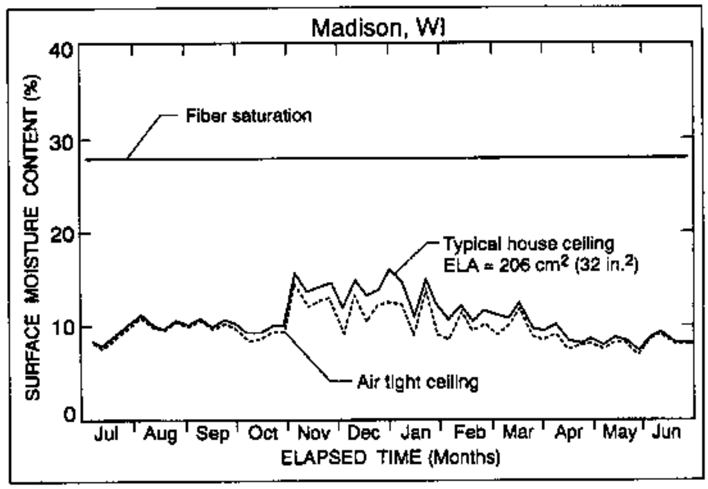

Figure 7. Effect of airflow from house into roof cavity on the moisture content of north-sloping plywood roof sheathing for current practice house.

Effect of a ceiling vapor retarder

The model was subsequently used to investigate the effect of a ceiling vapor retarder. Separate computer simulations were carried out with and without a ceiling vapor retarder. The results are given in Figure 6a for a house with roof cavity vents and in Figure 6b for a house without roof cavity vents. Mechanical attic ventilation was not used in either case. The presence of the vapor retarder has a small effect on the roof sheathing moisture content. A ceiling vapor retarder had a small effect because airflow from the house into the roof cavity was the dominant moisture transport mechanism.

Effect of airflow from house into roof cavity

A simulation was next conducted of the current practice house with the ceiling ELA reduced to zero, thereby eliminating airflow from the house into the roof cavity. Roof vents were included consistent with the 1/300 rule. The current practice house without airflow (lower curve) is compared to the same house with a representative airflow in Figure 7. In both simulations, a vapor retarder was included in the ceiling construction. Representative airflow was achieved by using a wall ELA of 387 cm^2 (60 in^2), a ceiling ELA of 206 cm^2 (32 in^2) and a roof ELA of 4,340 cm^2 (673 in^2) in the stack-effect airflow equations. Here the roof ELA is set equal to the net free opening specified by the 1/300 rule. When the ceiling airflow is zero, the roof sheathing moisture content is lower. Comparing these results to the previous results of Figure 6, airflow appears to have a larger impact on the roof sheathing moisture content than water vapor diffusion.

Effect of indoor relative humidity

In this section, the effect of indoor relative humidity on the roof sheathing moisture content is analyzed.

Humidified houses. The current practice house with a ceiling vapor retarder was simulated with a humidifier that maintained a constant indoor relative humidity of 45 percent during the winter. An indoor relative humidity of 45 percent was the highest humidity that could be maintained without condensation on double-pane windows. The roof sheathing moisture content of the humidified house is compared to the same house without humidification in Figure 8a. In the humidified house (upper curve), the moisture content of the north sloping plywood roof sheathing rose to a peak of 25 percent and approached fiber saturation (28 percent). How-

Parameter	Difference (percent mc)
Passive Attic Ventilation (Roof Cavity Vents vs. None)	12
Mechanical Attic Ventilation (Wide Range)	13
Ceiling Vapor Retarder (with vs. without)	
* with Roof Cavity Vents	1
* without Roof Cavity Vents	3
Ceiling ELA with Passive Ventilation (Typical vs. None)	2
Indoor Humidification (with vs. without)	14
Indoor Moisture Generation Rate (Low vs. High)	5
Whole House ELA (Leakier vs. Tighter House)	2
Indoor Mechanical Ventilation (High vs. None)	3

Table 1. Effect of Parameters on Roof Sheathing Moisture Content.[1]

[1] *The current practice house with a ceiling vapor retarder and 1/300 roof cavity vents was used as a baseline.*

ever, both roofs dried out quickly in the spring. Here the rate of moisture transport from the house into the roof cavity is approaching the limit of effective removal by passive attic ventilation. The large difference in roof sheathing moisture content between the humidified and non-humidified house is a direct consequence of the indoor relative humidity difference between the two houses (see Figure 8b).

