SELF-DRYING ROOFS: WHAT?! NO DRIPPING!

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ABSTRACT

Many roofs are replaced because water accumulates in portions of the roofing system. These accumulations can cause dripping, accelerated membrane failure, poor thermal performance, threat of structural decay, and depreciation of building assets. Traditionally, the roofing industry has been concerned with controlling the inflow of water into the roof. An example of this strategy would be the development of a more reliable membrane. However, roof membranes inevitably leak. For this reason, the roof design strategy of the future must be concerned with controlling water outflow.

Following are the requirements for this type of roof system. Under normal operating conditions (no leaks), the total moisture content of a self-drying roof system shall not increase with time and condensation shall not occur under the membrane during winter uptake. 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 and the water introduced by the leak must be dissipated to the building interior in a minimum amount of time.

Finite-difference computer modeling is used to demonstrate the effectiveness of the design. The impact of deck and insulation permeance, climate, leaks, and winter water uptake is simulated. A data base of simulations is qualitatively described; this data base will be used in future work to produce a simplified means of assessing the design parameters of a self-drying roof system.

INTRODUCTION

The service life of a roofing system ends when it can no longer provide the desired protection from the environment. All too often, water accumulation in the roof system has accelerated its demise. In earlier studies, the author attempted to assess the economic impact associated with moisture trapped in existing roofing systems. Kyle and Desjarlais (1994) calculated, based on the limited amount of available data, that existing moisture levels cause a 40% reduction in the R-value of the U.S. roofing inventory. They proposed that addressing the issue of moisture in roofing could greatly reduce the annual average cost of roofing and the amount of roofing debris generated.

In the early 1970s, Powell and Robinson (1971) conducted a comprehensive study on the effects of moisture on roof assemblies. They stated, "The most practical and economical solution to the problem of moisture in insulated flat-roof constructions (is) to provide a design that would have in-service self-drying characteristics." However, they believed the theoretical basis for understanding combined heat and mass transfer processes was not sufficiently developed and, therefore, analytical tools such as computer programs could not be produced.

These concerns are no longer warranted. The International Energy Agency (IEA 1993) has identified and evaluated 29 computer programs that are capable of analyzing heat and mass transfer. These tools now can be used to assist roofing professionals in designing roofing systems that, of themselves, will reduce or entirely eliminate the effects of water accumulation (the self-drying roof).

In this paper, the author outlines the characteristics that a self-drying roof must possess and, using a heat and mass computer model, tests several typical roofing systems to determine under what conditions they meet these requirements. The author also describes a roofing system that appears to satisfy most of these criteria for any U.S. continental climate.

CHARACTERISTICS OF A SELF-DRYING ROOF

A self-drying roof is a roofing system that is designed to eliminate or minimize the deleterious effects of water accumulation. Water accumulation can be reduced by delaying the inflow of water through the roofing membrane, as well as facilitating its controlled outflow to the building interior (downward drying). Furthermore, the roofing system must be composed of materials that do not rapidly degrade mechanically in the presence of water. The specific requirements of a self-drying roof are as follows.

1. A self-drying roof cannot be used in a climate in which the average yearly moisture content increases with time. If the combination of the local climate and

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the building's interior conditions creates a yearly average vapor drive upward into the roofing system, a vapor retarder is needed to control moisture pickup from the building interior. Roofs equipped with vapor retarders are not self-drying because downward drying is impossible.

2. The winter uptake of moisture into the roofing system must be controlled such that the moisture limit of the insulations used in the roofing system is not exceeded. By *moisture limit*, it is meant the maximum level of water content that can be contained in an insulation material without degradation of critical physical and thermal properties. Condren (1982) suggested that moisture-limit data were needed to determine the necessity of installing vapor retarders in roofing systems. Unfortunately, this information still is not available. Without it, the author chose to conservatively limit the winter uptake so condensation under the membrane does occur.
3. When the roofing system eventually leaks, a self-drying roofing system must passively prevent water from dripping into the building interior. This criterion is satisfied if condensation does not occur on the top surface of the deck.
4. The self-drying roof must include some means of preventing water vapor from traveling through the roofing system by convection; a vapor-tight monolithic deck or an air barrier will be included in the roof design if convection is a potential concern.
5. Water leaking through the membrane must be prevented from flowing, under the influence of gravity, through cracks between insulation boards and other openings in the insulation layers and, eventually, arriving at the top side of the deck. The use of a continuous absorptive layer is proposed. This layer will absorb the leaking water and dissipate it over a large area.
6. After satisfying these requirements, the roofing system can be optimized so downward drying, after a leak has occurred, can be as expeditious as possible. Long-term exposure of certain roofing system components (fasteners, metal decks) can lead to structural degradation. Obviously, the use of vapor retarders or other layers that will delay the flow of water vapor into the building interior is prohibited because downward drying is all but prevented.

