REVIEW OF EXISTING CRITERIA AND PROPOSED CALCULATIONS FOR DETERMINING THE NEED FOR VAPOR RETARDERS

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The NRCA (National Roofing Contractors Association) *Roofing and Waterproofing Manual, Fourth Edition* provides roofing professionals with three alternatives for determining the need for a vapor retarder in low-slope roof systems. In addition, new research at Oak Ridge National Laboratory's (ORNL's) Buildings Technology Center has examined the issue of vapor retarder requirements. This new research has developed simple algorithms that allow a roof designer to simply determine if a roof system design requires a vapor retarder.

This paper describes the finite-difference computer modeling that has been performed to develop this new vapor retarder selection tool. The authors will illustrate how modeling results were obtained, describe the process employed to develop algorithms, and demonstrate how these algorithms can be used to assess the need for vapor retarders in some roof systems. The benefits and limitations of the alternatives for determining the need for vapor retarders will be described.

KEYWORDS

Low-slope Roofs, Vapor Retarders, Condensation, Moisture, Modeling.

INTRODUCTION

Moisture accumulation in roof systems can create a number of costly problems, including dripping, accelerated insulation and membrane failure, roof structure deterioration, depreciation of assets and poor thermal performance. Moisture accumulation can severely impact the thermal performance of insulation in a roofing system. It is estimated that energy losses through roofs in the United States have increased by 70 percent because of the loss of the insulation's thermal resistance caused by moisture [1]. Wet roofing materials must be replaced at significant cost, financially and in terms of increased construction waste.

One method of controlling the inflow of moisture into a roof system is to add a vapor retarder. The uptake of water vapor from within a building into the roof system typically occurs during winter when cold outside conditions cause the exterior vapor pressure to be less than the interior vapor pressure. If this condition persists for a significant amount of time without a vapor retarder, moisture will accumulate within the roof system and condensation will occur. The addition of a vapor retarder will reduce the rate of moisture accumulation by adding significant vapor resistance to the roof system.

However, a vapor retarder can compromise the long-term durability of a roof system if a roof system is not periodically inspected or maintained. The roof system will leak eventually, and, if not caught and repaired, a vapor retarder can mask this leakage until a small leak has turned into a severe moisture problem that affects a large percentage of the roof area. Kyle has suggested that a moisture-tolerant and durable roof is one that "incorporates reliable ways of improving moisture flow out of the roof" [1]. In the authors' opinion, the addition of a traditional vapor retarder eliminates the possibility of a roof system drying and, therefore, should be included in a roof system as a last resort.

To determine whether a specific roof system requires a vapor retarder, roof system designers require accurate but convenient and cost-efficient analytical tools for evaluating their roof system designs. One such tool is computer modeling. Finite difference computer modeling has been used to demonstrate the effectiveness of moisture-tolerant roof designs in various U.S. climate zones [2]. In this paper, modeling is employed to predict the need for vapor retarders in some roof system designs.

Setting up the necessary data files, running a finite-difference simulation and interpreting the output requires computer skills and technical knowledge that limit the usefulness of this tool. Using the computer simulation data as a starting point, methods have been developed for predicting the need for vapor retarders for several new roof system designs using a series of algorithms requiring only the variables associated with components of a roof system and interior and exterior climate. These algorithms have been included in a Web page in a fast, user-friendly computer program that is accessible to a much wider user group. This enables a roof system designer to quickly and accurately determine whether a roof system constructed with a given type of membrane, insulation material and deck will need a vapor retarder in a given location with a indoor relative humidity without the need to set up and run a computer simulation.

WHAT IS CURRENTLY AVAILABLE

The NRCA Roofing and Waterproofing Manual, Fourth Edition, lists three procedures for determining the need for a vapor retarder. Along with a NRCA recommendation, the manual references the *ASHRAE* [American Society of Heating, Refrigerating, & Air-Conditioning Engineers] *Handbook* *of Fundamentals* and the work of Wayne Tobiasson as the bases for this determination [3, 4].

For many years, NRCA has maintained that vapor retarders should be considered when the outside average January temperature is below 40°F (4°C) and the expected winter indoor relative humidity is 45 percent or greater. Figure 1 depicts the areas of the United States that experience an outside average January temperature below 40°F (4°C).

