A DETAILED COMPUTER ANALYSIS OF THE MOISTURE PERFORMANCE OF ROOF CONSTRUCTIONS IN THE *U.S. DOE MOISTURE CONTROL HANDBOOK*

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A new mathematical model, called the MOIST Attic Model, has been used to predict the moisture performance of a current practice site-built prototype house with 15 different roof designs constructed in compliance with the *U.S. DOE Moisture Control Handbook* in cold (heating), mixed, and cooling (hot and humid) climates. These open attic or cathedral ceiling roof constructions were intended to be the best designs to minimize moisture problems. But prior to this study, their moisture performance had not been checked with a moisture model. Thus, this computer simulation study of their performance was undertaken. For each of the 15 roof designs, attention was focused on predicting the peak values of the plywood roof sheathing moisture content and the relative humidity at the bottom of the insulation adjacent to the various ceilings where mold and mildew might grow. Parametric sensitivity analysis was undertaken to determine the effect of a number of variables on the moisture performance of the various roofs. Findings of the study regarding the moisture performance of the 15 designs, as well as roof design suggestions and code implications, are presented.

KEYWORDS

Airflow, attics, attic ventilation, building technology, computer modeling, mathematical analysis, moisture, moisture analysis, moisture modeling, moisture performance, roofs, roof cavities, roof ventilation.

INTRODUCTION

It is possible for the moisture content of roof sheathing to rise above the so-called fiber saturation level, thereby posing a potential for material degradation (e.g., plywood delamination or wood decay) and shortened service life. For wood decay to occur, the wood must have a moisture content above the fiber saturation point (e.g., 28 percent moisture content for plywood), and the wood must be warm (above 10°C [50°F] and optimally between 24°C [75°F] and 33°C [90°F]).[1]

In addition to concern about material degradation, there is a growing concern about the growth of mold and mildew, especially because of the widening recognition of possible adverse health effects (e.g., allergic responses and/or respiratory illness).[2] This is of particular concern during the summer in hot and humid climates, when warm, moist outdoor air infiltrates into an attic and contacts a cool surface, such as a ceiling. When a vapor retarder is installed above the ceiling, moisture accumulates at its top surface. The surface relative humidity may approach a saturated state, thereby providing a conducive environment for mold and mildew growth. In cooling (hot and humid) climates, mold and mildew problems have been documented in field studies by Lstiburek,[3,4] and high relative humidities behind interior vapor retarders during the summer also have been predicted by computer analysis.[5] It may be that moisture control measures that are designed for winter conditions, such as a ceiling vapor diffusion retarder or roof cavity ventilation, may actually be counterproductive during the summer when used in a hot and humid or even a mixed climate.

In an effort to prevent roof cavity moisture problems, open attics and cathedral ceilings in site-built homes are typically passively ventilated according to the "1/300" rule, as mandated by most building codes. That rule specifies that there shall be 1 square foot (or square meter) of net free ventilation area from roof vents per 300 square feet (or square meters) of ceiling area. Furthermore, a 1 perm (57 ng/s•m^2•Pa) vapor retarder is often used or required to minimize the winter transport of moisture by diffusion into the roof cavity, especially in cold climates. In mixed and cooling (hot and humid) climates, that retarder is typically not used or required by code. It is generally felt that the retarder is not necessary because in the milder climates elevated moisture levels in the winter typically are a not a problem.

In terms of previous mathematical analyses of roof moisture performance, a transient heat and moisture transfer model developed at the National Institute of Standards and Technology (NIST) called MOIST[6] was used to analyze the effectiveness of various moisture control practices for roof cavities of manufactured housing.[7] In that study, it was found that a combination of passive measures consisting of a ceiling vapor retarder, sealing air leakage sites in the ceiling construction, and providing attic ventilation openings maintained the moisture content of the roof sheathing well below fiber saturation. However, the version (2.1) of the MOIST model used had several important limitations that likely influenced the results: it was intended to analyze only walls or flat roofs, the indoor relative humidity in the house below had to be held constant, the stack effect airflow from the house into the roof cavity was treated as constant, and the attic ventilation rate was taken to be constant.

It was decided to modify the model to remove those limitations. An essentially new model has been developed to analyze the moisture performance of both open-attic- and cathedral-ceiling-type roofs, rather than just flat roofs. The details of the new model, as well as the moisture performance of roofs of manufactured houses, as assessed using the new model, is the subject of a companion paper presented at this conference.[8] Although the wall analysis portion has been validated and predicts conditions that are exceedingly close to those measured in the field,[9] the roof analysis portion has not yet been validated by full-scale studies. That would require very detailed measurements of a variety of roof properties and conditions that currently are not available, as described by Burch et al.[8] The new MOIST Attic Model is a research version for which there is no users manual. It will not be available in the near future.

The new model was used in this study to assess the moisture performance of the 15 roof constructions recommended in the *U.S. DOE Moisture Control Handbook.*[10, 11] The handbook recommends roof, wall, and foundation constructions for three different climatic regions of the United States [the cold (heating), mixed, and cooling (hot and humid) climates]. The constructions were intended to be designs that would minimize moisture accumulation, thereby preventing degradation of materials and mold and mildew growth. However, at the time the handbook was prepared, there was no readily available computer model to assess the moisture performance of the proposed roof designs. Thus, it was decided to use the new MOIST Attic Model to do so.

Because the computer model theory and solution procedure used in this study are presented in detail in the companion paper[8] noted previously, they are not repeated in this paper to save space.

DESCRIPTION OF CURRENT PRACTICE HOUSE AND ROOF CONSTRUCTIONS

House and Roof Construction Characteristics

The current practice prototype house simulated in this study is a single-story, site-built house having a floor area of 139 m² (1500 square feet) and either a 2.44-m (8-foot) flat ceiling height or an average 3.4-m (11.1-foot) cathedral ceiling height. The moisture performance of 15 different roof constructions presented in the *U.S. DOE Moisture Control Handbook*[10, 11] was analyzed. There are nine open-type conventional attic constructions with flat ceilings (hereafter referred to as "open attics") and six cathedral ceilings. Of the 15 roof constructions, five are located in a cold (heating) climate (Madison, Wisconsin), four are located in a mixed climate (Washington, D.C.), and six are located in a cooling climate (also called a hot and humid climate) (Lake Charles, Louisiana).

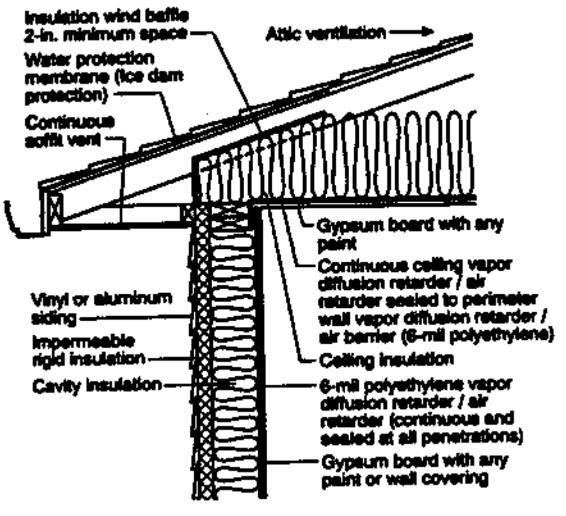
Cross sections of each roof construction for each of the three climates are shown in Figures 1, 2, and 3. The sloping roofs face north and south; the gable end walls face east and west. The slope of the roof is 5-in-12 (22.6° slope). The gable end walls are constructed of 10-mm (⅜-inch) asphalt-impregnated fiberboard and vinyl siding. All of the roofs are assumed to have medium-colored asphalt shingles with a total thickness of 6.4 mm (0.25 inch) and a solar absorptance of 0.8 (the average of 34 samples of different colors ranging from white to black[12]).

The construction of the exterior portion of all the roofs is composed of 12.7-mm (0.5-inch) exterior-grade plywood, asphalt felt underlayment, and asphalt shingles. The ceiling construction (or bottom of the roof cavity) consists of 12.7-mm (0.5-inch) gypsum board with 689 ng/s•m²•Pa (12.0 perm) latex paint applied to its interior surface, except for Mixed Climate Roof 4, which has impermeable paint (57 ng/s•m²•Pa [1 perm]). If a vapor retarder is present, it is 0.15-mm (6-mil) polyethylene ("poly"). In the roof and ceiling construction, the framing members (including trusses) are spaced 0.61 m (24 inches) on center. The insulation levels in the roof constructions are those required by local code in the three climate locations. The required R-values in each of the three climates happen to be the same for open attic and cathedral ceiling type roofs: RSI-6.7 m²•K/W (R-38 ft²•h•°F/Btu) in the cold (heating) climate and RSI-5.3 m²•K/W (R-30 ft²•h•°F/Btu) in each of the mixed and cooling (hot and humid) climates.

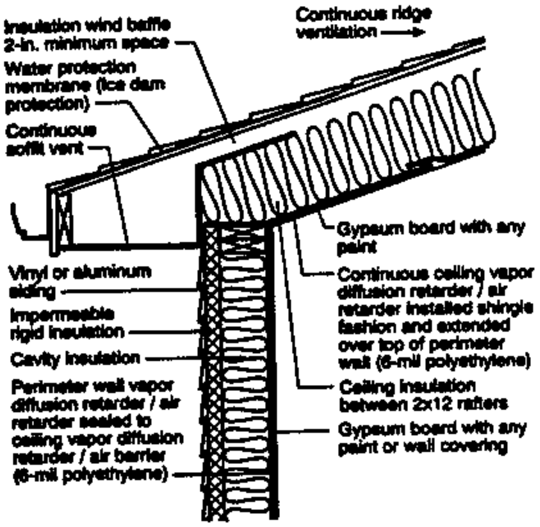
It was decided to assume a relatively airtight house to look at fairly worst case conditions. An overall whole house effective leakage area (ELA) of 355 cm² (55 square inches) was assumed for all roof cases, which corresponds to a natural air change rate of about 0.25 air changes per hour (ach). That is tight, but not overly so.

Based on airtightness test results of the five tightest homes in a total sample of 20 Canadian site-built houses,[13] the authors assumed that the ceiling ELA is 55 percent of the whole house total or 195 cm² (30 square inches). For ventilated roof cavities, the ELA of the house below the ceiling is 45 percent of the whole house total or 161 cm² (25 square inches). When relatively airtight roofs were assumed with some of the unventilated cathedral ceiling constructions (i.e., a roof ELA of 6.5 cm² [1 square inch]), then the house below ELA was 348 cm² (54 square inches). Although the same ceiling construction and ELA was assumed for all the roof cases except the one that utilized the airtight drywall sealing approach, it was felt that the unventilated cathedral-type roofs would be fairly airtight (asphalt shingles over continuous lapped felt underlayment over plywood sheathing over rigid insulation); hence, their low roof ELA.

