Predicting Moisture Problems in Low-Slope Roofing

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ABSTRACT

Moisture intrusion is the major reason why low-slope roofing systems fail prematurely. With approximately 75% of all roofing activity being reroofing, the roofing professional is faced with deciding what to do with an existing wet roof on almost a daily basis. Problems can originate from moisture entering the roofing system by two completely different mechanisms. In the wintertime, the vapor pressure in the building interior typically exceeds the vapor pressure in the roofing system, causing water vapor to migrate from the building interior into the roofing system. If the vapor pressure gradient is severe and persists for a long time, sufficient water vapor may build up under the roofing membrane to allow condensation to occur. The second mechanism that allows an appreciable amount of water into the roofing system is membrane failure. Breaks in the membrane will allow water to enter the roofing system from the exterior. Depending on the roof construction, the water will either build up in the roof or migrate to the roof deck where it may manifest itself as a leak.

The net effect of water entering the roofing system by either mechanism is the same: reduced energy efficiency, corrosion of metal components (decks and fasteners), mechanical degradation of the insulation materials, and bond failures between adhered components. These impacts lead to reduced durability, shorter service life, and health/safety issues.

This paper describes finite-difference computer modeling performed to address moisture control in low-slope roofing systems. Based on a large database of finite difference modeling results, algorithms have been developed that allow the roofing practitioner to simply determine if a roofing system design requires a vapor retarder or if the system can be modified to enhance its tolerance for small leaks.

This paper illustrates how modeling results were obtained, describes the process employed to develop the algorithms, and demonstrates how these algorithms can be used to design a moisture-tolerant low-slope roof. The range of applicability and limitations of these algorithms are also detailed.

INTRODUCTION

Moisture in low-slope roofing is a multibillion dollar problem for the U.S. roofing industry. It is estimated that energy losses through roofs in the U.S. are increased by 70% because of the loss of insulation's thermal resistance due to moisture contamination. Wet roofing must be replaced at significant cost, both financially and in terms of increased construction waste (Kyle and Desjarlais 1994). Since approximately 75% of roofing work performed in the U.S. each year is reroofing, moisture has a dramatic impact on the majority of roofing work performed. Clearly, the potential cost savings of a moisture-tolerant and energy-efficient roofing system are great.

Moisture can gain access into the roofing system two ways. Membrane and edge detailing failures due to aging, workmanship, or improper roof design permit water to enter the roofing system, potentially compromising the energy efficiency and the service life of that portion of the building envelope. The roof is exposed to a wide variety of environmental conditions that are governed by local weather and building use. Combinations of these conditions can cause moisture to migrate from the building interior into the roofing system. In addition to these mechanisms, the initial moisture concentration in the roofing system can be highly variable. Many materials traditionally used in roofing construction are highly hygroscopic, allowing substantial quantities of moisture to be built into a new roof.

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The existing moisture control strategies utilized by the roofing industry are concerned exclusively with moisture flow into the roofing system when the roofing system is performing properly. Most often, we require a waterproof membrane to be placed on the climate side of the roofing system to prevent water from penetrating into the insulation layers and deck below; however, our strategy cannot tolerate the inevitable leak that will allow water this access. We perform condensation (or dew-point) analyses that dictate whether a vapor retarder is needed to control moisture pickup from the building interior during wintertime, yet we know that these analyses include simplifications that impact the precision of their predictive capabilities. When our dew-point analyses indicate that a roofing system needs a vapor retarder, we know that the vapor retarder can compromise the long-term performance of the roof by trapping leak water in the insulation layers. Today, we accept this compromise due to the lack of a suitable alternative solution.

We have proposed new moisture control guidelines for low-slope roofing systems (Desjarlais 1995). These guidelines consider the impact of wintertime control of moisture as well as the performance of the system after a leak has occurred. A new technique for assessing winter moisture uptake based on computer modeling has been proposed and compared to existing procedures (Desjarlais and Byars 1997a). Procedures to evaluate leak prevention, as well as rapid dissipation of leak water into the building interior as water vapor, are discussed herein. The use of these new design tools is described and illustrated.