One drawback of requirement 3 is that leakage into the building interior traditionally has been the signal that the roofing membrane has been compromised and that membrane repair is needed. To alleviate this concern, routine inspection would be required to identify small membrane faults. Because the roof system is self-drying, the insulation materials could be left in place after the membrane has been repaired.

In summary, self-drying roof systems must not allow water to migrate between the deck and the membrane by convection or through gaps and voids, must limit the rate and quantity of water vapor driven into the roofing system during winter uptake, and must control downward drying to prevent excessive buildups under the membrane or over the deck. Self-drying roofs require climates where the yearly average vapor pressure drive is downward into the building, and should be optimized to remove water that has leaked into the roof as quickly as possible.

The self-drying roof requirements pertaining to convection control and leakage due to cracks and openings can be satisfied with the inclusion of appropriate materials in the roof system. The author assumes that these additions satisfy requirements 4 and 5; the remaining task is to satisfy the other four basic requirements pertaining to the effects of water vapor diffusion and is efficiently addressed by computer modeling.

DESIGN OF THE ANALYTICAL EXPERIMENTS

Can all of the diffusion-related self-drying criteria be satisfied in a roofing system using traditional materials and construction practices? The author used a combined heat and mass transfer model to address this question. Rode (1990), Rode and Courville (1991), Desjarlais et al. (1993a), Desjarlais et al. (1993b), and Kyle and Desjarlais (1994) have described, validated, and used the model on low-slope roofing applications. The author tried to identify the important parameters that would impact the performance of a self-drying roof and included these as variables in the simulations. The outside influences and the roof system properties that the author identified are listed in Table 1.

TABLE 1 **Environmental Conditions and Roof System Properties Included as Variables in the Simulations**
(Each variable impacts the moisture transport in a roof system.)

Variable	Simulation Values
Environmental Conditions	
Climate	Bismarck, ND; Chicago, IL; Knoxville, TN; and Miami, FL
Building Interior	40%, 50%, and 60% RH
Roof System Properties	
Insulation Type	Fiberboard, Polyisocyanurate, and Composite
Insulation Permeance	High (Fiberboard) and Low (Polyisocyanurate)
Insulation Absorptance	High (Fiberboard) and Low (Polyisocyanurate)
Insulation Thickness	25 mm and 76 mm (1 in. and 3 in.)
Membrane Solar Absorptance	0.1 (Black) and 0.7 (White)
Deck Permeance	36, 57, 290, and 570 metric perms (0.64, 1.0, 5.0, and 10.0 perms)

Environmental conditions were included in the author's list of parameters because they impact vapor pressure drives experienced by the roof. The climates of Bismarck, ND (heating degree-days [HDD] [65°F base] = 8,992); Chicago, IL (HDD = 6,151); Knoxville, TN (HDD = 3,818); and Miami, FL (HDD = 185) were selected because they represent the range of climates that exists in the continental United States (ASHRAE 1989). Interior relative humidity was selected to vary the inside vapor pressure of the building. For all simulations, the building interior temperature was fixed at 20°C (68°F).

The insulation materials in the roofing system play a complex part in the transport of water vapor. The rate at which the vapor transfers through the insulation is controlled by the insulation's permeance. The insulation material's absorptance (or hygroscopicity) dictates what water vapor level is required for condensation to occur, while its thermal resistance (which is a function of the material type and its thickness) affects the temperature distribution through the roofing system. When considering traditional roofing insulations, the material's key moisture properties can be classified into three categories. One group of insulation is hygroscopic and highly permeable and consists of organic roof insulations such as fiberboard and perlite. A second group has low permeance and is nonhygroscopic; this category contains all the closed-cell foam products currently in use. The final category consists of products that are permeable and nonhygroscopic. Fiberglass roof insulation is the only material in this category. Because there is not a significant amount of fiberglass roof insulation currently used in new construction (NRCA 1993), the author chose fiberboard and polyisocyanurate foam as representatives from the two widely used categories of roofing insulation. The author expects that other members of their respective categories would perform in a similar fashion.

Membrane solar absorptance controls the amount of visible-range solar radiation that is absorbed by the roof surface and therefore impacts the temperature of the roof membrane. The range of solar absorptance is estimated to be from 0.1 to 0.7. These limits are achieved by relatively new black and white membranes, respectively (Byerley and Christian 1994).

The rates of moisture migration into and out of roofing systems are affected by the permeance of the deck. Metal decks, which presently dominate the market, have permeances that have been estimated to range between 36 metric perms (0.64 perms) (Kyle and Desjarlais 1994) and 57 metric perms (1.0 perms) (Sheahan 1992). 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.