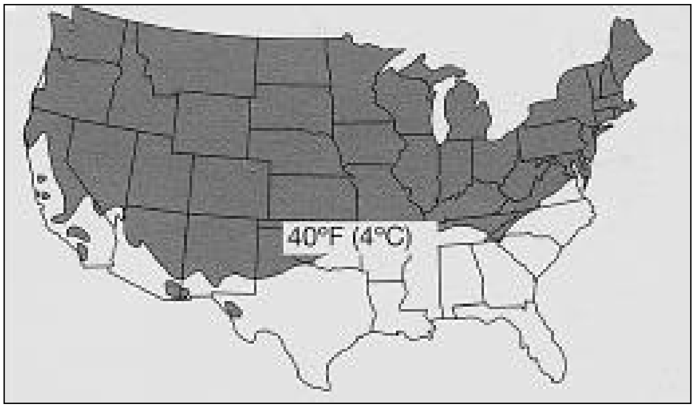

Figure 1. *NRCA's map for assessing the need for a vapor retarder. If a building's interior relative humidity is equal to or greater than 45 percent and the building is located in the shaded portion of the map, a vapor retarder is recommended. Source: NRCA 1996 [5].*

ASHRAE Handbook of Fundamentals is cited as the second source for vapor retarder criteria [6]. The handbook does not specifically include a procedure for determining the need for a vapor retarder in a low-slope roof system; however; a procedure for determining whether condensation occurs inside a building envelope component is described. The discussion presented in the handbook can be simplified to recommend the addition of a vapor retarder if the dew point falls within the insulation layer; we will assume that this is the procedure NRCA's manual references. The ASHRAE procedure indicates the need for a vapor retarder for most U.S. regions.

Many researchers, designers, construction professionals and building owners believe that the two assessments to determine the need for a vapor retarder did not fit their collective experience and the existing methods prescribed vapor retarders in situations where experience indicated that roof systems performed adequately without them. Following a procedure introduced by Baker [7], the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL) developed a series of maps of the United States to assess "progressive" and "seasonal" wetting of roof systems [3]. "Progressive" wetting refers to a yearly buildup of moisture in the roof system, and "seasonal" wetting describes the amount of moisture accumulated during the winter vapor drive. By comparing mean monthly air temperatures and vapor pressures for 363 U.S. cities, monthly vapor drive maps were created. Comparing the ratio of the vapor drive for the wetting and drying seasons yields the potential for "progressive" wetting, and looking at the vapor drive during the wetting season yields the "seasonal" wetting data. Because the "seasonal" map required vapor retarders for a larger area of the United States, it was selected as the controlling map. In a survey, roofing professionals were asked to select which map best represented their experiences; the map shown in Figure 2 with a seasonal wetting vapor drive of 2.0 kPa•month (0.6-in. Hg•month) was selected [4].

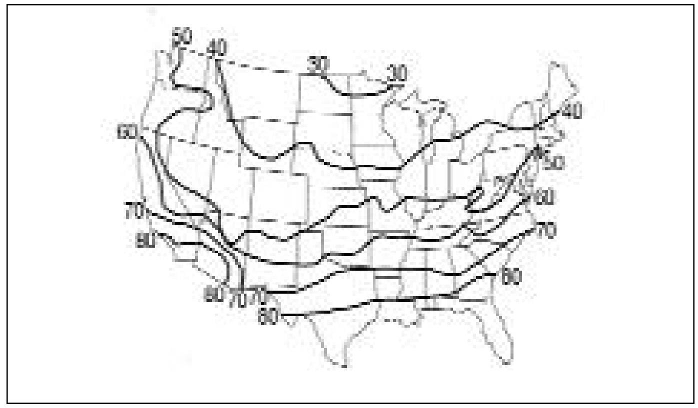

Figure 2. *CRREL's map for assessing the need for a vapor retarder. If a building's interior is controlled to 68°F (20°C), the map depicts the relative humidity contours as a function of location. If the building exceeds the relative humidity values on the map, a vapor retarder is recommended. Source: Tobiasson and Harrington, 1986.*

Each of the preceding procedures for determining roof system moisture-control strategy has limitations. NRCA does not consider the dynamic conditions created by weather and completely ignores the roof system design itself as having an impact on the need for a vapor retarder. The basis for the guideline is undocumented and its derivation is unknown to the authors. The ASHRAE guideline treats design conditions as if they are in a steady state and considers only the thermal performance (not the moisture properties) of the roof system components in its assessment. In the authors' opinion, the winter design conditions are much too severe to be used as a basis; the drawbacks of having a vapor retarder are too great to design for complete elimination of condensation. Finally, the CRREL analyses, by far the most sophisticated of the three procedures, required industry "calibration" to account for the dynamic nature of moisture flow driven by meteorological conditions and omitted solar effects (solar radiation) on roofs that heat up the roof surface appreciably. In addition, it does not include any consideration of the fact that the components of the roof system can affect on the need for a vapor retarder.