BACKGROUND

Existing moisture control strategies deal exclusively with defining the need for a vapor retarder. The National Roofing Contractors Association *Roofing and Waterproofing Manual* (NRCA 1996) lists three procedures for determining this need. Along with its own recommendation, the manual references the *ASHRAE Handbook—Fundamentals* (ASHRAE 1993) and the work of Wayne Tobiasson (Tobiasson and Harrington 1986; Tobiasson 1988) as the bases for this determination.

Desjarlais (1995) proposed a moisture control strategy that addresses the issues covered by the existing guides as well as topics that were previously not considered. Although the majority of moisture control problems stem from roof leaks, none of the existing moisture control strategies address this issue. Further enhancements obtained by the proposed moisture control strategy are that the makeup of the roofing system is considered and the physics of the moisture control problem is treated more rigorously so that conclusions regarding the roof design can be drawn with more confidence. The proposed moisture control strategy can be summarized as follows:

- Under normal operating conditions (no leaks), the total moisture content of a roof system shall not increase with time over the long term (Requirement 1), and condensation shall not occur under the membrane during winter uptake (Requirement 2).
- Moisture vapor movement by convection must be eliminated, and the flow of water by gravity through imperfections in the roof system must be controlled.
- After a leak has occurred, no condensation on the upper surface of the deck shall be tolerated (Requirement 3), and the water introduced by the leak must be dissipated to the building interior as water vapor in a minimum amount of time (Requirement 4).

This strategy contains four quantifiable and two qualitative requirements. The first two quantitative requirements echo those introduced by Tobiasson and Harrington (1986). If the total moisture content of the roofing system is increasing on a yearly basis ("progressive" wetting violating Requirement 1), then eventually condensation must occur in the roofing system. Additionally, we do not want to allow condensation to occur within the insulation layers of the roofing system during winter uptake ("seasonal" wetting violating Requirement 2) because of the deleterious effects water has on the thermal and mechanical performance of roofing systems.

Through proper roof design and selection of materials, it may be possible to eliminate drippage into the building interior from small to moderate leaks (Requirement 3). Dripping manifests itself as condensation on the interior surface of the roof deck. If the rate of water vapor being driven to the deck or the deck permeance can be controlled to prevent condensation on the upper surface of the deck, dripping from roof leaks into the building can be eliminated. After all the above criteria are satisfied, the roofing system shall be optimized to dissipate leak water into the building interior as water vapor through downward drying as expeditiously as possible (Requirement 4). Any water that is contained in the roofing system will begin to degrade the thermal and physical properties of the insulation, deck, and metal components, and we therefore want to minimize their exposure time to the leak water.

Finite difference computer modeling has been used to demonstrate the effectiveness of moisture-tolerant roof designs in several different climatic zones in the U.S. (Desjarlais 1995). However, it is necessary to set up, run, and analyze a computer simulation in order to determine the results. Algorithms, based on a large database of computer simulations, have been produced that can predict the quantifiable moisture control design requirements. In this paper, we offer this simpler, readily available technique for assessing the suitability of different moisture-tolerant roof designs and illustrate its application.

DEVELOPING THE DATABASE

Algorithms were developed in order to predict the moisture control performance of roofing systems without having to perform and analyze the results of a complex finite difference computer simulation. These algorithms enable the roofing professional in the U.S. to quickly and accurately determine if a roof designed with a given type of membrane, insulation material, and deck will be moisture-tolerant in a given location on a building controlled to a specific indoor relative humidity, without the need to set up and run a computer simulation.

The algorithms were developed using a database of 600 finite difference simulations. Five different 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 U.S. Indoor relative humidities of 40%, 50%, and 60% with an indoor temperature of 20°C (68°F) 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 roofing configurations evaluated included 25 mm and 76 mm (1 in. and 3 in.) thick wood fiberboard, 25 mm and 76 mm (1 in. and 3 in.) thick polyisocyanurate (PIR) insulation, and a 76 mm (3 in.) composite of the two. Four metal decks with permeances of 3.6, 5.7, 29, and 57 $\times 10^{-8}$ 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 roofing membrane was considered relatively impermeable for all simulations and was assigned a water vapor permeance of 0.1 $\times 10^{-8}$ 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 roofing configurations listed above were selected can be found in an earlier publication (Desjarlais 1995). In summary, the insulation materials were selected to represent the range of hygric properties available in typical roofing insulations while 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 (Kyle and Desjarlais 1994; Sheahan 1992); even higher values of deck permeance were simulated to address the need to minimize the time that a roof system would remain wet after experiencing a leak.