Non-humidified houses. A number of factors affect the indoor relative humidity in non-humidified houses, including the indoor moisture production rate, the house ELA and, if present, the indoor mechanical ventilation.

Separate computer simulations of the current practice house were conducted with the following moisture production rates: high: 16.3 kg/day (36 lb/day); typical: 10.9 kg/day (24 lb/day; and low: 5.4 kg/day (12 lb/day). The house contained a ceiling vapor retarder, and the attic contained roof vents consistent with the 1/300 rule. The resulting plywood moisture contents and indoor relative humidities are shown in Figures 9a and 9b, respectively. As the moisture production rate increases, the peak plywood moisture content rose in response.

Several simulations of the current practice house were conducted with the following three house ELA's: a leakier house: ELA=787 cm² (122 in²); a typical house: ELA=594 cm² (92 in²); and a tighter house: ELA=400 cm² (62 in²). In these simulations, the ceiling ELA was maintained at a constant value of 206 cm² (32 in²). Here the authors assumed that ceiling air leakage through partition walls, ceiling light fixtures, plumbing and HVAC penetrations would remain constant as the exterior wall ELA was varied. These three simulations are shown in Figure 10. As the house becomes tighter, less natural infiltration occurs, and the indoor relative humidity rises. This causes the roof sheathing moisture content to increase slightly during the fall and winter.

Several simulations were also conducted with the following three levels of continuous indoor mechanical ventilation: none; the current practice house at a typical rate of 0.023 m³/s (49 ft³/min); and at a very high rate of 0.071 m³/s (150 ft³/min). These ventilation rates are actual values, as opposed to rated values. The high ventilation rate corresponds to continuous operation of the kitchen and bathroom ventilation exhaust fans or a large "exhaust only" whole

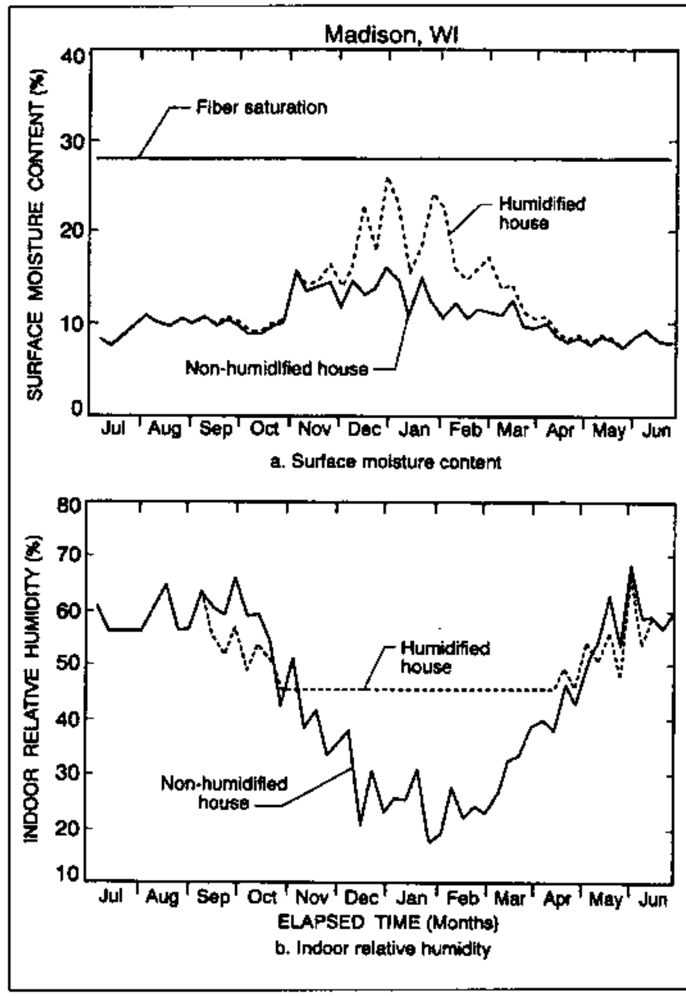

Figure 8. Effect of indoor humidification on the moisture content of north-sloping plywood roof sheathing and indoor relative humidity for current practice house.