ORNL METHOD

ORNL has developed a procedure for assessing the need for a vapor retarder using computer simulation as its basis. All the simulation work performed in this study used the computer program MATCH (Moisture and Temperature Calculations for Constructions of Hygroscopic Materials) to simulate the simultaneous effects of heat and moisture in roof systems [8]. Rode, Desjarlais and Kyle have described, validated and used the model on low-slope roof system designs [9, 10, 11, 2, 1]. The calculations of both modes of transfer are performed in a one-dimensional transient manner that accounts for the accumulation of heat and moisture. The version of the program the authors used utilizes vapor diffusion as the only moisture transport mechanism, with vapor diffusion being described by Fick's

Law. Liquid capillary flow has been ignored; trial runs with liquid capillary flow enabled had an insignificant impact on the results. The storage of moisture is described by sorption isotherms of the materials, and water vapor permeability is defined as a function of moisture content. Heat transfer is described by a contribution from the sensible conduction of heat (Fourier's Law) and a contribution from the energy of phase conversion of water between liquid and gaseous states. Changes in thermal conductivity caused by temperature and moisture content are both accounted for by the model.

The transport of moisture in low-slope roofing systems can be affected by the type of deck, type and thickness of insulation, color of roof membrane, interior temperature and relative humidity conditions of the building, and climate. A series of 1,200 simulations was performed to cover a range of these parameters for the continental United States. Five climates were analyzed: Bismarck, N.D.; Chicago, Ill.; Knoxville, Tenn.; Miami, Fla.; and Seattle, Wash. These were selected to represent the range of heating degree-days (HDD) seen in the continental United States. Indoor relative humidities of 40 percent, 50 percent, and 60 percent with an indoor temperature of 68°F (20°C) were used in the study. Although the interior vapor pressure (saturation moisture content at temperature (T) times the relative humidity) defines the inside boundary condition; fixing the temperature and varying the relative humidity allows for a variation in interior vapor pressure.

The range of roof system configurations evaluated included 25- and 76-mm- (1- and 3-inch-) thick wood fiberboard, 25- and 76-mm- (1- and 3-inch-) thick polyisocyanurate (PIR) insulation, and a 76-mm (3-inch) composite of the two. Four metal decks with permeances of 3.6, 5.7, 29, and 57 10^{-8} g/Pa s m^2 (0.64, 1, 5, and 10 English perms) were included. Two values for membrane absorptance, 0.1 for a white roof and 0.7 for a black roof, were also used. The roof membrane was considered relatively impermeable for all simulations and was assigned a water vapor permeance of 0.1 10^{-8} g/Pa s m^2 (0.02 English Perms). All possible combinations of the above parameters were simulated using the finite-difference model.

A detailed discussion of why the roof configurations listed were selected can be found in an earlier publication [2]. In summary, the insulation materials were selected to represent the range of hygric properties available in typical roof insulations, and the composite allows for the combination of low water vapor permeance and high water vapor absorptance. The thicknesses represent the limits of typical applications. The two lower values of deck permeance were found in the literature [1, 12]; even higher values of deck permeance were simulated to address the issues of gaps between decks, burn holes and open air feeds between the deck and walls along the perimeter of the building.

For modeling purposes, the roof system was divided into a series of layers. In the case where a single type of insulation is used in the roof, the system was comprised of a single-ply membrane, an 8.5-mm- (0.33-inch-) thick layer of insulation, a 17- or 68-mm- (0.67- or 2.67-inch-) thick layer of insulation and a 8.5-mm (0.33-inch) thick layer of insulation. The deck was modeled simply as a vapor resistance between the bottom insulation layer and the building interior. For the composite roof insulation, we replaced the monolithic insulation layer with a sandwich comprised of a 51-mm (2-inch) core of polyisocyanurate foam between layers of 13-mm- (0.5-inch-) thick fiberboard.

To model this system, each layer of fiberboard was subdivided into 8.5- and 4-mm- (0.33- and 0.17-inch-) thick layers. The thicker fiberboard layers were in contact with the membrane and deck. Based on the input parameters provided by the user, the model computed hourly the temperature, heat flow and moisture content of each layer. It uses the data from the previous hour along with weather data and building interior condition information supplied by the user to compute new values of temperature, heat flow, and moisture content for each layer of the roof system. These data were written to a file for subsequent analysis.

Algorithms were developed to predict the need for vapor retarders in roof systems without having to perform and analyze the results of a complicated finite-difference computer simulation. The algorithms were based on the following set of simulations. After an initial two-year simulation to estimate the initial moisture contents of each of the roof system components, an additional one-year simulation was performed. To determine if condensation occurred under the membrane and a vapor retarder was needed, the relative humidity for the uppermost thin layer of insulation was examined and the amount of time that the relative humidity of this layer was at 100 percent (saturated) was recorded. Roof systems that showed a relative humidity of 100 percent in this outer insulation layer just below the roof membrane for more than 24 hours were determined to fail the no condensation requirement. These systems would require vapor retarders.