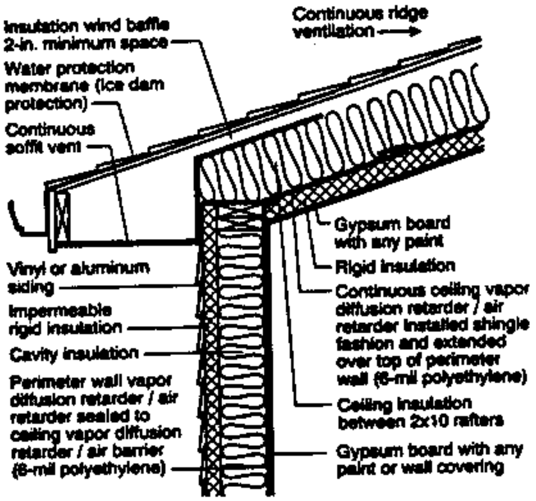
Consistent with the current roof ventilation code for site-built homes, the roof construction was fitted with roof cavity vents having a net free open area of 1/300 of the ceiling area or 0.465 m² (720 square inches) for the open attics and 0.553 m² (858 square inches) for the ventilated cathedral ceilings (based on the sloped ceiling area). The attic volume for the open attics was simply based on the ceiling area and the peak height for the given roof slope. The roof cavity volume for the ventilated cathedral ceilings assumed a 51-mm- (2-inch-) high air slot above the insulation between each of the rafters,



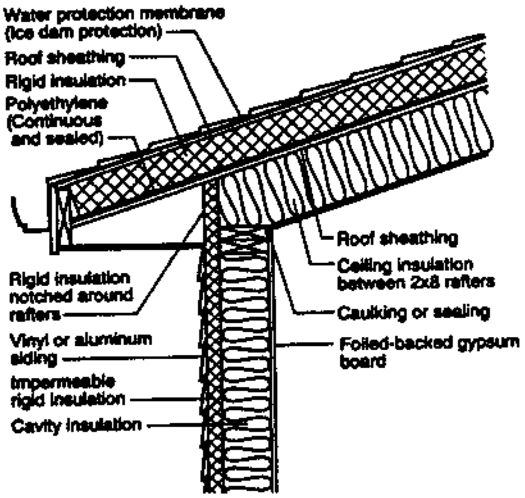
a. Roof 1 - Heating Climate (Vented Attic)



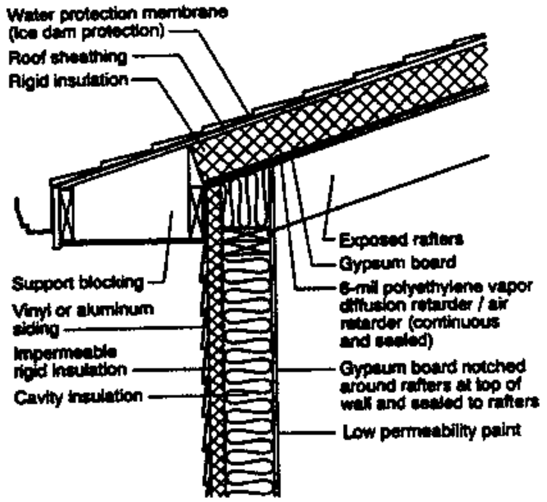
b. Roof 2 - Heating Climate (Vented Cathedral Ceiling)



c. Roof 3 - Heating Climate (Vented Cathedral Ceiling)

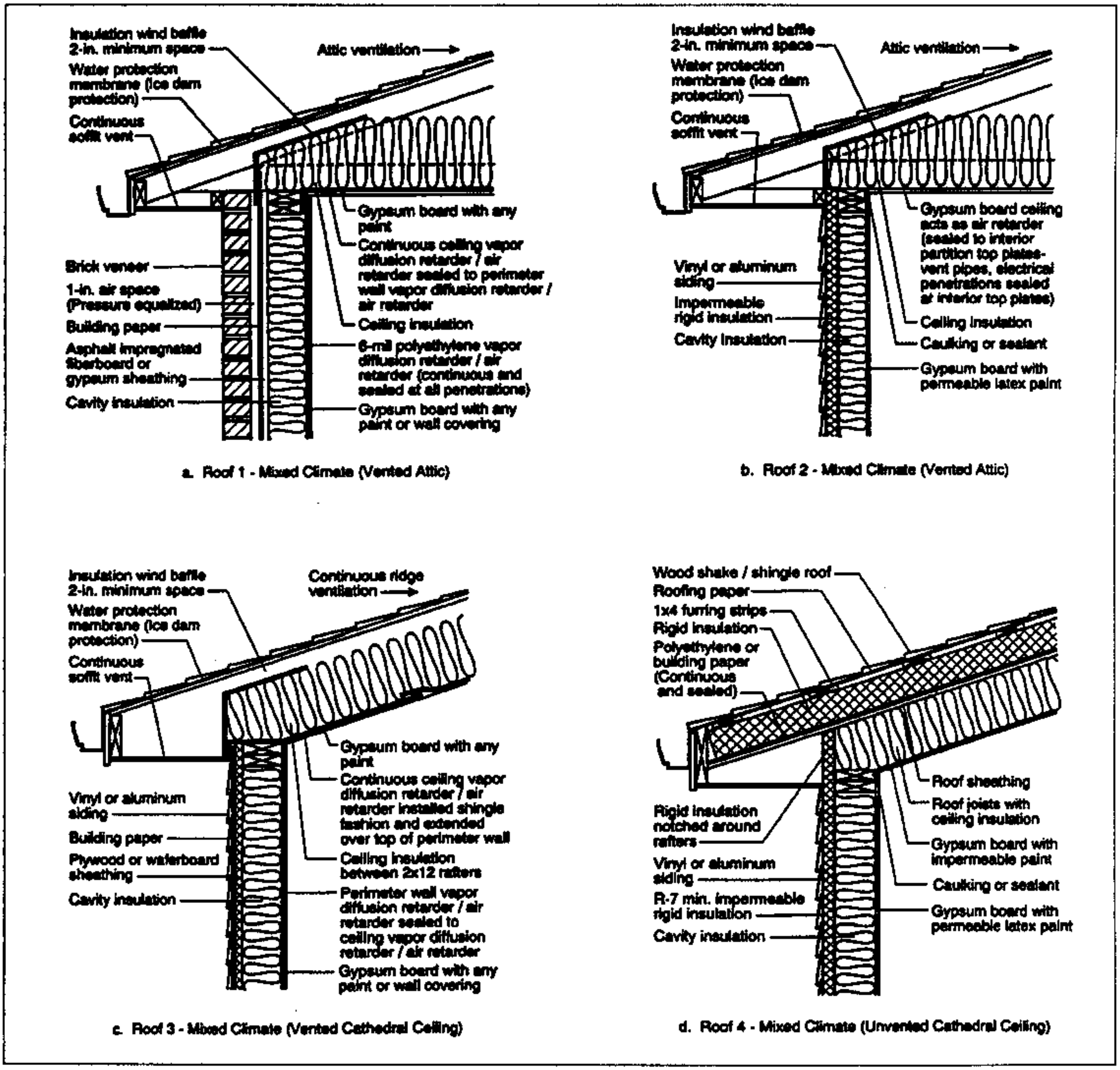


d. Roof 4 - Heating Climate (Unvented Cathedral Ceiling)



e. Roof 5 - Heating Climate (Unvented Cathedral Ceiling)

Figure 1. Half cross sections of cold (heating) climate roof constructions.



a. Roof 1 - Mixed Climate (Vented Attic)

b. Roof 2 - Mixed Climate (Vented Attic)

c. Roof 3 - Mixed Climate (Vented Cathedral Ceiling)

d. Roof 4 - Mixed Climate (Unvented Cathedral Ceiling)

Figure 2. Half cross sections of mixed climate roof constructions.

as per the *Moisture Control Handbook* specifications. However, for the unventilated cathedral ceilings, a thin (3.2-mm-[0.125-inch-]) high cavity was assumed between each of the rafters (the model requires the existence of a cavity).

Weather, Indoor, and Occupant Conditions

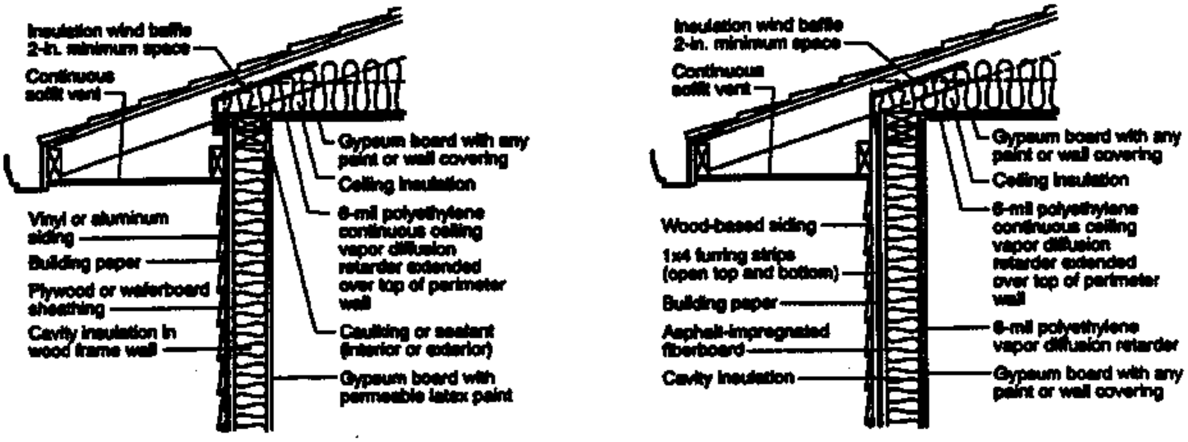
In the computer analysis, the hourly outdoor conditions were obtained from ASHRAE WYEC weather data.[14] The space heating set point temperature was 20°C (68°F). The occupant activities produced moisture at a rate of 10.9 kg/day (24.0 pounds/day), and the indoor relative humidity floated and was predicted from a moisture balance of the whole building. The space cooling set point temperature and indoor relative humidity were 24°C (76°F) and 56 percent, respectively. Summer air conditioning was assumed because that cooling would produce the worst mold and mildew conditions at the insulation-poly/ceiling interface (the most likely location for summer mold and mildew growth).