house ventilation system. The typical rate is the ventilation rate currently specified by the HUD Standards. Predicted roof sheathing moisture contents for the three cases are given in Figure 11. The results indicate that indoor mechanical ventilation slightly decreased the moisture content of the roof sheathing due to reductions in indoor relative humidity. The results of Figure 11 also indicate that, if the homeowner were to modify the HVAC equipment and turn off the continuous ventilation specified in the HUD Standards, then the roof sheathing moisture content would increase by only approximately 2 percent, but moisture levels would still be below fiber saturation (28 percent).

Summary of the effect of parameters

The effect of the various parameters on the moisture content of the roof sheathing is summarized in Table 1. The difference in moisture content presented in the last column is the estimated difference in moisture content observed during the period when the roof sheathing moisture content is at its maximum.

From Table 1, attic ventilation (both passive and mechanical) and indoor humidification are seen to affect the roof sheathing moisture content by more than 12 percent mc. The effect of indoor moisture generation rates is 5 percent mc. The effect of the other parameters is less than 3 percent mc.

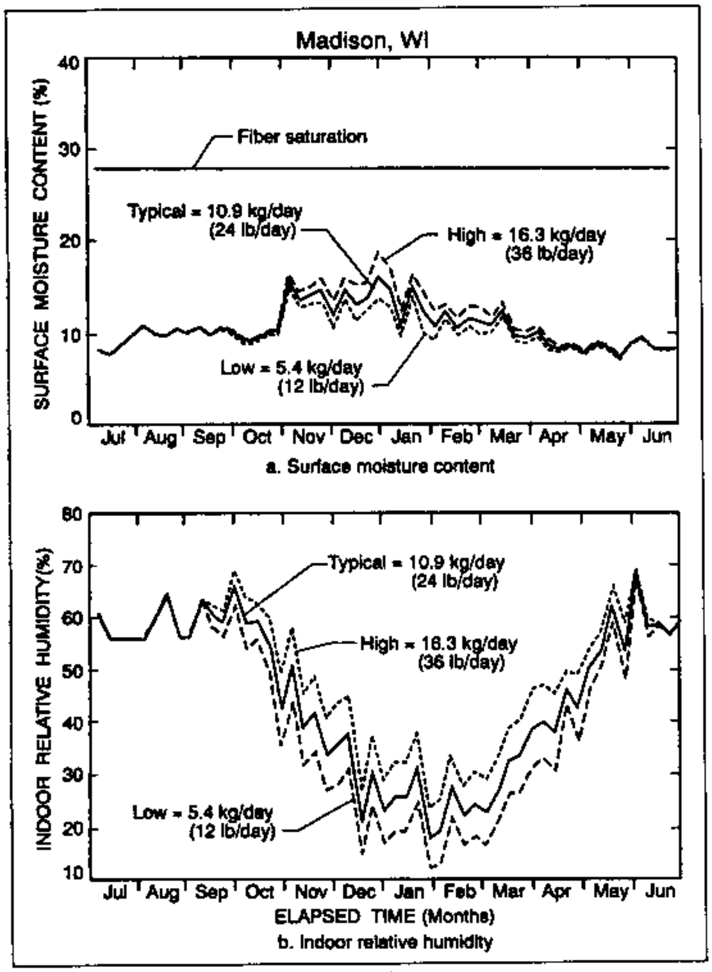

Figure 9. Effect of moisture production rate on the moisture content of north-sloping plywood roof sheathing and indoor relative humidity for current practice house.