For modeling purposes, the roofing system was divided into a series of layers. A schematic of the simulated roof is shown in Figure 1. Where a single type of insulation is used in the roof, the system was composed of a single-ply membrane, an 8.5 mm (0.33 in.) thick layer of insulation, a 17 mm or 68 mm (0.67 in. or 2.67 in.) thick layer of insulation, and a 8.5 mm (0.33 in.) 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, the author replaced the monolithic insulation layer with a sandwich composed of a 51-mm (2-in.) core of polyisocyanurate foam between layers of 13 mm (0.5 in.) thick fiberboard. To model this system, each layer of fiberboard was subdivided into 8.5 mm and 4 mm (0.33 in. and 0.17 in.) thick layers. The thicker fiberboard layers were in contact with the membrane and deck.

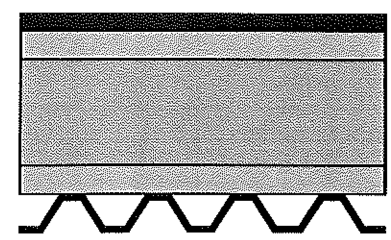

Figure 1 *A schematic representation of the simulated roofing system. The insulation layer is divided into a thin outer and inner layer surrounding a thick core. The outer and inner layers are used to determine whether self-drying roof requirements are being satisfied.*

For each of the four climates, a total of 120 roofing configurations were analyzed. Each roofing configuration was simulated three times. An initial estimate was performed to develop appropriate initial boundary conditions for the subsequent simulations. Initial estimates for the temperature and moisture content of each layer were input and the model was run for a period of 24 months (January, year one to December, year two). December, year two, temperatures and moisture contents generated from this series of simulations were then used as initial conditions for the other two simulations.

The second simulation was performed to test the self-drying roof requirements that the overall moisture content of the roofing system does not increase as a function of time and, that during winter uptake, the moisture content of the uppermost layer in the roofing system remains below saturation (requirements 1 and 2). The December, year two, results from the first simulation were used as initial conditions and the author performed an additional one-year simulation. To determine if the moisture content of the roof increased, the author compared the moisture contents computed for the final month of the simulation with the initial moisture contents of this simulation. The comparison yields a quantitative assessment of whether any additional water remains in the roof system at the end of the simulated year. To determine if condensation occurs under the membrane, the author examined the results for the uppermost thin layer of insulation and counted the amount of time that the relative humidity of this layer was at 100%.

The 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 6). To perform these simulations, the author assumed that a roof leak occurred on January 1 of the third year and that the leak added 10% by volume moisture content to the uppermost layer in 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. The author added this amount of water to the December, year two, moisture content of the uppermost insulation layer and assumed that the initial conditions for the remaining layers were the same as predicted in the first simulation. To determine if condensation occurs on the top surface of the deck, the author examined the results for the bottom thin layer of insulation and totaled the amount of time that the relative humidity of this layer was at 100%. To determine the time required for the roof system to dry, the author performed two separate analyses. First, the author examined the monthly relative humidity of all the layers in the roofing system and identified the first month when all the layers had a relative humidity less than 100%. This technique identifies the length of time that each roof system needs before there is no liquid in the system. To determine the total amount of water removed, the author again compared the final month's computed moisture content for the total roof system to the initial conditions after the leak; the difference indicates, quantitatively, how much water was dissipated to the building interior.