All of the simulation work performed in this study used the computer program MATCH (Moisture and Temperature Calculations for Constructions of Hygroscopic Materials) (Rode 1990) to simulate the simultaneous effects of the transfer of heat and moisture in roofing systems. Rode and Courville (1991), Desjarlais et al. (1993a, 1993b), Kyle and Desjarlais (1994), and Desjarlais (1995) have described, validated, and used the model on low-slope roofing applications. 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 we 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. The transfer of heat 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 due to temperature and moisture content are both accounted for by the model.

The algorithms were based on the following set of simulations. After an initial one-year simulation to estimate the initial moisture contents of each of the roofing system components, two additional one-year simulations were performed. The moisture contents of the roofing system components for the final month of the two one-year simulations were compared to determine whether Requirement 1 was satisfied. To determine if condensation occurred under the membrane (Requirement 2), 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% (saturated) was recorded. Roofing systems that showed a relative humidity of 100% in this outer insulation layer just below the roof membrane for more than 24 hours were determined to fail the "no condensation" requirement.

A final simulation was undertaken to assess whether water introduced into the roofing system because of leakage would condense on the top of the deck (and, therefore, drip into the building interior) and to determine how quickly the water that leaked dissipated into the building interior (Requirements 3 and 4). To perform these simulations, it is assumed that a roof leak occurred on 1 January[1] of the third year and that the leak added 10% by volume moisture content to a control volume in the uppermost layer of the roofing system. A leak of this magnitude adds 1.7 kg/m^2 (0.35 lb/ft^2) of water to the roof system. This amount of water was added to the final moisture content of the uppermost insulation layer after the second of the two one-year simulations, and it is assumed that the initial conditions for the remaining layers were the same as predicted by the second one-year simulation. To determine if condensation occurs on the top surface of the deck, the results for the bottom thin layer of insulation just above the deck were examined and the amount of time that the relative humidity of this layer was at 100% (saturation) was

1. We have noted that the time required to dry is a function of when a leak occurs. All the climates that we have modeled have several winter uptake months when the average vapor drive is into the roofing system and no drying can occur; in fact, the moisture content of the roof system increases during this period of time. By selecting January for the leak to occur, the roof system's moisture contents increase prior to the initiation of their drying cycle and the time required to dry is extended because water accumulated due to winter uptake must also be removed. The time required to dry is, therefore, a somewhat conservative estimate. Longer drying times would be predicted if we introduced the leak at the beginning of the winter uptake period (November/December), while shorter drying times would be computed if the leak was introduced during the spring or summer months.

recorded. Again, a 24-hour limit was set as the pass/fail criteria. To determine the time required for the roof system to dry, the monthly relative humidity of all the layers in the roofing system was examined and the first month when all of the layers had a relative humidity less than 100% was identified. This technique identifies the length of time that each roof system needs before there is no liquid water remaining in the system. To determine the total amount of water removed, the final month's computed moisture content for the total roof system was compared to the initial conditions after the leak; their difference indicates quantitatively how much water was dissipated to the building interior.

DEVELOPING AND USING THE ALGORITHMS

All 600 configurations that were simulated were evaluated to determine if they satisfied the four quantifiable requirements. The database was analyzed for each of the quantifiable moisture control requirements to develop the predictive 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 correlations.

The following procedures can be used to predict the moisture tolerance of a roofing system using the following algorithms for the four quantifiable requirements for moisture control in low-slope roofing. First, the parameters listed below for the roofing system need to be determined.

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

- H = heating degree-days for the location (°F)
- Φ = relative humidity of the indoor environment (e.g., 40% = 0.4)
- α = membrane absorptance (herein, 0.1 for white and 0.7 for black)
- P = deck permeance (in English perms [see Table 1])
- T = thickness of each insulation layer (in inches).

Requirement 1: The average yearly moisture content of the roof must not increase with time. Results showed that all the roofing systems in all the climates evaluated satisfied this requirement. The "algorithm" for this requirement is therefore simple: If the roofing system of the types evaluated is located in the continental U.S. ($H < 8992°F$), it passes Requirement 1.