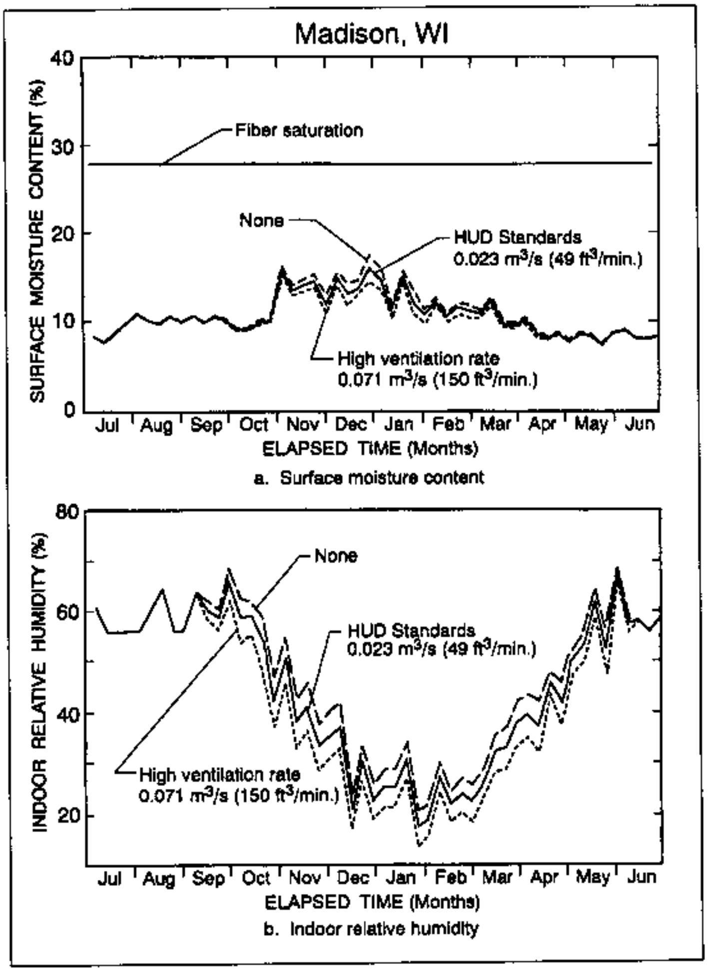

Figure 11. Effect of indoor mechanical ventilation on the moisture content of north-sloping plywood roof sheathing and indoor relative humidity for current practice house.

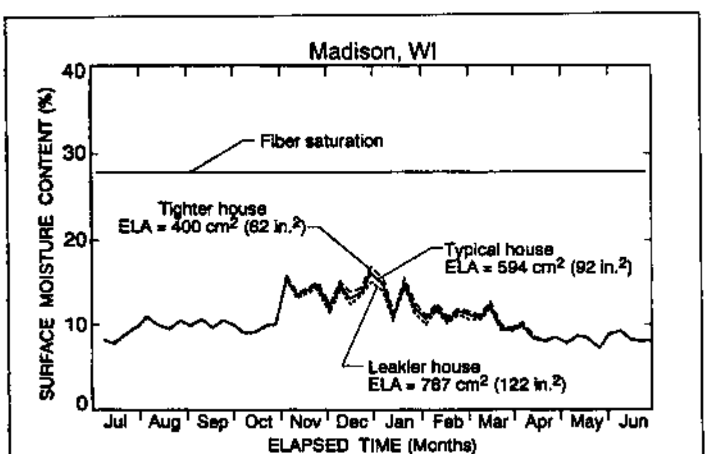

Figure 10. Effect of house tightness on the moisture content of north-sloping plywood roof sheathing for current practice house.

EFFECTIVENESS OF MOISTURE CONTROL PRACTICES IN COLD CLIMATES

In this section, the effectiveness of roof cavity vents consistent with the 1/300 rule is investigated for two worst case indoor relative humidity situations: a tight house having an ELA of 400 cm² (62 in²) with a high moisture generation rate of 16.3 kg/day (36 lb/day) and a humidified house. These situations represent worst-case scenarios, but such extreme conditions are quite likely to exist within a fraction of the manufactured housing stock. It is crucial that moisture control practices work satisfactorily in houses operated under worst-case humidity conditions. Consistent with the current HUD Standards, the house had a 57 ng/s·m²·Pa (1 perm) ceiling vapor retarder.

Tight house with high moisture production rate

Separate computer simulations of this worst-case house were carried out for the following levels of attic ventilation: no roof cavity vents; lower bound roof cavity vents; mean correlation roof cavity vents; and upper bound roof cavity vents (see Figure 2). The results are given in Figure 12. For all three levels of roof cavity ventilation, the peak roof sheathing moisture content was below fiber saturation (28 percent). In contrast, when no roof cavity vents were provided (upper curve), the roof sheathing moisture content rose considerably above fiber saturation during the winter and spring. This high roof sheathing moisture content poses a risk of material degradation, although the roof sheathing dries out satisfactorily during warmer spring and summer periods when decay is more likely to occur.