All 1,200 configurations that were simulated were used to develop the algorithms. Multiple linear regression was done using combinations of first, second, and third order and inverse terms of each of the variables to develop the necessary algorithms. These regressions were performed using parameters listed below as inputs. The coefficients will, therefore, account for the variation in units (Fahrenheit degrees for heating degree-day data, English perms for deck permeance, etc.). Algorithms were generated to predict the average vapor pressure under the membrane during the winter uptake period and length of time that the vapor drive is into the roof system. These parameters, coupled with building interior conditions, define the moisture accumulation in a roof system during the wintertime uptake period. Comparing this level of accumulation to a predetermined pass/fail threshold will dictate whether a vapor retarder is needed.

The flow rate of water vapor into a roof system occurs during the winter uptake period when the indoor vapor pressure is greater than the vapor pressure at the underside of the roof membrane. This creates a vapor pressure drive that forces water vapor into the roof system. This drive will cause water vapor to accumulate within the roof system under the membrane until the vapor drive reverses at the end of the winter uptake period. If the accumulation is rapid enough because of high water vapor permeability of the deck and insulation layers or the winter uptake period is long, condensation will occur within the roof system under the roof membrane, and the roof system will fail this requirement.

The following procedure can be used to predict the need for a vapor retarder. First, the parameters listed below for a roof system need to be determined.

Type of insulation (fiberboard, foam or a composite of the two);

H = Heating degree-days for the location (degrees Fahrenheit);

α = Relative humidity of the indoor environment (e.g. 40 percent = 0.4);

ϕ= Membrane absorptance (herein, 0.1 for white and 0.7 for black);

P = Deck permeance (in English perms [See Table 1]); and

T = Thickness of each insulation layer (in inches).

Calculate p_{vm} (the average vapor pressure at the roof membrane during the winter uptake period, in pounds per square inch [psi]) and t (the length of time of winter uptake in months):

$$p_{vm} = -0.934 + 0.284\phi + 4.85\text{x}10^{-4}H - 8.00\text{x}10^{-8}H^2 + 4.22\text{x}10^{-12}H^3 - 2.05\text{x}10^{-5}H\phi + 161/H + 0.00230P - 8.01\text{x}10^{-5}P^2 - 1.34\text{x}10^{-7}HP - 0.00889\alpha; \quad \text{(Eqn. 1)}$$

$$t = -66.1 - 1.51\phi + 0.0339H - 5.66\text{x}10^{-6}H^2 + 3.07\text{x}10^{-10}H^3 + 0.00442H\phi - 4.33\text{x}10^{-7}\phi H^2 + 11400/H. \quad \text{(Eqn. 2)}$$

Compute p_{vi} (the vapor pressure of the indoor air, in psi):

$$p_{vi} = \phi p_{vsat}, \quad \text{(Eqn. 3)}$$

where p_{vsat} is the saturation vapor pressure, found in any standard saturated steam table at the indoor temperature (for example, p_{vsat} at 68°F [20°C] is 0.342 psi [2.36 kPa]; at 70°F [21°C], it's 0.363 psi [2.50 kPa]).

Calculate m (the moisture accumulation in the roof system, in pounds per square [lb/ft^2]):

$$m = 0.215\, t\, (p_{vi} - p_{vm}) / (R_{bl} + R_d + R_i) \quad \text{(Eqn. 4)}$$

where R_{bl} is the air-boundary layer vapor resistance (0.21 reps) and R_d and R_i are the deck and insulation vapor resistances (in reps), respectively. Table 1 lists the vapor resistances for typical roofing materials.

Compare m, the calculated moisture accumulation, with the appropriate pass/fail threshold shown in Table 2. Systems with moisture accumulation, m, greater than or equal to the failure threshold do not pass the requirement. To determine the failure thresholds, the calculated values of moisture accumulation were listed in ascending order for each type of insulation material. Next to each value of moisture accumulation was the identifying roof system code and whether the roof system failed the stated condensation control requirement. These lists were examined to determine the thresholds of moisture accumulation where most roof systems begin to fail for each type of insulation. By comparing the moisture accumulation data to the simulation outputs that indicated whether condensation occurred, the critical thresholds were readily identified by determining what value of moisture accumulation indicated the onset of condensation. See Desjarlais and Byars for more information regarding the derivation of these thresholds [13, 14].