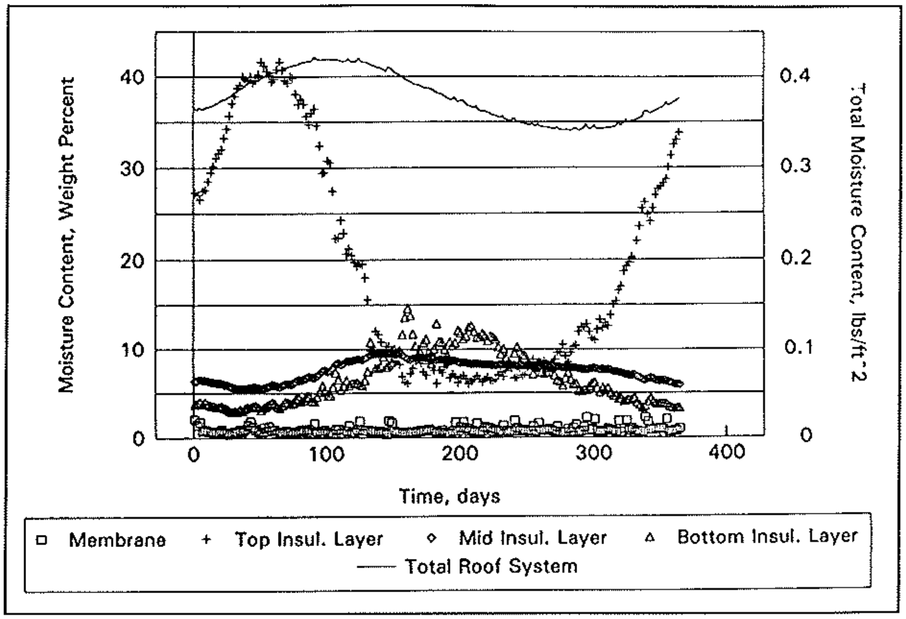

Figure 2 *An example of a typical simulation output. The simulation depicted in this figure is for a roof system composed of 76 mm (3 in.) thick fiberboard insulation with a deck having a permeance of 57 metric perms (1.0 perms) and a white roof membrane. This roofing system is exposed to the Chicago climate and is on a building where the interior is maintained at 60% relative humidity. See text for a description of the results.*

Does the amount of water that the author added to the roof system accurately represent a real leak? This question was wrestled with for some time. The amount of water added is equivalent to a 0.8-mm (0.03-in.) layer of water placed directly under the membrane. Although a leak may allow an appreciably greater amount of water to be introduced to the roofing system locally, the addition was uniformly distributed over the entire surface area of the roof. If the guidelines for the design of self-drying roofs are followed, it is recommended that an absorptive layer be added somewhere near the outboard side of the insulation layers to intercept leak water that would otherwise flow through voids and openings in the insulation layers. That same layer can be used to disperse water entering through leakage, allowing for the localized concentrations to be significantly diminished. Although not critically established, the amount of leakage that the author has modeled can be considered as appreciable.

The author has noted that the time required to dry is a function of when a leak occurs. All four climates that were modeled have several winter uptake months during which 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. 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 also must be removed. The time required to dry is therefore a somewhat conservative estimate. Longer drying times would be predicted if the author 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.

SIMULATION RESULTS

The results of the simulations are organized in a manner that addresses each of the self-drying roof requirements. A typical simulation result is depicted in Figure 2.

This simulation models the performance of a roof system composed of 76 mm (3 in.) thick fiberboard insulation with a deck having a permeance of 57 metric perms (1.0 perms) and a white-roof membrane. This roofing system is exposed to the Chicago climate and is on a building where the interior is maintained at 60% relative humidity. The author is testing this roof system for conformance with requirement 2, condensation under the membrane during winter uptake. The symbols (o, +, ◊, and Δ) represent the daily moisture content (expressed as a weight percent) of the membrane, top insulation layer, middle insulation layer, and bottom insulation layer, respectively. The solid line depicts the total daily roof system moisture content expressed in lb/ft^2 (to convert to kg/m^2, multiply by 4.88).

At the beginning of the simulation (January 1), the moisture content of the top insulation layer increased dramatically, peaking approximately on day 65 (March 6) and then decreasing rapidly until day 135 (May 15), where it stabilized for the duration of the summer. On approximately day 285 (October 12), the moisture content began to rise and continued this process through the remainder of the calendar year. The saturation moisture content for fiberboard is 36.5 weight percent. Therefore, that simulation failed to satisfy requirement 2 because between days 29 and 83 (January 29 and March 24), the moisture content of the top insulation was above saturation and water had condensed below the membrane.

The bottom insulation underwent a dramatically different moisture content cycle. The moisture content of the bottom insulation layer slowly increased throughout the winter and spring seasons and, about day 150 (May 30), surpassed the moisture content level of the top insulation layer. This condition continued until approximately day 260 (September 17), when the moisture-driving forces reversed and water vapor was driven into the roof system. At that time, the moisture content of the bottom insulation layer decreased and was surpassed by the upper layers.

Note that the total moisture content of the roof did not appreciably increase. On days 0 and 365, the total roof system moisture contents were 1.81 and 1.83 kg/m^2 (0.370 and 0.375 lb/ft^2), respectively. By updating the initial boundary conditions and rerunning this simulation, the author found closer agreement between the initial and final moisture contents. Two years of preconditioning typically indicated that the differences between the initial and final total moisture contents were diminishing.

Requirement 1: Does Water Accumulate in the Roof System?