PARAMETERS USED IN ANALYSIS AND MATERIAL PROPERTY MEASUREMENTS

Water Vapor Diffusion Properties

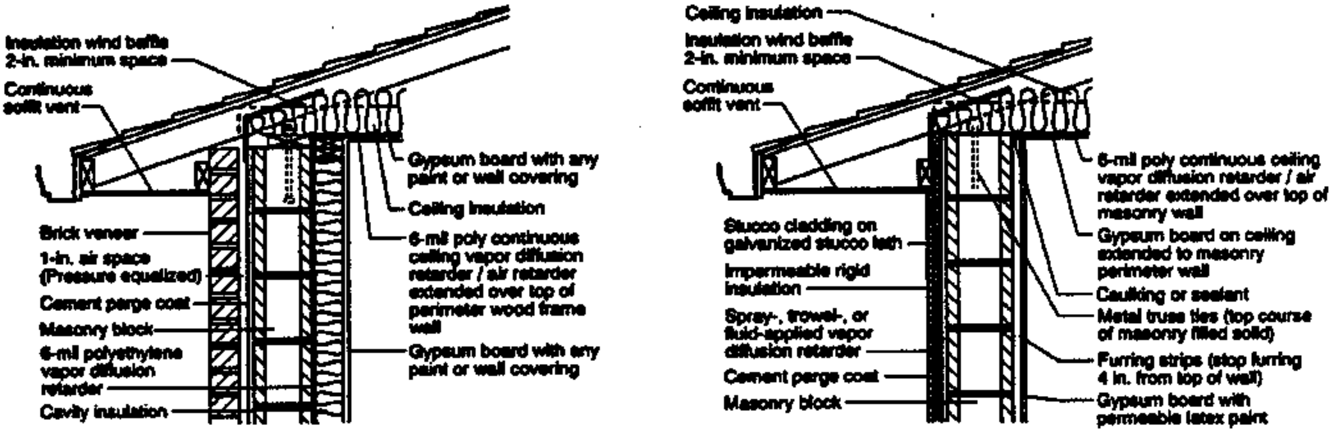
Moisture and Heat Transfer Measurement

The sorption isotherms (i.e., the relationship between equilibrium moisture content and relative humidity) of the mate-



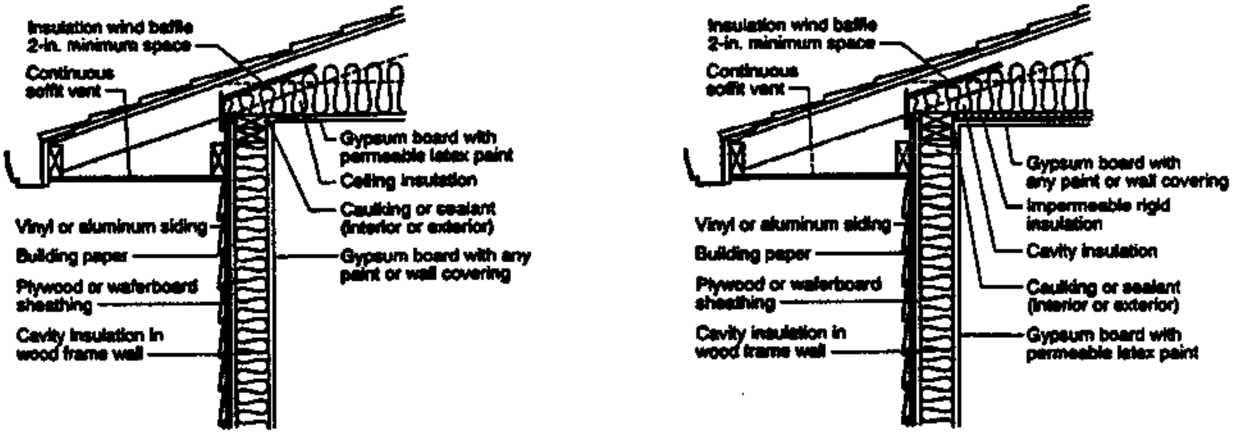
a. Roof 1 - Cooling Climate (Vented Attic)

b. Roof 2 - Cooling Climate (Vented Attic)



c. Roof 3 - Cooling Climate (Vented Attic)

d. Roof 4 - Cooling Climate (Vented Attic)



e. Roof 5 - Cooling Climate (Vented Attic)

f. Roof 6 - Cooling Climate (Vented Attic)

Figure 3. Half cross sections of cooling climate roof constructions.

rials were based on measurements conducted at NIST.[15] The permeability (i.e., the relationship between water vapor permeability and relative humidity) of the materials also was based on NIST measurements.[6] The liquid diffusivity (i.e., the relationship between liquid diffusivity and moisture content) of the materials was based on measurements by Richards.[16] The thermal conductivity, density, and specific heat of the materials were from ASHRAE.[17] 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. measured 60 attic ventilation rates in 20 houses in several Canadian climates.[13] The houses had different types of attic ventilation with a wide range of ELAs measured using a blower door 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 of this paper applied this set of data and used regression analysis to determine the empirical stack and wind speed coefficients. The stack coefficient was determined to be a very small value, and so it was taken to be zero in this analysis.

Because there is no known empirical data for ventilation rates for cathedral ceilings, the NIST CONTAM Model[18] was used to predict outdoor to cavity ventilation rates for the cathedral ceiling constructions to be analyzed using MOIST. Because there were either 76-mm (3-inch) or 51-mm (2-inch) air spaces above the insulation in the ventilated cathedral ceilings, the flow through air spaces of those sizes was modeled. In addition, a thin (3.2-mm [0.125-inch]) air space was also modeled to predict the airflow in the unventilated cathedral ceilings. It was assumed that the airflow through the 76-mm (3-inch) air space was the same as through the open attics. As one might expect, the predictions revealed that the ventilation rate becomes reduced as the height of the cavity air space decreases, significantly so below 25 mm (1 inch). The predicted ventilation rates were used to proportion the cavity ventilation rates for the three air space thicknesses, given the open attic value. Although this clearly is a rough approximation to the actual cavity flow rates for the cathedral ceilings, it was used in the absence of empirical data. Obviously, there is a substantial need for such empirical data to properly pursue modeling of cathedral ceiling performance.

COLD (HEATING) CLIMATE RESULTS (MADISON, WISCONSIN)

The authors used the MOIST Attic Model to predict the moisture content of the roof cavity wood members as a function of time of year. They focused on the moisture content of a thin (1.6-mm [0.0625-inch]) layer of the surface adjacent to the roof air cavity that was found to have the highest moisture content of any portion of the wood member. In the case of the plywood roof sheathing, which typically was the wettest roof component, this thin layer was at the bottom or cavity side of the plywood. Thus, one of the major aims of the analysis was to find out if the moisture content of that plywood lower surface layer ever rose above the fiber saturation point (28 percent moisture content for plywood).

In addition to examining the plywood moisture content, the authors also analyzed the relative humidity of the air at the top of the poly vapor retarder above the ceiling gypsum board in those cases where poly existed, and directly above the gypsum board in those cases where there was no vapor retarder. This was done to check for conditions conducive to the growth of mold and mildew. The International Energy Annex has determined that the monthly mean relative humidity at a surface must be above about 80 percent to support mold and mildew growth,[19] so the simulation results were checked for the existence of that condition.

The moisture content and surface relative humidity results presented in this study are weekly average values. Typically, the simulations were run for one year. In all cases, six months of weather data were used to initialize the simulations to reduce any effect of the assumed initial moisture content and temperature of the construction layers.

The authors first used the MOIST Attic Model to investigate the moisture performance of the five different roofs on the current practice prototype house in the cold (heating) climate of Madison, Wisconsin.

Cold (Heating) Climate Roof 1

This roof design is the only open attic design in the cold (heating) climate (see Figure 1). It is ventilated with passive roof vents consistent with the 1/300 rule, and there is a poly vapor diffusion retarder just above the gypsum board ceiling. The moisture contents of the different roof members at the interior roof cavity surfaces are plotted versus time of year in Figure 4. "N. Plywood" is the north-facing plywood roof sheathing, and "N. Rafter" is the north plywood with a rafter below it. "E. End" is the east gable end wall asphalt-impregnated fiberboard sheathing. "Int. Wood" is the interior attic trusses, while "Ceiling Insulation and Joist" is both the ceiling insulation and the ceiling insulation over a ceiling joist (their moisture contents are essentially the same). The moisture content of the gypsum board remained less than 1 percent throughout the year and is not shown.

In all wood members, the moisture contents are lowest during summer and rise to a maximum during the winter. The construction part having the highest surface layer moisture content is the north-sloping plywood roof sheathing. The portion of the plywood sheathing in contact with a rafter is fairly similar in moisture content. The south facing plywood is not quite as moist. The peak plywood moisture content is seen to be 19 percent, which is well below fiber saturation. For all the 14 other roof designs, only the north plywood moisture content results are presented, because that roof construction part always has the highest, or close to the highest, moisture content compared to all the other parts.

The surface relative humidity just above the poly also is shown in Figure 4. Whereas the plywood moisture content typically peaks in the winter, the surface relative humidity peaks in the summer. That is when warm outdoor air infiltrates the roof cavity and accumulates on the poly that is relatively cold because the indoor air is air-conditioned. Conditions conducive to the growth of mold and mildew do not exist for Cold (Heating) Climate Roof 1.

Cold (Heating) Climate Roofs 2 and 3

These roof designs are ventilated cathedral ceilings (see Figure 1). The plywood surface moisture content and surface relative humidity results are presented, along with those of Roof 1 for comparison, in Figure 5. Those two ventilated roofs experience neither elevated plywood moisture contents nor elevated surface relative humidities. The peak winter moisture content of Roof 3 is about the same as for Roof 1, while the peak for Roof 2 is about 1 to 2 percent lower. All three roofs have about the same peak surface relative humidity, which is below the 80 percent level required for the onset of mold and mildew.

Cold (Heating) Climate Roofs 4 and 5

These roof designs are unventilated cathedral ceilings (see Figure 1). The performance of Roofs 4 and 5 is compared to that of Roof 2 in Figure 6. The moisture contents remain considerably below fiber saturation. Note that in Roof 4, which has two layers of plywood roof sheathing, the moisture content shown in Figure 6 is for the upper sheathing. The ceiling-insulation interface RHs never rise above the critical 80 percent level.

It can be seen that Roofs 4 and 5 perform similarly from a plywood moisture content point of view. Their peak moisture contents are very similar to those of Roofs 1, 2, and 3. More importantly, the results suggest that moisture is accumulating in both of the unventilated roofs (4 and 5), because the moisture content at the end of the simulation year (July 1) is greater than that at the start of the simulation (the previous July 1). Note that it was assumed in these unventilated cases that the ceiling ELA was $195\ \text{cm}^2$ (30 square inches), where-

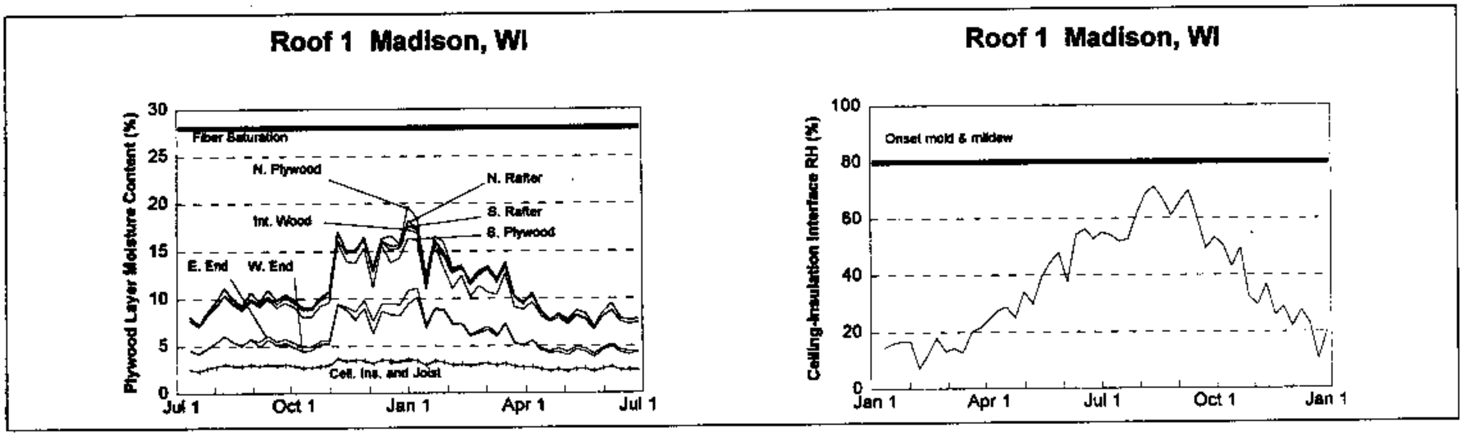


Figure 4. Moisture performance of heating climate roof #1.