Requirement 2: No condensation can occur under the roof membrane. Algorithms were generated to predict the average vapor pressure under the membrane during the winter uptake period and the length of time that the vapor drive is into the roofing system. These parameters, coupled with the building interior conditions, define the moisture accumulation in the roofing system during the wintertime uptake period. Comparing this level of accumulation to a predetermined threshold will dictate whether a vapor retarder is needed.

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

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

$$p_{vm} = -0.934 + 0.284\Phi + 4.85\times10^{-4}H - 8.00\times10^{-8}H^2 + 4.22\times10^{-12}H^3 - 2.05\times10^{-5}H\Phi + 161/H + 0.00230P - 8.01\times10^{-5}P^2 - 1.34\times10^{-7}HP - 0.00889\alpha \quad (1)$$

$$t = -66.1 - 1.51\Phi + 0.0339H - 5.66\times10^{-6}H^2 + 3.07\times10^{-10}H^3 + 0.00442H\Phi - 4.33\times10^{-7}\Phi H^2 + 11400/H \quad (2)$$

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

$$p_{vi} = \Phi\, p_{vsat} \quad (3)$$

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 is 0.363 psi [2.50 kPa]).

Calculate m (the moisture accumulation in the roofing system, in lb/ft^2):

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

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 these vapor resistances for typical roofing materials.

Compare m, the calculated moisture accumulation, with the appropriate Requirement 2 failure 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 or not the roofing system failed the stated condensation control requirement. These lists were examined to determine the thresholds of moisture accumulation where most roofing 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 (1997b) for more information regarding the derivation of these thresholds.

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

TABLE 1
Vapor Resistances and Permeances for Decks and Insulation Materials

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

Figure 1. The line in Figure 1 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%. For passes, it is 95% (Desjarlais and Byars 1997b).

TABLE 2
Requirement 2 Failure Thresholds for Insulation Materials Used in Low-Slope Roofing (Desjarlais and Byars 1997b)

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

Requirement 3: If a leak occurs in the roofing system, no condensation can occur on the deck. Condensation on the deck is most likely to occur during the summer, when the vapor pressure at the outer membrane of the deck is greater than the indoor vapor pressure. Leakage into the building interior occurs when the amount of water vapor being driven through the insulation to the deck exceeds the amount of water vapor driven through the deck into the building interior. Effectively, the deck acts as a vapor retarder in this situation and allows accumulation to occur on its exterior surface. To compare these two quantities, an algorithm to determine the vapor pressure at the deck was developed and the vapor pressure drive across the deck is determined. Because various insulation types will yield different vapor drives to the deck, the analysis must be separated by insulation type. Following a procedure identical to that described under Requirement 2, a vapor pressure drive threshold value was determined through comparison with the simulation results. Comparison with this threshold value determines if leakage into the building interior will occur.

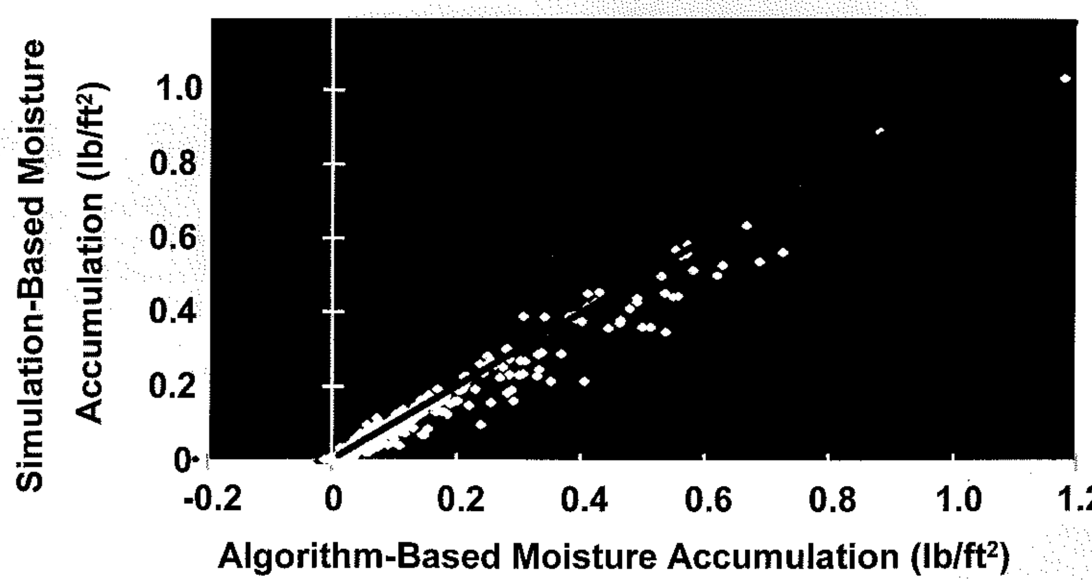

Figure 1 *Comparison of the simulation-based and correlation-based moisture accumulation (Desjarlais and Byars 1997b).*