For all of the simulations that the author performed, there were no instances where there was a buildup of water in the roofing assemblies. Even in the simulations where the author optimized the conditions to maximize the winter uptake (Bismarck climate, a white membrane, and a high interior relative humidity), the overall water content of the roof system did not increase appreciably. Multiple simulations were performed for each set of roof system components and environmental conditions. Each subsequent simulation used the final results of the previous simulation as updated initial conditions. The author noted that the magnitude of the difference between initial and final moisture contents decreased with each subsequent simulation and that any increase in the overall roof moisture content was small (less than 2%). Additional simulations eventually would eliminate any differences.

These data are in conflict with a previous study (Tobiasson and Harrington 1986), where it was determined that certain portions of the climate of the continental U.S. created net vapor drives into the roofing system. In these locations, moisture levels in the roof increased yearly. In this previous study, the authors used meteorological data from weather stations and computed the exterior (membrane) temperature based on the ambient air temperature. Kyle and Desjarlais (1994) reported that the exterior vapor pressure is roughly independent of ambient temperature. The authors included solar effects in determining the membrane temperature of the roof system. This omission would reduce their exterior vapor pressure within the roof and probably accounts for the discrepancy in findings. Based on the author's results, the recommendation for using a vapor retarder in a roof system to prevent moisture buildup in the roof system is unwarranted for any climate in the continental U.S. (given the modeling limit of an interior vapor pressure created by 20°C [68°F] air controlled at a relative humidity of less than 60%).

Requirement 2: Does Water Condense Under the Membrane During Winter?

Tests to determine whether water condenses under the membrane during winter uptake yielded results that were influenced strongly by climate, insulation material, and deck permeance. A summary of these results is shown in Table 2. Each simulation was given a five-digit code. The first digit indicates the total thickness of the insulation layer ("1" for 25 mm or 1 in. and "3" for 76 mm or 3 in.); the second digit represents the deck permeance ("M," "L," "P," and "H" for 36, 57, 290, and 570 metric perms [0.64, 1.0, 5.0, and 10.0 perms], respectively). The third digit, "B" or "W," indicates whether the roof membrane is black or white, while the fourth and fifth digits—"40," "50," or "60"—indicate the interior relative humidity. A "•" indicates that condensation occurred under the membrane during the simulation; a "—" indicates that the simulation was not performed.

TABLE 2 **Summary of Results Assessing the Satisfaction of Requirements 2 and 3 of a Self-Drying Roof**
("•" indicates that requirement 2 is not satisfied, "—" indicates that the simulation was not performed, and a shaded box indicates a failure to satisfy requirement 3)

	Bismarck			Chicago			Knoxville			Miami		
CODE	WFBD	PIR	COMP	WFBD	PIR	COMP	WFBD	PIR	COMP	WFBD	PIR	COMP
1HB40	•	•	—	•	•	—		•	—			—
1HB50	•	•	—	•	•	—		•	—			—
1HB60	•	•	—	•	•	—	•	•	—			—
1HW40	•	•	—	•	•	—		•	—			—
1HW50	•	•	—	•	•	—	•	•	—			—
1HW60	•	•	—	•	•	—	•	•	—			—
1LB40		•	—		•	—			—			—
1LB50		•	—		•	—		•	—			—
1LB60		•	—		•	—		•	—			—
1LW40		•	—		•	—		•	—			—
1LW50		•	—		•	—		•	—			—
1LW60		•	—		•	—		•	—			—
1MB40		•	—		•	—			—			—
1MB50		•	—		•	—			—			—
1MB60		•	—		•	—		•	—			—
1MW40		•	—		•	—			—			—
1MW50		•	—		•	—		•	—			—
1MW60		•	—		•	—		•	—			—
1PB40	•	•	—		•	—		•	—			—
1PB50	•	•	—	•	•	—		•	—			—
1PB60	•	•	—	•	•	—		•	—			—
1PW40	•	•	—		•	—		•	—			—
1PW50	•	•	—	•	•	—		•	—			—
1PW60	•	•	—	•	•	—	•	•	—			—
3HB40	•	•		•	•							
3HB50	•	•		•	•			•				
3HB60	•	•	•	•	•			•				
3HW40	•	•		•	•			•				
3HW50	•	•		•	•		•	•				
3HW60	•	•	•	•	•		•	•				
3LB40		•			•							
3LB50		•			•							
3LB60	•	•			•			•				
3LW40		•			•			•				
3LW50		•			•			•				
3LW60	•	•		•	•			•				
3MB40		•			•							
3MB50		•			•							
3MB60		•			•			•				
3MW40		•			•							
3MW50		•			•			•				
3MW60	•	•			•			•				
3PB40	•	•			•							
3PB50	•	•		•	•							
3PB60	•	•		•	•			•				
3PW40	•	•			•			•				
3PW50	•	•		•	•			•				
3PW60	•	•	•	•	•		•	•				

The author's simulations indicated that, for the Miami climate, none of the roof configurations yielded condensation under the membrane.