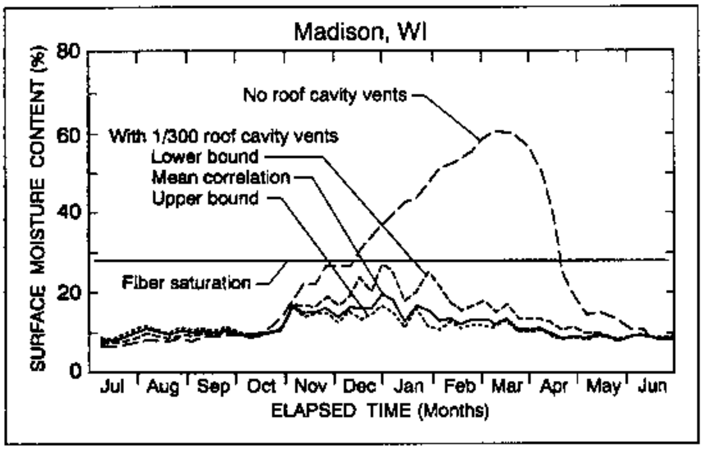

Figure 12. Effectiveness of roof cavity vents in tight house with high moisture production rate.

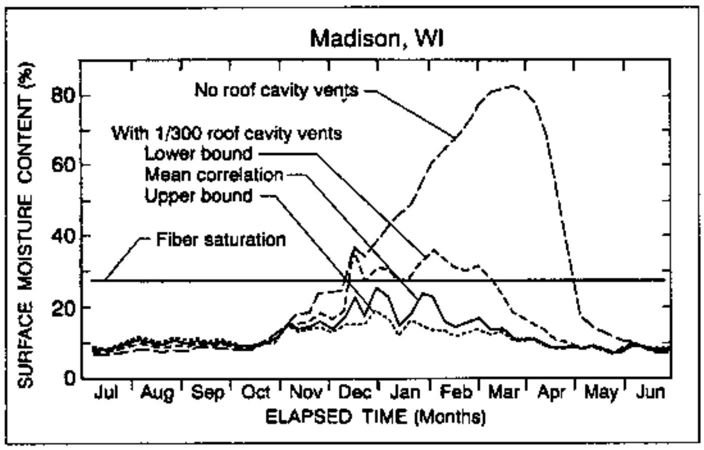

Figure 13. Effectiveness of roof cavity vents in a humidified house.

Humidified house

A similar set of simulations was carried out for a humidified house. The results are given in Figure 13. When roof cavity vents were not provided (upper curve), moisture accumulated in the roof sheathing considerably above fiber saturation. The high roof sheathing moisture contents did not extend significantly into spring and summer periods, when material degradation is likely to occur. For the three levels of roof cavity ventilation, the mean and upper bound curves were below fiber saturation, but the lower bound curve rose somewhat above fiber saturation. These results indicate that some humidified houses with roof cavity vents, consistent with the 1/300 rule, may experience roof sheathing moisture contents above fiber saturation. Therefore, it is recommended that manufactured houses not be humidified.

EFFECTIVENESS OF MOISTURE CONTROL PRACTICES IN HOT AND HUMID CLIMATES

The attic moisture performance of a current practice house in a hot and humid climate (Miami, FL) was investigated. The current HUD Standards require that manufactured houses distributed in hot and humid climates have their attics ventilated consistent with the 1/300 rule. While a ceiling vapor retarder is not mandatory, it is nonetheless installed in many manufactured houses distributed to hot and humid climates.