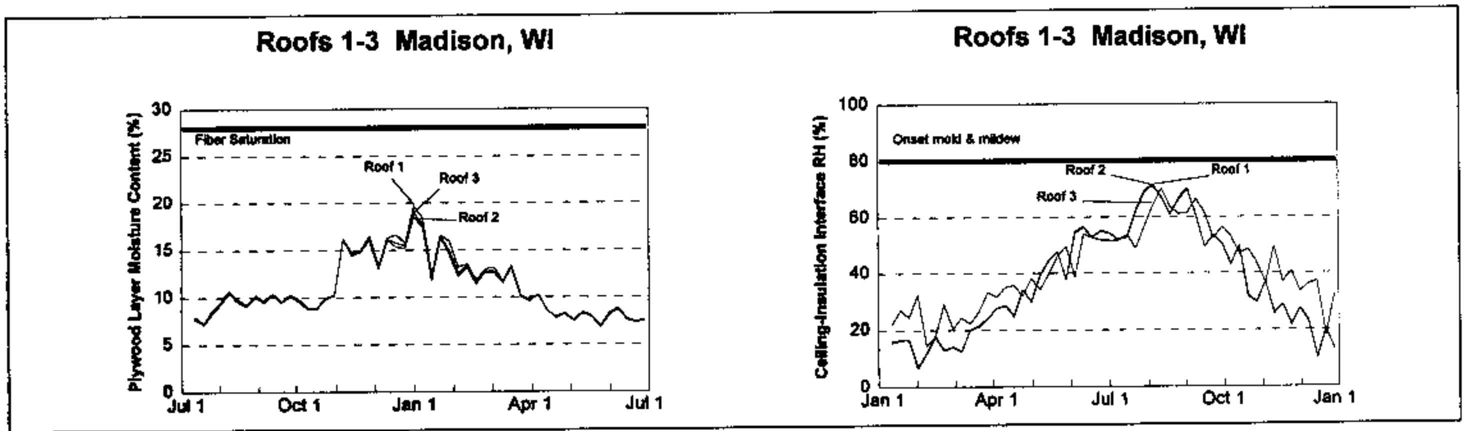


Figure 5. Moisture performance of heating climate roofs #1, #2 and #3.

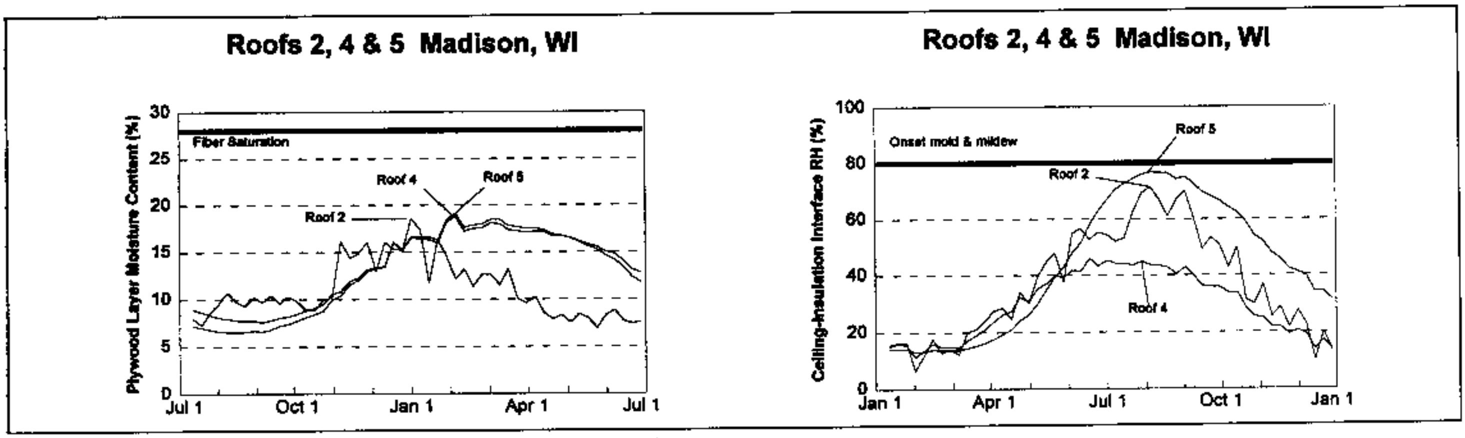


Figure 6. Moisture performance of heating climate roofs #2, #4 and #5.

as the roof ELA was assumed to be only 6.5 cm² (1 square inch). Thus, with the assumed conditions for these unventilated designs, the opportunity for accumulation exists. To check this, simulations were run for a 10-year period. As shown in Figure 7, the roofs do eventually reach a state of long-term moisture equilibrium in a few years, which is below the fiber saturation level.

Although the plywood sheathing moisture content does not reach fiber saturation, the interface relative humidity does get above the point of mold and mildew onset for about a month in the summer for Roof 5, as shown in Figure 7. Note that it has a vapor retarder that keeps the roof from readily drying to the indoor air in the summer. Roof 4, on the other hand, can dry out to the indoor air more readily because of the absence of a vapor retarder just above the ceiling gypsum board.

MIXED CLIMATE RESULTS (WASHINGTON, D.C.)

The model was next used to investigate the moisture performance of the four mixed climate roof constructions. Two of the roofs were open-attic types, whereas the other two were cathedral-ceiling types (see Figure 2).

Mixed Climate Roofs 1 and 2

These are the open-attic type ventilated with passive roof vents consistent with the 1/300 rule. There is a poly vapor diffusion retarder just above the gypsum board flat ceiling for Roof 1, whereas Roof 2 does not have a vapor retarder but uses a well-sealed, airtight drywall approach [the authors assumed a ceiling ELA for this one case of 48.4 cm² (7.5 square inches)]. Roof 1 had a ceiling ELA of 195 cm² (30 square inches). For each roof, the moisture contents of the lower plywood surface layer are plotted vs. time of year in Figure 8. All of these roofs have a lower moisture content than any of the cold climate roofs. Importantly, neither of these ventilated roofs was close to fiber saturation.

Roof 1 with a vapor retarder gets just above the critical 80 percent RH level for a few weeks in the summer. However, Roof 2 with its more permeable ceiling (without a vapor retarder) has a lower interface relative humidity that is well below the onset level for mold and mildew. That is one good reason for leaving out the vapor retarder in Roof 2. Thus, it was decided to examine whether removing the vapor retarder in Roof 1 would help its summer performance. The results are shown in the bottom plot of Figure 8. The interface RH is then about the same as that of Roof 2 without a vapor retarder. Thus, it appears that eliminating the ceiling vapor retarder in open attics in a mixed climate may actually be a good idea. That allows the moisture at the bottom of the insulation to more readily diffuse into the living space during the summer where it is removed by the air conditioning system.

Not shown are results for Roofs 1 and 2 without ventilation. Removing the ventilation of Roof 1 also reduces the interface RH about the same amount as removing the vapor retarder, but the winter peak plywood moisture content is more adversely affected (reaching a peak of about 21 per-

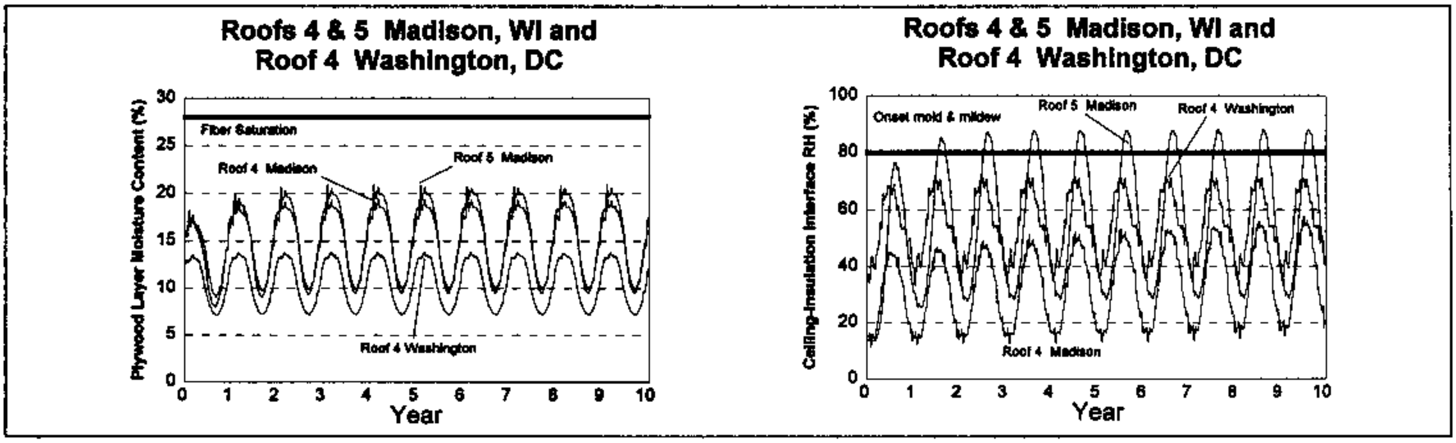


Figure 7. Ten-year simulations for heating climate roofs #4 and #5 in Madison, WI, and mixed climate roof #4 in Washington, D.C.