For Knoxville, there were seven configurations containing fiberboard (WFBD) insulation that exhibited condensation under the membrane. The environmental and component combinations that yield condensation most readily are high interior relative humidity and a highly permeable deck. Because the insulation layer is permeable, the amount of water entering and passing through the roof system is controlled by the deck permeance.

By simply replacing the insulation material with polyisocyanurate (PIR), the number of simulations where condensation occurred under the membrane increased to 36 (out of 48 simulations). With the exception of the simulations with the lowest interior relative humidity and deck permeance, all the simulations yielded condensation.

The results for Chicago and Bismarck are similar to the Knoxville data. For Chicago, 21 simulations with fiberboard insulation indicate that condensation occurs under the membrane, while all the PIR simulations indicated that condensation occurred. For the Bismarck climate, 27 fiberboard and all the PIR simulations exhibited condensation. As the winter climate becomes more severe, simulations with lower levels of deck permeance and lower interior relative humidity began to exhibit condensation.

A summary of the total moisture content of the simulated roof systems at the end of the simulated year (December) is shown in Figure 3. The moisture content of the roof system is dramatically impacted by the type of insulation material; substituting fiberboard for PIR increases the roof system moisture content by a factor of 10. Insulation thickness is next in importance; increasing the thickness from 25 mm to 76 mm (1 in. to 3 in.) increases the moisture content by a factor of 2. The other parameters affected the total roof system moisture content to a lesser extent. Increasing the deck permeance from 36 metric perms (0.64 perms) to 57, 290, and 570 metric perms (1.0, 5.0, and 10.0 perms) increases the moisture content by 3%, 32%, and 56%, respectively. When analyzing the fiberboard and PIR simulations separately, the impact of deck permeance was found to be similar.The additional vapor resistance of the PIR does not impact the effect of varying deck permeance.

Changing the roof color from black to white increased the total moisture content by 19%. Increasing the interior relative humidity from 40% to 50% and 60% yielded increases of 24% and 59%, respectively. Finally, changing the climate from Miami to Knoxville, Chicago, and Bismarck increased the total moisture content by 26%, 47%, and 91%, respectively.

The most surprising result obtained from this family of simulations was that the onset of condensation was insensitive to moisture content. Based on the author's simulations, the key parameter that controls the onset of condensation is the absorptance of the insulation material. The author postulated that a composite insulation material composed of a vapor-resistive core (PIR) and an absorptive outer layer (fiberboard) could reduce the probability of condensation. The author has demonstrated that PIR significantly reduces the moisture content of the total roofing system. An absorptive layer directly under the roof membrane that has a much higher saturation moisture content (5.32% for PIR vs. 36.5% for fiberboard) might absorb the reduced amount of water vapor passing through the PIR without reaching saturation.

The author limited the composite simulations to the 76-mm (3-in.) thickness because it seems impractical to produce a composite product at the lower thickness. Because the author anticipated that the same logic could be applied to leak water condensing on the deck (see the next section discussing requirement 3), a fiberboard layer also was added to the interior side of the composite insulation. An informal survey of roofing professionals suggested that 13-mm (½-in.) fiberboard was the most frequently used thickness; as a component of a composite insulation, it is applied over foam insulation for mechanical protection.

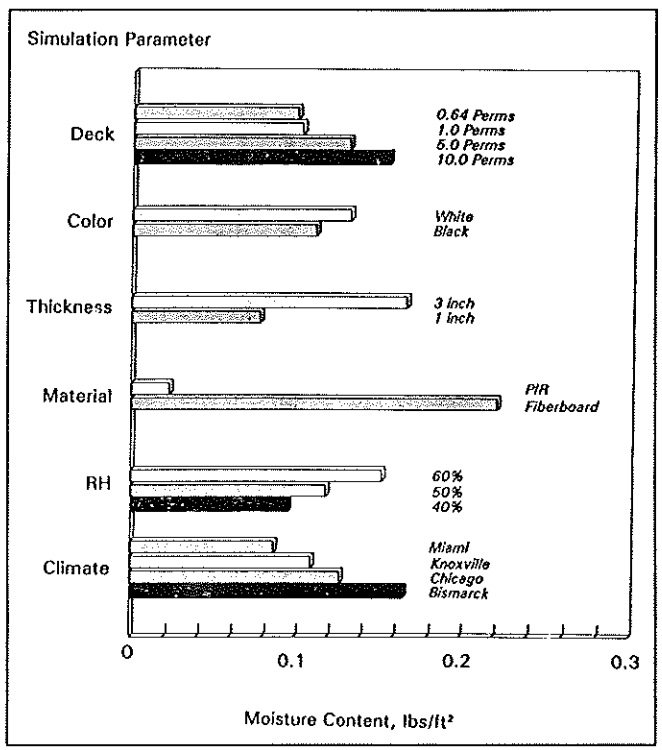

Figure 3 *The average moisture contents of the roof system at the end of the simulated year as a function of simulation parameter. Each result represents the average of all simulations (excluding the composite roof system) that included the specified simulation parameter.*