Roofing Material	Vapor Resistance Reps	Permeance English Perms
Solid metal deck with tight joints	1.56	0.64
Solid metal deck with loose joints	1.00	1.00
Slotted metal deck	0.20	5.0
Slotted metal deck with burn holes	0.10	10.0
1-inch (25-mm) fiberboard	0.024	42
3-inch (76-mm) fiberboard	0.071	14
1-inch (25-mm) polyisocyanurate foam	0.46	2.16
3-inch (75-mm) polyisocyanurate foam	1.39	0.72
Composite (2 inches [51-mm] of foam between two layers of ½-inch [13-mm] fiberboard)	0.95	1.05

Table 1. *Vapor resistances and permeances for decks and insulation materials.*

	Moisture Accumulation Failure Threshold	
Insulation	lbs/ft^2	kg/m^2
Fiberboard	0.20	1.0
Foam	0.012	0.06
Composite	0.14	0.69

Table 2. *Pass/fail thresholds for insulation materials used in low-slope roofing. Source: Desjarlais and Byars, 1997b.*

To assess the accuracy of the algorithms in predicting moisture accumulation, a comparison between the simulation-based and algorithm-based moisture accumulation is shown in Figure 3. Simplifications that are required to develop the algorithms can therefore be assessed. For example, the algorithms use a single value of water vapor permeance for each material whereas the simulation adjusts the water vapor permeance as a function of relative humidity. The line in Figure 3 depicts perfect agreement between the two methods in predicting moisture accumulation. Data points below this line are cases where the algorithm is overpredicting the moisture accumulation. This algorithm-based method is conservative in that it tends to slightly overpredict failures. For the given database, the accuracy in predicting failures is 98 percent. For passes, it is 95 percent [13, 14].

ADVANTAGES AND LIMITATIONS OF THE PROPOSED METHOD

The proposed procedure for determining the need for a vapor retarder has many advantages over the procedures listed in *The NRCA Roofing and Waterproofing Manual, Fourth Edition.*

Similar to the existing procedures, the proposed procedure considers the building interior and climate to which a roof system is exposed. However, these boundary conditions are considered at hourly intervals and not steady-state "design" conditions.

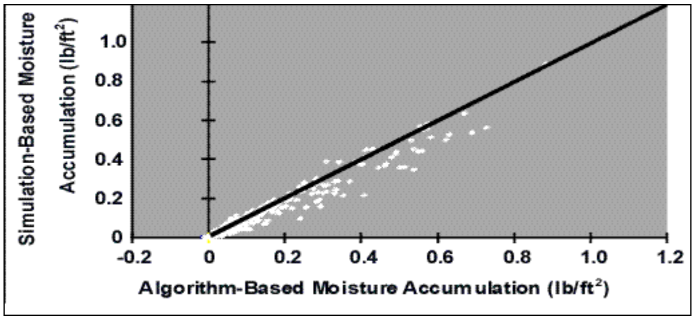

Figure 3. *Comparison of the simulation- and correlation-based moisture accumulation. Source: Desjarlais and Byars, 1997b.*

Similar to the ASHRAE Method, the components of the roof system are part of the analysis. In addition to the thermal characteristics of the roof system used by the ASHRAE method, the proposed procedure includes the moisture or hygric properties of the deck, insulation and membrane.

The use of this procedure has been simplified by its inclusion on the ORNL Web site (www.ornl.gov/roofs+walls). Accessing this Web site reduces the effort of using this procedure to simply selecting items from menus. Once a roof system is configured and the boundary conditions are specified, the calculations all are performed automatically.

The algorithms proposed in this paper are presently limited to roof systems and environmental conditions detailed in this paper. Future work will include the analysis of roof systems with a wider range of properties to establish the limitations of the predictive algorithms. A wider variety of insulation types, decks, and indoor vapor pressures needs to be evaluated to assess the accuracy of the proposed algorithms to roof systems and components that are presently not in the authors' database.

CONCLUSIONS

Algorithms have been developed that can be used by roof system designers to assess the need for vapor retarders in a variety of roof systems. Roof system designers can vary roof membrane color, insulation type and thickness, and deck permeance to design a roofing system that does not require a vapor retarder. Experimenting with these algorithms may offer insight into the basics of moisture control. The algorithms are now available on a Web site (www.ornl.gov/roofs+walls) where a roof system designer can simply select roof system components from menus and determine whether his roof system design requires a vapor retarder.

The algorithms offered in this paper should be considered as a replacement for the existing procedures to assess the need for a vapor retarder. Although limited in terms of the roof system types that can be studied, these algorithms are appropriate for the roof systems employed in the database.

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