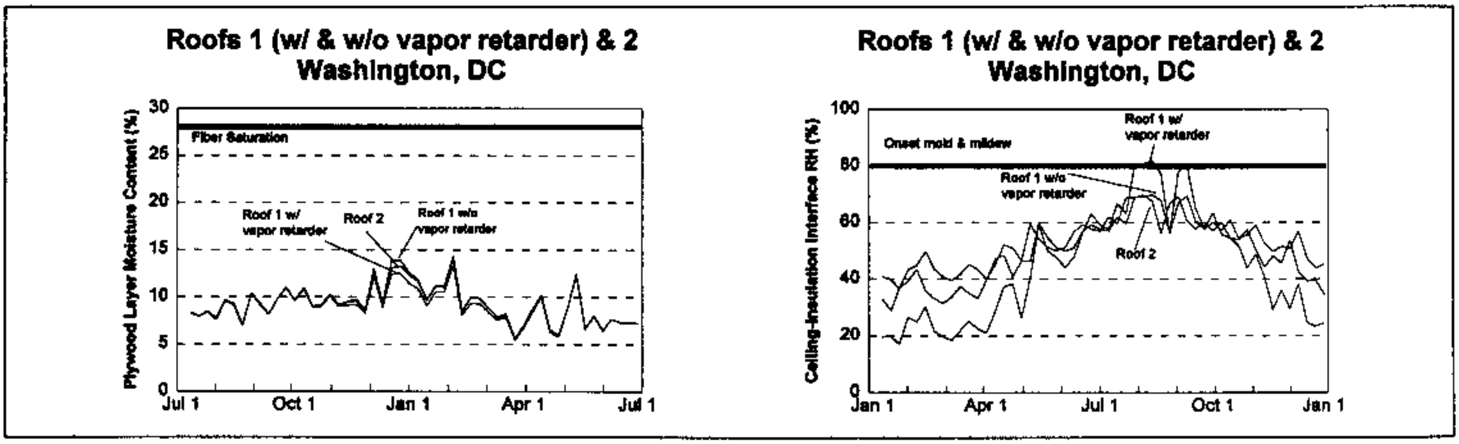


Figure 8. Moisture performance of mixed climate roofs #1 (with and without a vapor retarder) and roof #2 in Washington, D.C.

cent). In Roof 2 without ventilation, the interface RH is the lowest of the cases investigated, but the peak plywood moisture content is even higher and approaches fiber saturation. Hence, eliminating ventilation in either case does not appear to be wise. These results indicate that leaving out the vapor diffusion retarder is the better approach in mixed climates.

Mixed Climate Roofs 3 and 4

These roof designs are cathedral ceiling types—Roof 3 has ventilation above the batt insulation, and Roof 4 has no ventilation space, although there is rigid insulation above the plywood sheathing (see Figure 2). Both roofs employ a poly vapor retarder. The simulation results are shown in Figure 9. The two roofs perform well in terms of the plywood moisture content. However, although the unventilated Roof 4 performs well from a mold and mildew point of view, the ventilated cathedral type Roof 3 with a vapor retarder experiences summer periods where the interface RH is above 80 percent. The beneficial effect of removing the vapor retarder in Roof 3 and allowing moisture at the interface to diffuse into the indoor space rather than collect is also shown in Figure 9. There is no serious adverse impact of removing the vapor retarder on the plywood moisture content in this mild winter climate.

COOLING (HOT AND HUMID) CLIMATE RESULTS (LAKE CHARLES, LOUISIANA)

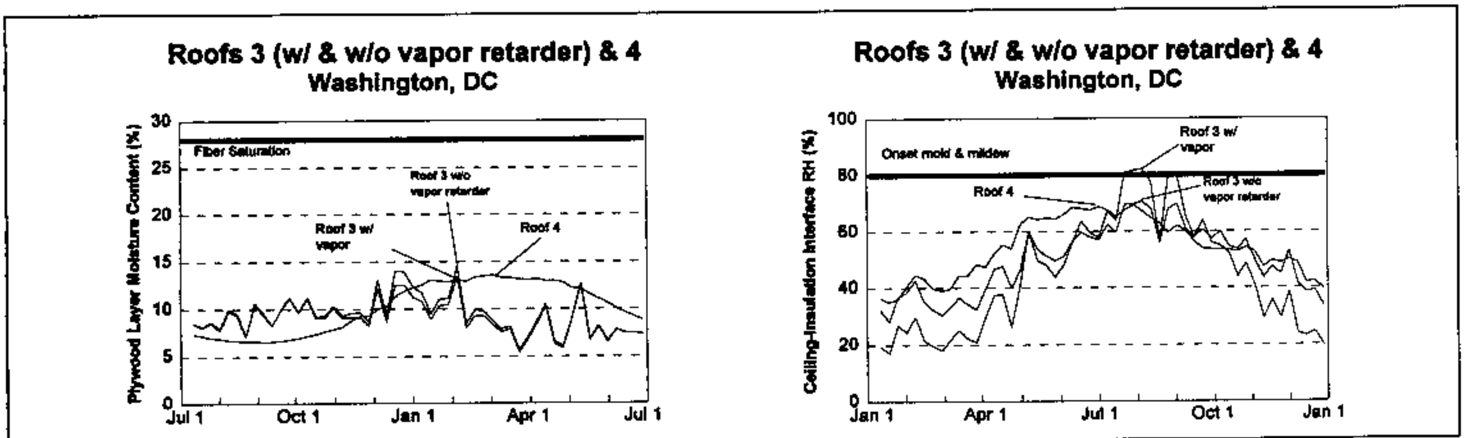
The authors next investigated the moisture performance of the six hot and humid climate roofs. All the roofs were the open-attic type (see Figure 3). The first four employed a ceiling vapor retarder just above the gypsum board, whereas the last two did not employ a vapor retarder. From a moisture performance point of view the first four roofs are the same so they are treated as just one case (Roofs 1-4).

Cooling (Hot and Humid) Climate Roofs 1-4, 5, and 6

The simulation results for Roofs 1 through 4, along with those for Roofs 5 and 6 are shown in Figure 10. The results clearly show that the plywood stays quite dry for all of the roof designs. Although the hot and humid climate is quite conducive to the growth of decay fungi from the point of view of temperatures being quite warm, these results point out that it is very difficult to get wood wet enough to decay.

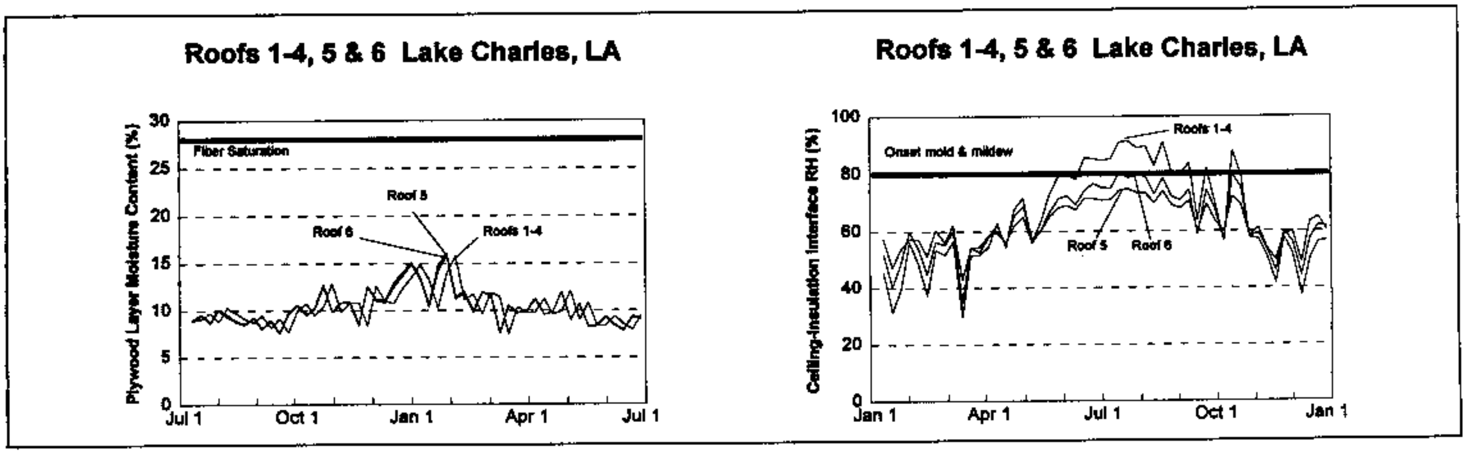
For the two roofs without a ceiling vapor retarder (5 and 6), the interface RH did not rise above the critical 80 percent level, although it was close for Roof 6 because the 25 mm (1 inch) of rigid insulation adjacent to the gypsum board acted somewhat like a vapor retarder that minimized summer diffusion of moisture into the indoors. Thus, Roof 5 has better moisture performance than Roof 6. However, for Roofs 1 through 4, the effect of the presence of a ceiling vapor retarder was to cause the interface RH to rise well above the 80 percent level for about three months in the summertime. That is the worst of any of the roofs analyzed in any climate and clearly is unacceptable moisture performance.

The impact of removing the vapor retarder and also elim-


Roofs 3 (w/ & w/o vapor retarder) & 4
Washington, DC

Roofs 3 (w/ & w/o vapor retarder) & 4
Washington, DC

Figure 9. Moisture performance of mixed climate roofs #3 (with and without a vapor retarder) and roof #4 in Washington, D.C.


Roofs 1-4, 5 & 6 Lake Charles, LA

Roofs 1-4, 5 & 6 Lake Charles, LA

Figure 10. Moisture performance of cooling climate roofs #1-4, #5 and #6.

inating the attic ventilation in Roofs 1 through 4 is shown in Figure 11. Removing the vapor retarder is helpful, as is closing or removing the attic vents, but removing the vapor retarder is the most helpful. That is because even without attic ventilation, the vapor retarder and its influence still exists. Closing the vents reduces the influx of warm moist outdoor air into the roof cavity where its water vapor can condense on the vapor retarder surface that is cooled by indoor air conditioning. Doing both provides the best conditions from a mold and mildew point of view, while not adversely impacting the plywood moisture content very much at all.

PARAMETRIC SENSITIVITY ANALYSIS

Need for Parametric Sensitivity Analysis and Parameters Assessed

This study has so far described the moisture performance of the 15 roof constructions based on a limited set of assumed inputs to the computer model. Thus, it was decided to examine the effect of a number of parameters that might influence the moisture performance of the different roofs. The sensitivity of the moisture performance results to the various factors was explored by varying each of the individual factors and some combinations over an appropriate range.

Parametric Sensitivity Analysis Results and Findings

Based on the moisture performance results presented earlier for all the 15 roof constructions, it was decided to focus for most cases on the most typical open-attic and cathedral-ceiling roof types in the three climates. Thus, the following six roof constructions were analyzed: Cold (Heating) Climate Roofs 1 (open attic) and 2 (cathedral), Mixed Climate Roofs 1 (open attic) and 3 (cathedral), and Cooling (Hot and Humid) Climate Roofs 1 through 4 (all the same open-attic types with a ceiling vapor retarder) and 5 (open-attic type without a ceiling vapor retarder). The results and findings are presented below and summarized at the end of this section.

Effect of Roof Cavity Passive Ventilation

The roof cavity ventilation was varied by changing the roof ELA. Four cases were examined: a base case of a roof ELA corresponding to the 1/300 rule; 1/150; 1/600; and sealed vent openings (assumed ELA of 10 percent of the base case due to unintentional leakage). As far as the plywood moisture contents were concerned, the amount of roof ventilation had some effect on the cold (heating) climate roofs, a small effect on the mixed climate roofs, and essentially no effect on the cooling (hot and humid) climate. There was some difference in the results for the three ventilation rates of 1/150, 1/300, and 1/600, but generally the differences were small and not noteworthy. The 1/300 amount appears to be a prudent choice for a code level of passive roof ventilation.