Only three composite simulations yielded condensation under the membrane (Table 2). Those three simulations were for the Bismarck climate and included a 60% relative humidity interior and a relatively permeable deck. In addition, the composite roof system reduced the moisture content of the overall roof system. The average moisture content of the composite roof systems was only 67% of the monolithic roof insulation systems if only the 76-mm (3-in.) insulation simulations are compared. Except for the harshest combination of environmental and roof component combinations, all composite roof systems satisfy requirement 2. The author anticipates that increasing the PIR thickness for the failed simulations would yield results that would satisfy requirement 2; the increased water vapor resistance will limit the level of moisture that the upper fiberboard would need to absorb.

Requirement 3: Does Water Condense on the Deck After a Leak?

If water condenses on the upper surface of a nonmonolithic (e.g., metal) deck, the water would flow to an opening in the deck and drip into the building interior. As described in an earlier section, the author introduced a leak into the roofing system (by increasing the moisture content of the uppermost insulation layer) and monitored how this moisture redistributed during the course of the simulated year. To meet requirement 3, the moisture content of the insulation layer in direct contact with the deck must remain below saturation for the entire simulation. Those results also are summarized in Table 2, where a shaded box is used to indicate the simulations where condensation occurred on the upper deck surface.

The Miami and Knoxville simulations yielded similar results. For both climates, there were no simulations with fiberboard insulation that failed requirement 3. When PIR is substituted for the fiberboard, 22 and 24 simulations for Miami and Knoxville, respectively, had condensation occurring. The critical variable that controls this condensation is the deck permeance; the two least permeable deck values modeled are part of all the simulations that fail requirement 3.

For Chicago, there are 9 fiberboard and 31 PIR simulations that show condensation on the deck. The fiberboard failures are limited to 25 mm (1 in.) thick insulation layers and appear to be strongly influenced by the interior relative humidity. In addition to the 24 PIR simulations that failed to satisfy requirement 3 in the Knoxville climate, 7 additional PIR simulations indicate that condensation occurs on the deck. These additional simulations primarily are limited to the thinner insulation layer and to the next to the lowest level of deck permeance that the author modeled.

Using the Bismarck climate, condensation on the upper surface of the deck occurs in only three additional simulations; these simulations include 25-mm (1-in.) fiberboard insulation and the higher levels of interior relative humidity and deck permeance.

The author also modeled the composite roof system to determine if it would preclude the onset of condensation on the upper surface of the deck. Again, the author limited these simulations to a 76-mm (3-in.) overall insulation layer thickness. The author found that none of the simulations performed on the composite insulation system indicated that condensation occurred on the deck.

Requirement 6: How Quickly Does the Roof Dry After a Leak?

There are different methods that can be employed to address how quickly a roof system dries out after a leak. The definition of a dry roof plays a role in how the author assesses the time required to dry. The author proposes two alternatives:

— A roof can be considered "dry" when there is no liquid present in the roof system. From a modeling perspective, the author could address requirement 6 by measuring how much time is required to reduce the relative humidity in each layer of the roof system to less than 100%. In this analysis, the author simply monitors the relative humidity of each layer of the roofing system on a monthly basis until all layers have a relative humidity of less than 100%.

— A roof can be considered "dry" when all of the water that has entered a roof system because of the leak has been removed. To determine if this interpretation of requirement 6 is satisfied, the author monitors the total roof system moisture content until it is at the same level as the preleak simulation at any given point in time. This analysis is difficult to perform because it requires a continuous comparison of two separate simulations. For the purpose of this paper, the author simplified this comparison to how much of the original leak water had been removed by the end of the one-year simulation. The comparison generates results that suggest relative drying rates.