The analysis is separated by insulation type. The conditions are listed in specific order for each insulation type. If a roofing system meets one of the conditions, pass or fail is decided and the analysis is terminated. If not, the analysis must be continued.

Composite: All the composite roofing systems passed this requirement for all conditions tested. Therefore, any composite system, as described above, passes this requirement

Fiberboard:

1. If H is greater than 6151, T is less than or equal to 1 inch, and the indoor relative humidity F is less than or equal to 50%, the system fails. Higher levels of indoor relative humidity reduce the vapor pressure drive across the insulation layer sufficiently to prevent condensation from occurring on the deck.
2. All other fiberboard systems pass.

Foam:

1. If the vapor resistance ratio of insulation to deck, R_i/R_d, is less than or equal to 1.5, the system fails.
2. If the above condition is not met, continue with the vapor pressure drive calculations shown below.

Calculate the deck vapor pressure, p_{vd}:

$$p_{vd} = -48.4 + 0.326\Phi - 0.0205P - 0.0166\alpha - 0.000443H - 0.0173R_i + 0.000597P^2 - 0.0268\Phi^2 + 0.00240R_i^2 + 17300/H + 0.0129P\Phi + 0.00232P\alpha + 4.77\times10^{-7}PH + 0.0178/P - 2534000/H^2 + 5.56*\ln(H) + 5.626\times10^{-8}H/R_i \quad (5)$$

Calculate the vapor pressure drive, D_{vp} (the determination of p_{vi} is discussed in the previous section on Requirement 2). If the vapor pressure drive is greater than or equal to the failure threshold of 0.038 psi (0.26 kPa) (Desjarlais and Byars 1997b), the system fails Requirement 3:

$$D_{vp} = p_{vd} - p_{vi} \quad (6)$$

Following the procedure described for Requirement 2, the precision of the algorithm-based computation was compared to the simulations. The algorithm-based method is once again conservative because it overpredicts failure. The accuracy in predicting failures for the given database is over 99% and for passes it is 93%.

Requirement 4: If a leak occurs in the roofing system, the drying time will be as short as possible. Simulations were performed for each roofing system to determine the drying time after a leak of 10% by volume occurs. Separate correlations were developed for each insulation type: wood fiberboard, polyisocyanurate, and the composite of the two. These algorithms are not intended to indicate in an absolute sense how long it will take a roofing system to dry since the analysis assumes that a leak of specific magnitude occurs at a specific time of year and that the leak is repaired instantaneously. However, the following correlations can be used to rank roofing systems in a relative sense; systems with predicted shorter drying times will dissipate leaks more expeditiously.

Note that a quantitative assessment of how long a roof can remain wet is beyond the scope of this paper. The length of time a roofing system can have wet insulation is a function of the type of roof, its attachment method, the type of insulation, and the use of the building. As an extremely conservative estimate, it is recommended that the drying time should be less than one year. The "drying season" typically happens during the spring and summer months when the vapor drive pushes water vapor out of the roofing system and into the indoor environment. If the moisture is not removed during this time, it will remain in the roofing system until the next drying season. This calculation method is also conservative and tends to slightly overpredict drying time. For the given database, it predicts whether drying time is greater than 12 months with 100% accuracy. It predicts whether the drying time is 12 months or less with 97% accuracy.