However, the lack of passive ventilation (the sealed vent openings case) caused a significant increase in the plywood moisture content in the cold (heating) climate such that values rose well above fiber saturation. For Roof 1, the peak moisture content reached 57 percent, as can be seen in Figure 12. Moreover, the plywood stayed above fiber saturation

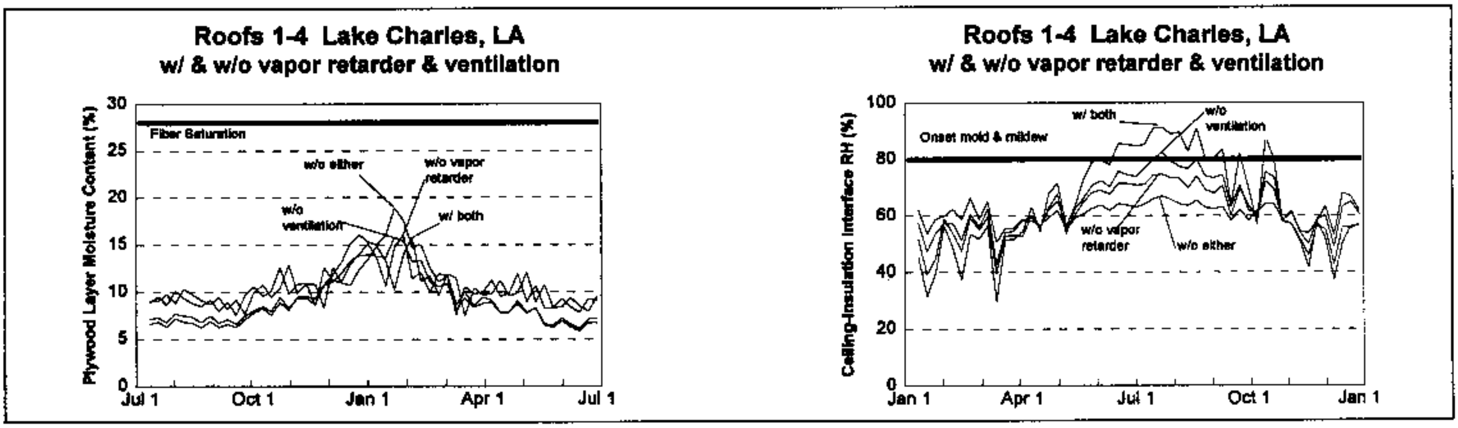


Figure 11. Moisture performance of cooling climate roof #1-4 with a vapor retarder and ventilation, without a vapor retarder, without ventilation and without both.

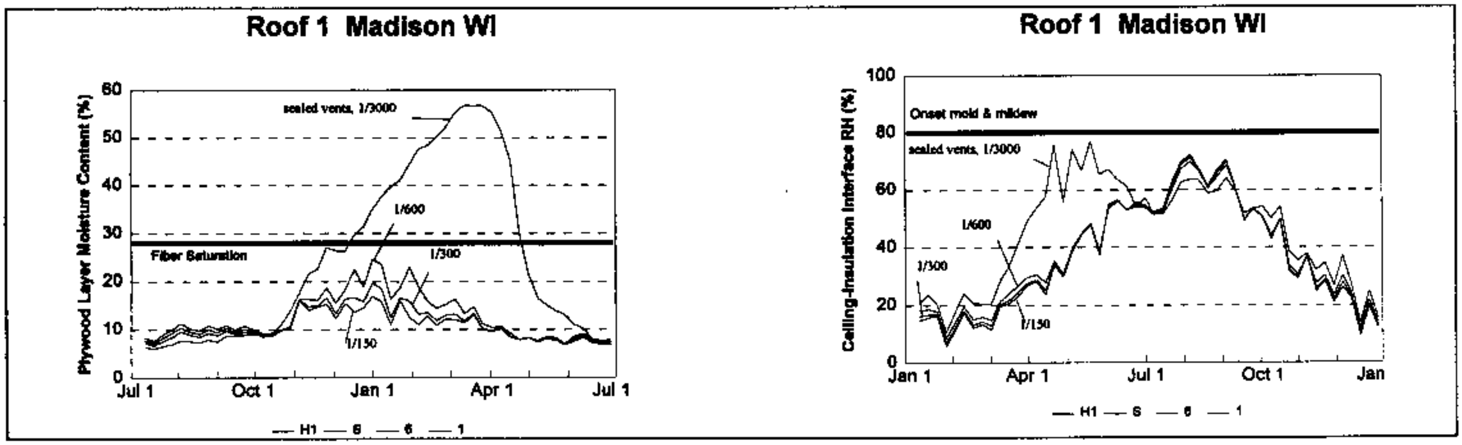


Figure 12. Effect of roof cavity passive ventilation for cold (heating) climate roof 1.

until well into weather that was warm enough for decay to occur. Although sealing the vents caused an increase in the plywood moisture content in the mixed climate roofs, the peak value never rose above 21 percent. The cooling (hot and humid) climate roofs were even dryer. In the cold (heating) and mixed climates, there was no significant difference in the peak moisture content of the plywood between the open attic roofs and the cathedral ceiling roofs.

Although in the cold (heating) climate there was only a minor effect of sealing the vents on the surface relative humidity, there was a beneficial effect in the mixed climate and the cooling (hot and humid) climate. The surface relative humidity dropped in those climates except for Cooling (Hot and Humid) Climate Roofs 1 through 4 because they had a ceiling vapor retarder in place, as did the cold (heating) climate roofs. In general, depending on the climate, sealing the vents can have a beneficial or an adverse impact on moisture performance.

Effect of Ceiling Leakage Area

The amount of ceiling leakage area was assessed for the six roofs with 1/300 ventilation by varying the ceiling ELA from 0 to 195 cm^2 (0 to 30 square inches), with the latter value being the base case. The effect on the plywood moisture contents was small in the cold (heating) climate, very small in the mixed climate, and indistinguishable in the cooling (hot and humid) climate. There was essentially no effect on the surface relative humidity. Although one would expect to see a significant reduction in the plywood moisture content as the ceiling ELA was reduced, the reduction in exfiltration was offset by a corresponding increase in the indoor relative humidity as a result of the reduced ceiling leakage. As an example, for Roof 1 in the cold (heating) climate, decreasing the ceiling ELA from 195 to 0 cm^2 (30 to 0 square inches) caused an increase in the winter indoor relative humidity from around 40 percent to almost 60 percent. Thus, although the leakage was reduced, the source strength was increased. Of course, eliminating all the ceiling leakage is not realistic. Reducing the ceiling leakage by 50 percent is more realistic. Yet, there was no difference in the peak plywood moisture content between the cases with 50 percent and 100 percent ceiling leakage. It was not until the ceiling leakage was reduced by 75 percent that there was a difference in the peak plywood moisture content (a reduction from 20 percent to 17 percent).

Simulations were rerun to see if the results would be similar for the same six roofs, but with the roof vents sealed. As seen in Figure 13, the results with sealed vents for Roof 1 in the cold (heating) climate were notably different. With the ceiling ELA of 195 cm^2 (30 square inches), the plywood moisture content reached over 50 percent, and the wood did not dry quickly in the spring. As the amount of ceiling leakage area was reduced, the plywood moisture contents did drop, but the levels dropped below fiber saturation only after the ceiling ELA was reduced to 24.2 cm^2 (3.75 square inches). Realistically, it is unlikely that a ceiling can be sealed that tight. So, again, it is seen that sealing the roof vents in a cold (heating) climate produces unacceptable moisture performance. However, the moisture performance in the mixed and cooling (hot and humid) climates was quite acceptable with sealed vents. Although reducing the ceiling ELA did reduce plywood moisture contents somewhat, even with the largest ceiling ELA investigated, the values never rose above 20 percent.

Some building scientists have advocated sealing ceiling penetrations as an alternative to using roof ventilation as a prudent means of minimizing the chance for roof moisture problems. This analysis shows that although reducing air leakage into the ceiling may save energy, it has little effect on moisture performance for ventilated roofs and is unsatisfactory for unventilated roofs. Of course, even for ventilated roofs, reducing air leakage around ceiling penetrations such as vent pipes is probably prudent in very cold climates. In such cases, sealing penetrations would reduce the chance for localized frost buildup and any resultant melting with consequent interior damage.

Effect of Removal of Vapor Retarder

For this analysis, three cold (heating) climate roofs (1, 2, and 5) as well as three mixed climate roofs (1, 3, and 4), all with ceiling vapor retarders, had the vapor retarder removed and the corresponding performance compared with that of the roofs with the vapor retarders in place. In all cases, the peak winter plywood moisture content increased when the vapor retarder was not present, but the difference was minor. Thus, at least in the climates analyzed, the existence of a ceiling vapor retarder is not crucial as long as there is code attic ventilation. That may not be true in much colder climates; roofs in much colder climates than Madison, Wisconsin, were not analyzed.

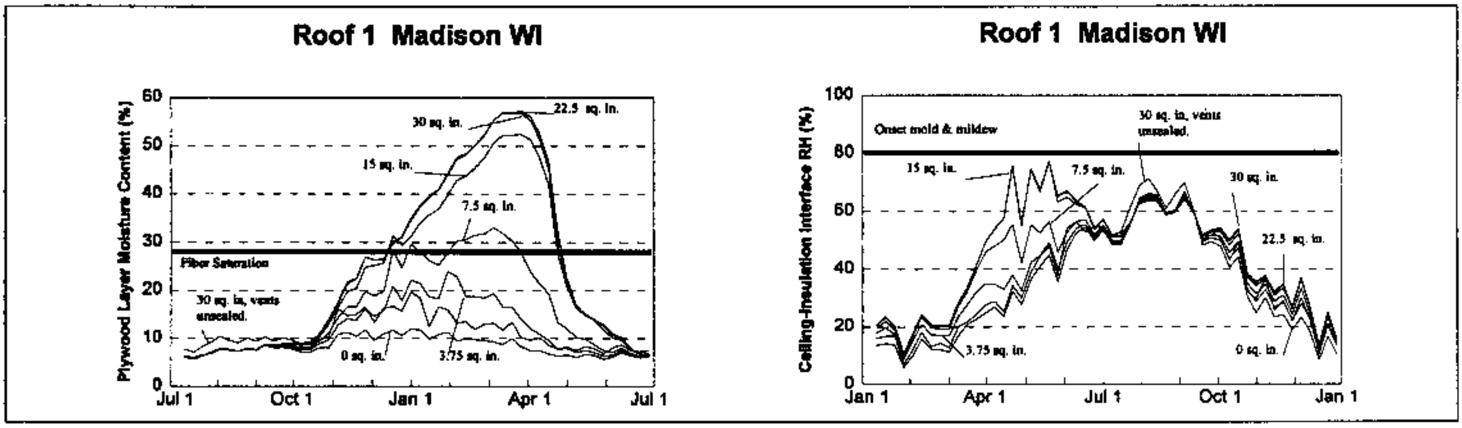


Figure 13. Effect of ceiling leakage area with sealed vents in cold (heating) climate roof 1.