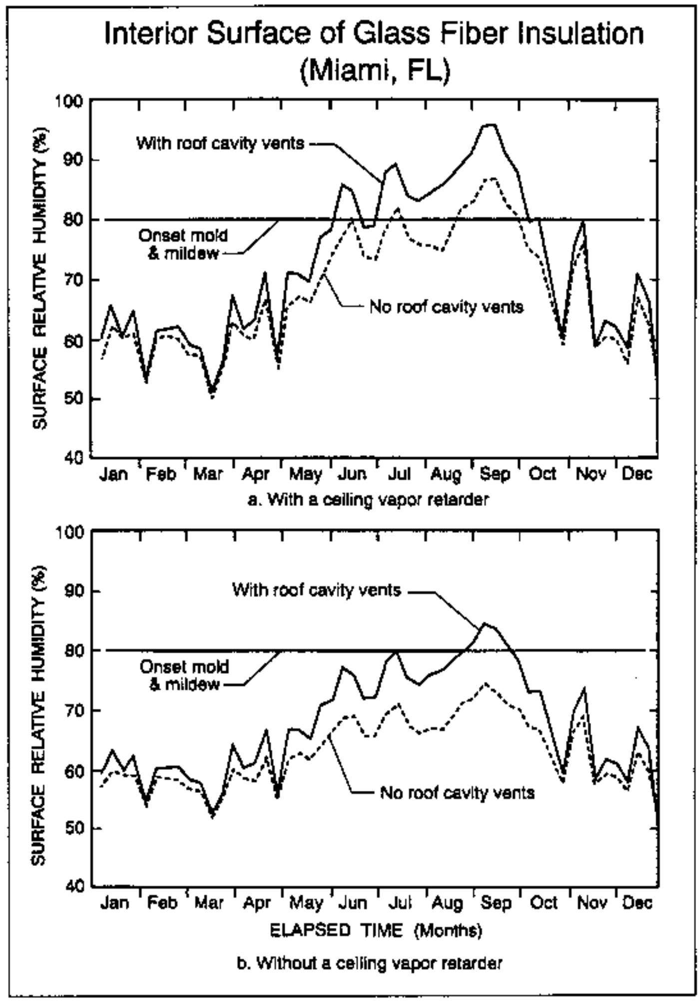

Figure 14. Effect of current HUD Standards moisture control practices in a hot and humid climate.

For the current practice house with a ceiling vapor retarder, separate computer simulations were carried out for cases with and without roof cavity vents. The results are given in Figure 14a. For both cases, the surface relative humidity above the ceiling vapor retarder rose above 80 percent and reached a peak during the summer. When roof cavity vents were present, the surface relative humidity was higher and above a relative humidity of 80 percent for a longer period of time. An explanation is that the roof cavity vents introduce more moisture (from the humid outdoor air) to the upper surface of the roof cavity insulation where it readily diffuses to the upper surface of the vapor retarder.

In Figures 14 a and b, the horizontal line depicts the critical relative humidity of 80 percent believed to coincide with mold and mildew growth. The International Energy Agency[4] has published *Guidelines and Practices* (Volume 2) for preventing mold and mildew growth at building surfaces. This consensus document indicates that a monthly mean surface relative humidity above 80 percent is conducive to mold and mildew growth. In the computer simulation with a ceiling vapor retarder and with roof cavity vents, the surface relative humidity rose above the critical 80 percent relative humidity during a four-month summer period, thereby posing a risk of mold and mildew growth during that period.

A similar pair of computer simulations were conducted for the same house without a ceiling vapor retarder. The results are given in Figure 14b. When roof cavity vents were not present, the roof cavity performed satisfactorily. That is, the surface relative humidity at the upper surface of the gypsum board remained below the critical 80 percent level. In this situation, the ceiling construction functioned as a "pass through system" where moisture readily flowed through it from the roof cavity to the indoor environment where it was removed by the air conditioning equipment. However, when roof cavity vents were present, the surface relative humidity rose above the critical 80 percent relative humidity for about a one-month period. Before leaving this section, it is worth mentioning that the surface relative humidities in other parts of the construction were below the critical 80 percent level. In addition, the source of moisture in a hot and humid climate is the outdoor environment, as opposed to the indoor environment for cold climate applications.

The above results indicate that ceiling vapor retarders and roof cavity vents should not be installed in manufactured homes exposed to hot and humid climates.

NEED FOR MODEL VERIFICATION

The results of this paper are based upon a theoretical model. It goes without saying that a strong need exists to experimentally verify the theoretical model and corroborate the predicted results. As part of such an effort, the attic of a test house would be instrumented to measure the moisture content of the roof sheathing as a function of time. The outdoor boundary conditions (i.e., outdoor temperature, relative humidity, wind speed and direction, solar radiation) would also be measured as a function of time. In addition, special tests would be conducted to develop semi-empirical correlations that relate the attic air exchange rate to the outdoor wind speed and wind direction, and a separate semi-empirical correlation would be developed that predicts the airflow from the house into the attic. The moisture and heat transfer properties of the building materials would be independently measured. The moisture content of the roof sheathing would be predicted and compared to corresponding measured values.