Calculate the relative time to dry. For a fiberboard system:

$$t = -5.85 + 0.0564P + 5.65\alpha + 0.00126H + 0.0746\Phi + 0.452\alpha^2 + 0.000238\alpha H + 7.75\times10^{-6}\Phi H + 0.0375\Phi\alpha - 0.00062\Phi^2 - 7.84\times10^{-8}H^2 - 0.0541T + 678/H - 0.558/P - 0.00462\alpha P - 1.63\times10^{-12}H^3 - 12.3\alpha^3 \quad (7)$$

For a foam system:

$$t = -602 + 0.1774P + 407\alpha + 0.131H - 0.679\Phi - 511\alpha^2 + 0.00142\alpha H + 2.96\times10^{-5}H\Phi + 0.502\Phi\alpha + 0.00531\Phi^2 - 2.17\times10^{-5}H^2 + 0.754T + 443/H + 2.04/P - 0.393\alpha P + 114\times10^{-9}H^3 \quad (8)$$

For a composite system:

$$t = 18.7 + 0.0200P - 35.1\alpha + 0.0133H + 0.00681\Phi - 29.0\alpha^2 + 0.000255\alpha H + 5.86\times10^{-6}H\Phi + 0.0208\Phi\alpha + 0.000125\Phi^2 - 2.018\times10^{-6}H^2 - 14.3T + 4700/H - 0.385/P - 0.00614\alpha + 9.87\times10^{-11}H^3 + 102\alpha^3 \quad (9)$$

AN EXAMPLE

In this example, two roofing systems are examined. These systems are identical except for the insulation material. Both are analyzed for the climate in Chicago with a building interior relative humidity of 50% and interior temperature of 20°C (68°F). Both have a white outer membrane and a solid metal deck with tight joints. Fiberboard and foam systems are analyzed; the insulation thickness is 76 mm (3 in.) for both.

Requirement 1: Both systems pass Requirement 1, since the H of Chicago is 6151, which is less than or equal to 8992.

Requirement 2: For both systems:

H = 6151

P = 0.64 English perms

α = 0.1

Φ = 0.5

T = 3 in.

R_d = 1.56 reps

For 3-in. fiberboard: $R_i = 0.071$ reps.

For 3-in. foam: $R_i = 1.39$ reps.

Substituting these values into Equations 1, 2, and 3 yields:

p_{vm} = 0.110 psi

t = 6.4 months

p_{vi} = 0.171 psi

These results are common for both systems. Then, using Equation 4, for fiberboard:

$$m = 0.215\ (6.4)(0.171 - 0.110)/(0.211 + 1.56 + 0.071)$$

$$m = 0.046\ \text{lb/ft}^2$$

The failure threshold for fiberboard is 0.20 lb/ft^2. Since $0.046 < 0.20$ lb/ft^2, this system passes. Using Equation 4 again, this time for foam:

$$m = 0.215\ (6.4)(0.171 - 0.110)/(0.211 + 1.56 + 1.39)$$

$$m = 0.027\ \text{lb/ft}^2$$

The failure threshold for foam systems is 0.012 lb/ft^2. Since $0.027 > 0.012$ lb/ft^2, this system fails.

Requirement 3: For the fiberboard system, the condition for failure is not met, so this system passes.

For the foam system, the vapor resistance ratio is calculated:

$$R_i / R_d = 1.39/1.56$$

$$= 0.9.$$

Since $0.9 < 1.5$, we fail.

Requirement 4: Using Equations 7 and 8 to determine the relative time to dry for the fiberboard and foam systems:

t = 3 months (for fiberboard)

t = 7 months (for foam)

The fiberboard system dries more quickly than the foam system, but both dry in less than the maximum of 12 months.

The fiberboard system passes all four requirements and, therefore, represents an acceptable design for moisture control for this roofing application. The foam system would likely see condensation at the roof membrane in the winter and represents a poor design for moisture control in this case.

CONCLUSIONS

Algorithms have been developed that can be used by the roofing designer to assess the moisture tolerance of a roofing system. Given the location and indoor conditions of the building, the designer can use these algorithms to determine if a vapor retarder is needed, if small leaks in the roofing system will translate into leaks into the building, and the relative ability of the roofing system to be self-drying. The roofing designer can vary roof membrane color, insulation type and thickness, and deck permeance until optimum moisture tolerance (subject to other limitations) is achieved. Experimenting with these algorithms will hopefully offer insight into the basics of moisture control.

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 roofing systems with a wider range of properties in order 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 roofing systems and components that are presently not in our database.

The algorithms are now available on an Internet home page (www.ornl.gov/roofs+walls) where the roofing designer can simply select the roofing components from menus and determine the moisture tolerance of his roofing creation.

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