On the other hand, removing the vapor retarder significantly reduced the surface relative humidity in all cases except for Roof 4 in the mixed climate. Roof 4 had relatively impermeable rigid insulation above the vapor retarder, and so removing the vapor retarder had a minimal effect. However, in the other mixed climate cases (all without rigid insulation), elimination of the vapor retarder allowed the moisture in the roof cavity to diffuse into the indoor air where it was removed by the air conditioning system.

Effect of House Tightness

The effect of house tightness was examined by varying the house ELA, starting with the base case house that had a total house ELA of 355 cm² (55 square inches) with a ceiling ELA of 195 cm² (30 square inches) and a house below the ceiling ELA of 161 cm² (25 square inches). The second case was for a total house ELA of 226 cm² (35 square inches) with the same ceiling ELA and a house below the ceiling ELA of 32.5 cm² (5 square inches). The third case was for a total house ELA of 179 cm² (27.5 square inches) with a ceiling ELA of 146 cm² (22.5 square inches) and a house below the ceiling ELA of 32.5 cm² (5 square inches). Only Roofs 1 in the cold (heating) climate and the mixed climate were assessed. The effect on plywood moisture content in the cold (heating) climate was relatively small (about 5 percent maximum in the peak values), and in the mixed climate it was negligible. The effect on the surface relative humidity also was negligible in both climates.

Effect of Roof Shingle Absorptivity

The absorptivity of the asphalt roof shingles was varied over the full range of typical values from 0.7 for white ones to 0.96 for black ones[12] for Roof 1 in each of the cold (heating) and mixed climates. The effect on plywood moisture content and surface relative humidity was negligible.

Effect of Indoor Mechanical Ventilation

The effect of whole house indoor ventilation was investigated by comparing the base case of no mechanical ventilation with actual installed (rather than rated) values of 50 and 100 cfm for Roofs 1 in the cold (heating) climate and in the mixed climate. Although the addition of mechanical indoor ventilation did reduce the plywood moisture contents by a few percent in the cold (heating) climate, that was not noteworthy. The effect was otherwise negligible.

Effect of Indoor Moisture Generation Rate

The moisture generation rate was varied from the base case value of 10.9 kg/day (24 pounds/day) to 21.8 kg/day (48 pounds/day) for all 15 roof constructions in the three climates. That higher value is about as high as one would reasonably expect the moisture generation rate to go.[20] With that high rate, there was an increase in the peak winter plywood moisture content of up to 4 percent in the cold (heating) climate roofs, except for unventilated Roofs 4 and 5, which had a slighter higher peak increase of about 8 percent because of the moisture trapping effect of the rigid insulation in those roofs. There was little or no increase in the mixed and cooling (hot and humid) climate roofs except for the Mixed Climate Roof 4, which also had rigid insulation and was unventilated (the peak increased only about 4 percent). In no climate did any of the roofs get above fiber saturation by the end of the first year of the simulation, but it was noticed that the plywood moisture content in Roofs 4 and 5 in the cold (heating) climate was increasing in the summer at the end of the one year simulation period rather than decreasing. So the simulations were rerun for Roofs 4 and 5 in the cold (heating) climate for a period of ten and later three years. In the third year, the peak plywood moisture content stabilized at just over 40 percent in both roofs, as seen for Roof 4 in Figure 14. More importantly, the roofs did not dry out quickly in the spring, leading to concern over the possibility of wood decay occurring.

There was no effect of the higher moisture generation rate on the summer peak value of the surface relative humidity for any of the roofs except Roof 5 in the cold (heating) climate and Roof 4 in the mixed climate. Those two roofs had rigid insulation and were unventilated. Roof 5 in the cold (heating) climate did get above the critical 80 percent surface relative humidity for more than a month in the first year and then for about two months in succeeding summers. Thus, the moisture performance of that roof is unsatisfactory when high indoor moisture generation conditions exist.

Effect of Indoor Temperature

The base case indoor temperatures were 20°C (68°F) during the heating season and 24°C (76°F) during the air conditioning season. The effect of three new indoor temperatures was determined: a winter indoor set point of 16°C (60°F) and summer indoor set points of 23°C (72°F) and 27°C (80°F). All 15 roof constructions were analyzed. However, the reduced

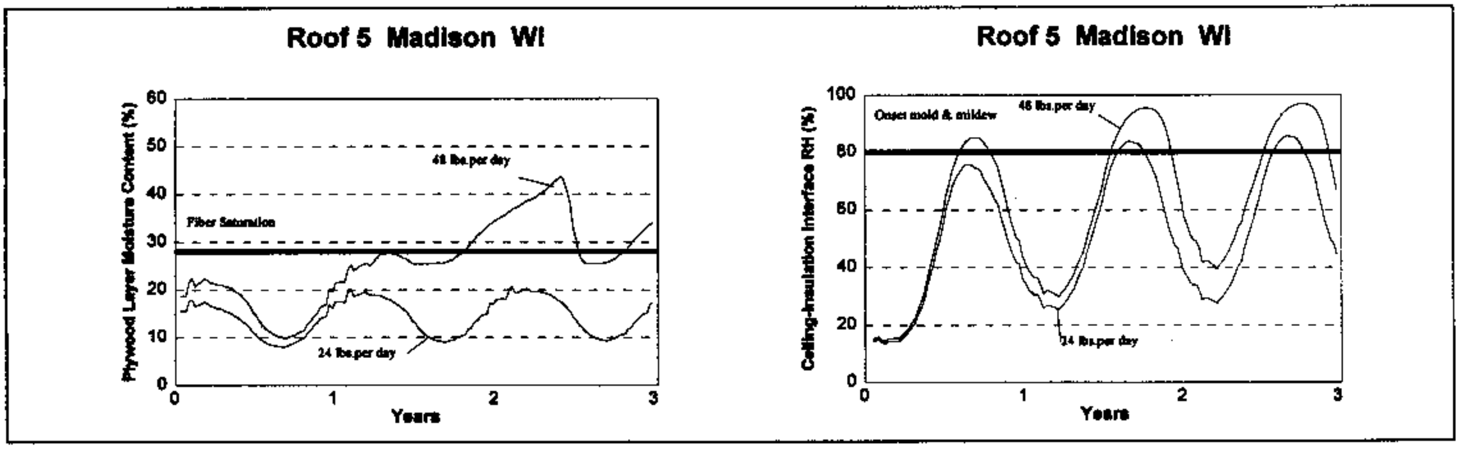


Figure 14. Effect of indoor moisture generation rate for cold (heating) climate roof 5.

winter indoor temperature was assessed only for the cold (heating) climate roofs, whereas the changed summer indoor temperatures were applied to only the mixed and cooling (hot and humid) climate roofs. There was essentially no effect of any of those temperatures on the plywood moisture contents. However, there were surprisingly large effects on the surface relative humidity peak values in the mixed and cooling (hot and humid) climates as a result of the changed indoor summer set point temperatures. When the summer set point was reduced, the peak surface relative humidity values went up as much as about 12 percent, whereas when the indoor summer set point was increased, the surface relative humidity values went down by the same amount. Clearly, the cooler indoor temperature cooled the interface where the surface relative humidity was being evaluated, and that resulted in a higher value. In six of the 10 mixed and cooling (hot and humid) climate roofs, going to the lower summer set point increased the surface relative humidity such that mold and mildew could now grow. Thus, reducing the summer set point to provide comfort can potentially have serious health consequences (i.e., increased allergic reactions to mold and mildew). Increasing the set point is a way of avoiding such problems.

Effect of Humidification

The effect of humidification was simulated by maintaining a constant indoor relative humidity during the heating season of either 45 or 56 percent (rather than letting the indoor relative humidity float as in the base case). The six roofs mentioned earlier were analyzed. There was little or no effect of maintaining the houses at 45 percent because the variable or floating indoor relative humidity was not much different from that fixed value during the winter months when the plywood moisture content peaks. However, the fixed value of 56 percent resulted in plywood moisture content increases of as much as about 5 percent in the cold (heating) climate and insignificantly in the mixed and cooling (hot and humid) climates. Even so, the plywood never rose above fiber saturation.

It was decided to also analyze the effect of humidification with sealed roof vents for the six roofs. In that situation, the results were substantially different. The results for Roof 2 properly ventilated and with sealed vents in the cold (heating) climate are compared in Figure 15. Sealing the roof vents is seen to produce surprisingly high plywood moisture contents; the values for Roof 1 in the cold (heating) climate are even slightly higher. Interestingly, the values for the base case with a floating indoor relative humidity are seen to be almost identical to the case with a fixed 45 percent relative humidity. Sealing the roof vents in those cases is clearly potentially problematic because of the high moisture contents during spring weather. However, the plywood moisture content rose even higher to more than 70 percent for the fixed 56 percent indoor relative humidity case with sealed vents. More importantly, the plywood did not dry out as soon in the spring in those cases, thus leading to concern regarding wood decay occurring. In the mild and cooling (hot and humid) climates, sealing the vents with humidification was never a problem, as plywood moisture contents never approached fiber saturation. This is a case where climate makes a significant difference in roof performance.

Effect of Replacement of Plywood Sheathing with Oriented Strand Board

Given that plywood and OSB have somewhat different properties, it was decided to see if they performed differently from a moisture point of view. The plywood sheathing was replaced with OSB sheathing of the same thickness for the six roofs in code ventilated (1/300) and sealed vent (1/3000) configurations. In general, the sheathing moisture content and surface relative humidity results were almost the same. However, for the cold (heating) climate sealed Roofs 1 and 2, the winter peak moisture content was about 10 to 15 percent higher for OSB than plywood (65 percent vs. 50 percent for Roof 2). However, the OSB in the unventilated (sealed vent) roofs in the cold (heating) climate dried out below fiber saturation about a month sooner than plywood in the late spring. Thus, the OSB may have slightly less potential for degradation because of decay in cases where the roof vents are sealed, although sealing is against code in most states in the cold (heating) climate.

Effect of Weatherizing Existing Homes

When existing homes are weatherized, attic insulation often is added. When that is done, it is common practice to increase the amount of attic ventilation, especially if it is minimal. It has been argued that if the roof was fairly airtight prior to adding attic ventilation, then adding it might increase the airflow into the attic and lead to elevated plywood sheathing moisture contents or create a *less* airtight house after weatherization.