SUMMARY AND CONCLUSIONS

The analysis revealed the following:

- airflow from the house into the roof cavity, as opposed to water-vapor diffusion, was the dominant moisture transport mechanism into the roof cavity during the winter;
- high roof sheathing moisture content occurred in houses having high indoor relative humidity (i.e., high moisture production rate, or tight construction, or both);
- passive roof cavity vents consistent with the 1/300 rule were found to maintain the roof sheathing moisture content in non-humidified houses below fiber saturation during the winter;
- the mechanical roof cavity ventilation rate specified in the HUD Standards for removing moisture during the winter was found to be too small and thus needs to be revised;
- the presence of a ceiling vapor retarder was found to provide very small reductions in roof sheathing moisture content;
- when an interior vapor retarder was installed in the ceiling construction of an air-conditioned house exposed to a hot and humid climate, the relative humidity at its upper surface rose above 80 percent, thereby providing a conducive environment for mold and mildew growth.

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NOMENCLATURE

Symbol	SI Units	English Units	Definition
A_n	m²	ft²	Area of surface n
c	J/kg•K	Btu/lb•°R	Specific heat
C_v	(L/s)²•cm⁻⁴•(m/s)⁻²	cfm²•in.⁻⁴•mph⁻²	Wind coefficient for roof cavity
$C_{\Delta T}$	(L/s)²•cm⁻⁴•K⁻¹	cfm²•in.⁻⁴•°F⁻¹	Stack coefficient for roof cavity
h_{lv}	J/kg	Btu/lb	Latent heat of vaporization
$h_{c,n}$	W/m²•K	Btu/h•ft²•°R	Convective heat transfer coef. at surface n
H_c	m	ft	Stack height for roof cavity
H_h	m	ft	Stack height for house
k	W/m•K	Btu/h•ft•°R	Thermal conductivity
K	kg/m•s•Pa	lb/h•ft•inHg	Hydraulic conductivity
L_c	m²	ft²	Effective leakage area for ceiling construction
L_s	m²	ft²	Effective leakage area for stack effect airflow
L_h	m²	ft²	Effective leakage area for whole house
L_w	m²	ft²	Effective leakage area for house exterior walls
L_r	m²	ft²	Effective leakage area for roof construction
m_n	kg/s•m²•Pa	lb/h•ft²•inHg	Mass transfer coefficient at surface n
p_l	Pa	inHg	Capillary pressure
p_v	Pa	inHg	Water vapor pressure
p_{vi}	Pa	inHg	Water vapor pressure of indoor air
p_{vc}	Pa	inHg	Water vapor pressure of cavity air
$p_{v,n}$	Pa	inHg	Water vapor pressure at surface n
Δp_r	Pa	inHg	Stack-effect reference pressure (4 Pa)
Δp_t	Pa	inHg	Total stack-effect pressure
t	s	h	Time
T	°C	°F	Temperature
T_c	°C	°F	Cavity air temperature
T_i	°C	°F	Indoor temperature
$T_{s,n}$	°C	°F	Temperature of surface n
T_o	°C	°F	Outdoor air temperature
v	m/s	mi/h	Average wind speed
$\dot{V}_c$	m³/s	ft³/min	Outdoor cavity ventilation rate
$\dot{V}_{h-c}$	m³/s	ft³/min	Airflow rate from house to cavity
y	m	ft	Distance
γ	kg/kg	lb/lb	Moisture content on dry mass basis
ρ_a	kg/m³	lb/ft³	Air density
ρ_d	kg/m³	lb/ft³	Dry material density
μ	kg/s•m•Pa	lb/h•ft•inHg	Water vapor permeability
ω_c	kg/kg	lb/lb	Cavity air humidity ratio
ω_i	kg/kg	lb/lb	Indoor air humidity ratio
ω_o	kg/kg	lb/lb	Outdoor air humidity ratio