To investigate that possibility, the moisture performance of a loose house that originally had no ceiling insulation, but

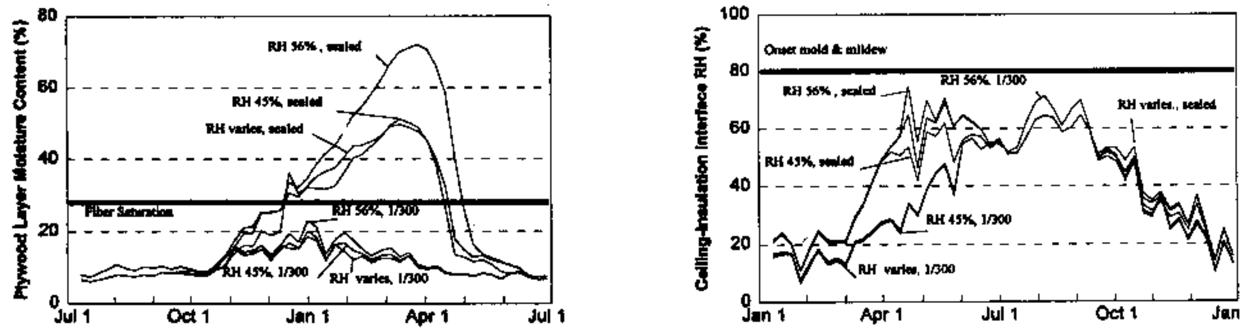


Figure 15. Effect of humidification for cold (heating) climate roof 2 with sealed vents.

had a tight roof, was examined and compared with the performance of the same unweatherized house and a weatherized, tighter house—both of which had code attic insulation added along with 1/300 roof ventilation. Two such houses with an open attic were assessed in each climate. Simulations were performed with indoor moisture generation rates of both 10.9 kg/day (24 pounds/day) and 21.8 kg/day (48 pounds/day).

The results show that in the cold (heating) climate, the loose house without attic insulation had very low plywood moisture contents (a maximum of 11 percent) and low surface relative humidity (less than 60 percent). Almost exactly the same moisture performance was observed in the mixed and cooling (hot and humid) climate. The indoor relative humidity was comparatively low because the house was so loose, and the attic was relatively warm and dry. For the cases with attic insulation added along with roof ventilation, the plywood moisture content increased by a factor of about 1.6 or less, but it was still well below fiber saturation, especially in the spring. The surface relative humidity also did increase somewhat, but it, too, was not a problem. The changes in the mixed and cooling (hot and humid) climates were even smaller, and there never was a problem. Doubling the moisture generation rate did increase the plywood moisture content to about 26 percent in the cold climate, but again, it was never a problem in that climate or the others where the increases were much smaller. The summer peak surface relative humidity values were essentially unaffected by the higher moisture generation rate. So while there has been concern about ventilating attics after installing ceiling insulation, the simulation results presented here suggest that no adverse moisture performance problems are created when doing so. Of course, care must be taken that the new insulation does not block the vents at the eves; otherwise, the results of this study suggest possible adverse moisture conditions. The fact that overall house air leakage may go up is another issue not dealt with here.

Summary of Effect of Parameters on Roof Moisture Performance

The effect on the moisture performance of varying the selected parameters or combinations is summarized in Table 1. The values presented in the columns for each of the three climates are the differences in winter or spring peak plywood roof sheathing moisture content or the summer peak surface relative humidity between the base case and the case or parameter under consideration. The differences are based on the highest peak condition computed for the basic open attic and cathedral ceiling roof designs considered in each of the three climates (Roofs 1 and 2 in the cold [heating] climate, Roofs 1 and 3 in the mixed climate, and Roofs 1 through 4 and 5 in the cooling [hot and humid] climate). The base case peak values are shown in the first row in italics for comparison. If the roof sheathing moisture content stays above fiber saturation into warm spring weather (assumed to be later than April 1), it is noted with a ***bold difference value.*** If the surface relative humidity stays above the critical 80 percent level for more than a month in the summer, then that is designated with a bold value, as well. Blank spaces mean the parameter was not varied for that climate. The major findings observable in the results shown in Table 1 are summarized in the following section.

SUMMARY AND CONCLUSIONS

A new mathematical model, called the MOIST Attic Model, has been used to predict the moisture performance of a current practice site-built prototype house with 15 different roof designs constructed in compliance with the *U.S. DOE Moisture Control Handbook.* Those 15 roof constructions were suggested in 1991 as the best designs to control moisture in roofs, but at that time, there was no readily available computer model to check their moisture performance.

Of the 15 roof constructions, nine were the conventional open attic type (six were distinct from a moisture point of view), and six of the designs were cathedral ceilings (three ventilated and three unventilated). Some of the roofs had an interior vapor retarder installed in their ceiling construction, and some did not. Most of the roofs had glass fiber insulation, but a few had a combination of that and rigid insulation or rigid insulation alone. Passive roof ventilation, where incorporated, was installed consistent with the 1/300 rule. Moisture performance was analyzed in three distinct climates: cold or heating (Madison, Wisconsin), mixed (Washington, D.C.), and cooling or hot and humid (Lake Charles, Louisiana). The roof construction material with the highest moisture content was found generally to be the lower surface layer of the north-facing plywood roof sheathing. Its moisture content was predicted as a function of time of year, as was the relative humidity of the air at the bottom of the insulation adjacent to the poly vapor retarder above the gypsum board ceiling or just above the gypsum board if no poly was present. The International Energy Agency Annex 14 *Guidelines and Practices*[9] indicates that a monthly mean surface relative humidity exceeding 80 percent is conducive to mold and mildew growth. Such growth could have adverse health repercussions.

Overall, in all 15 roof constructions under base case conditions (open attic and cathedral ceiling roofs ventilated according to the 1/300 rule and some unventilated cathedral ceilings), independent of climate, the highest moisture content was 21 percent for the plywood roof sheathing, which is much lower than its 28 percent fiber saturation level. Therefore, moisture-induced material degradation should not be a problem under the assumed base case conditions.

However, a number of simulations also were performed by varying selected parameters or combinations of them to examine their effect on roof moisture performance. Sealing the roof vents in normally vented open attics or cathedral ceilings resulted in plywood moisture content values well above fiber saturation in the cold (heating) climate. Moreover, the sealed roofs did not dry out in warm spring weather, leading to concern about the possibility of structural degradation. Furthermore, humidification in the cold (heating) climate made matters even worse. However, sealing the roof vents with or without humidification did not create plywood moisture content values above fiber saturation in either the mixed or cooling (hot and humid) climates, and thus, that was not a problem. In addition, in the cold (heating) climate, high moisture generation indoors caused the plywood in unventilated cathedral ceilings with rigid insulation to rise well above fiber saturation and raise concern about long-term structural degradation. Thus, those two unventilated cathedral ceiling designs would have to be considered unsatisfactory in cold (heating) climates.

Some building scientists have recommended that sealing the ceiling leakage area is a good way of reducing roof moisture problems as an alternate to ventilating a roof. The simulation results of this study suggest otherwise. Although sealing the ceiling leak sites does reduce the amount of exfiltration into the roof cavity, it also increases the indoor relative humidity. That increase in the indoor moisture source strength balances out the reduced exfiltration such that there is little or no effect of reduced ceiling ELA on plywood moisture contents until unrealistically small ceiling leakage areas are achieved. That was a surprising result.

The results of this investigation also point out that when assessing the moisture performance of roof constructions, one must analyze not just the maximum moisture content of the various wood members to determine if they could degrade. It is also necessary to assess the surface relative humidity at critical locations to see if it is high enough in the summertime to cause the growth of mold and mildew that could be a health risk. Many of the ventilated roof constructions did not perform well from a mold and mildew and health point of view. Having a vapor retarder above the gypsum board ceiling in cooling (hot and humid) climates also lead to excessive surface relative humidity conditions for more than a month in the summer. Reducing the indoor temperature in the summer to increase comfort in either the mixed or the cooling (hot and humid) climate lead to conditions more conducive to mold and mildew growth. Increasing the summer set point temperature is a way of minimizing the risk of mold and mildew growth and health problems.

The current roof moisture control practices required in most states by building codes (i.e., installing an interior vapor retarder in the ceiling construction and installing roof cavity vents consistent with the 1/300 rule) were found to be effective in cold climates. That is, the peak moisture content of the roof sheathing was maintained well below fiber saturation, even in tight houses having fairly high indoor relative humidity. However, those same moisture control practices did not result in acceptable performance in mixed or cooling (hot and humid) climates. There, moisture from the outdoor environment accumulated at the upper surface of the vapor retarder where the surface relative humidity approached a saturated state during the summer. That location provided a conducive environment for mold and mildew growth. *Thus, based on this analytical study, it is recommended that a ceiling vapor retarder not be required or used in mixed or cooling (hot and humid) climates. It is further recommended that roof cavity ventilation not be required in cooling (hot and humid) climates.* It should be mentioned that there is some concern about closing off vents because of the possibility of eliminating or reducing the potential for drying of water that may leak into the attic or be present from wet construction materials. That tradeoff certainly needs to be considered when deciding whether to close vents. It may be better to avoid mold and mildew related health problems in the bulk of homes by closing vents rather than keeping them in the event that a roof leak might occur or the roof might be constructed with very wet wood.

Finally, this study has shown that there are conditions when roof wood members can have moisture contents above

Table 1. Summary of Effect of Parameters on Roof Peak Moisture Performance

Parameter Varied	Cold (Heating) Climate		Mixed Climate		Cooling (Hot) Climate	
	Roof 1/Roof 2		Roof 1/Roof 3		Roof 1-4/Roof 5	
	PMC*	SRH*	PMC*	SRH*	PMC*	SRH*
Base case (1/300)	*20/18*	*73/71*	*13/14*	*82/82*	*16/16*	***91**/74*
Roof ELA(sealed roof vents [1/3000])	**37/32**	5/-3	8/5	-9/-8	-1/3	-8/-7
Ceiling ELA (50% of base case)	0/0	0/0	0/-1	0/0	0/0	**0**/0
Ceiling ELA (sealed ceiling & roof)	-8/-8	-7/-10	-4/-4	-1/-1	-4/-1	**-3/**
Ceiling ELA (50% base, sealed roof)	**32/28**	4/1	7/4	-8/-8	-1/3	-6/-6
Ceiling vapor barrier removed	2/3	-9/-7	1/0	-13/-12	0/0	-17/0
Total house ELA (50% of base case)	-5/	-2/	-1/	0/		
Shingle absorptivity (0.8 0.7)	0/	0/	0/	0/		
Indoor mech. ventil. (50 cfm actual)	-3/	0/	-1/	0/		
Humidification (fixed RHindoor = 56%)	4/5	0/2	0/0	0/0	0/0	0/0
Humidification (56% RH), sealed roof	**58/52**	10/4	11/7	-8/-8	-2/-1	-9/-8
Indoor moisture gen. rate (48 lb/day)	4/4	0/0	1/1	0/0	0/0	**0**/0
Moisture gen. (48 lb/day), sealed roof	?/	?/				
Reduced winter indoor temp. (60°F)	0/0	0/2	NA	NA	NA	NA
Reduced summer indoor temp. (72°F)	NA	NA	0/0	**12/12**	0/0	**9**/6
OSB vs. plywood sheath., sealed roof	**46/47**	-1/1	9/6	0/-9	-1/1	-9/-8

* PMC - highest peak winter/spring plywood sheathing moisture content value
SRH - highest peak summer/fall surface relative humidity value

the fiber saturation level during warm weather such that wood decay might occur. However, it is also clear that more data is needed to more exactly determine the combination of high moisture content, duration, and elevated temperature that will lead to decay in wood.

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