A summary of the data to test the first alternative definition of drying is presented in Figure 4. The author reviewed the monthly relative humidity data for each insulation layer and computed the minimum time required to drop the relative humidity of all the insulation layers below 100%. The overall average for all of the simulations with monolithic insulations is 5½ months. The parameters that have the greatest impact on time are climate (2½ and 8½ months for Miami and Bismarck, respectively) and insulation type (3½ and 7½ months for fiberboard and PIR, respectively). The climate impacts

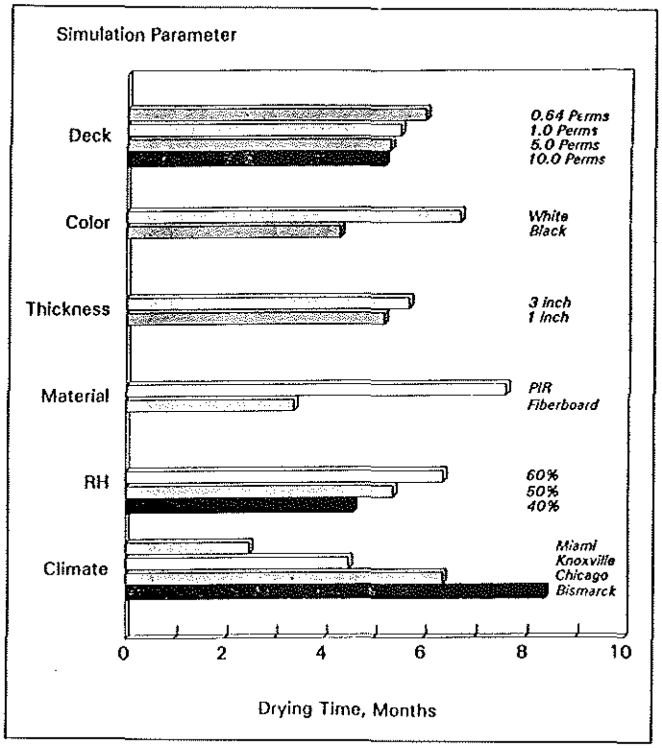

Figure 4 *The average times required for the roof system to dry until no water is present in any of the insulation layers. Simulations were initiated in January; starting simulations at a different time would appreciably affect the results. See text for a more complete discussion.*

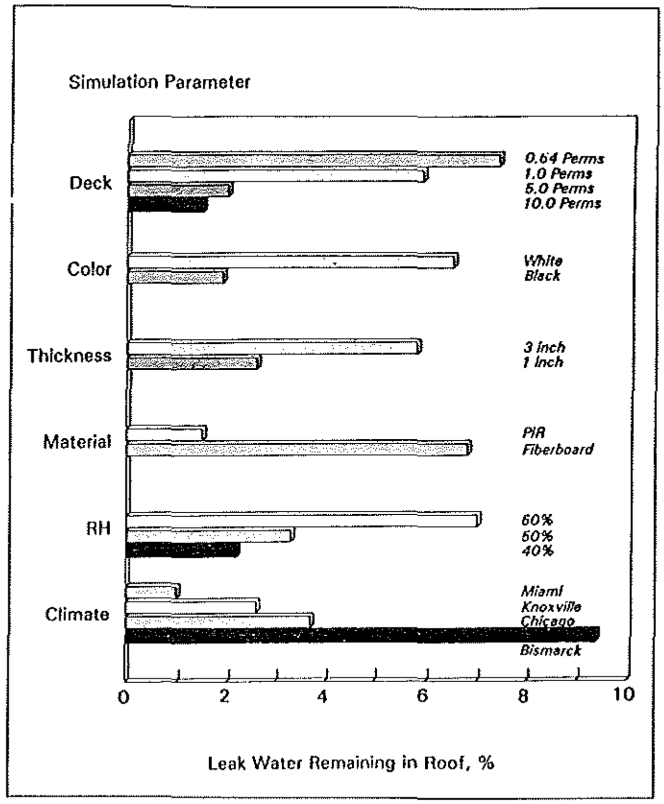

Figure 5 *The average amount of water that has leaked into the roof system that remains in the roof after a one-year period, expressed as a percent of the amount of leak water.*

the drying time in two ways: the length of the winter uptake season and the effect that ambient temperature and solar radiation have on the exterior surface of the roof system. Because the simulations start in January, no drying occurs until the winter uptake season is completed. For Miami, there is virtually no delay in the onset of drying, while drying in Bismarck does not begin until April. Insulation permeance is the material property that controls the drying time; the more permeable fiberboard allows the water vapor to diffuse to the deck more rapidly.

For the composite insulation system, the overall average for all of the simulations is 3½ months. As with the monolithic insulations, climate had the greatest impact on the drying time, ranging from 1 month for Miami to 5¼ months for Bismarck. The increased moisture capacitance of the external layers in the composite insulation system, coupled with the somewhat increased overall permeance (compared to PIR), allows the roof to dry more rapidly.

The second alternative definition of drying time compares how much of the leak water is retained in the roof system after a full year of simulation. The results on the monolithic insulation simulations are summarized in Figure 5. On average, only 4.2% of the water introduced into the top insulation layer of the roof system remains. The author found that all of the parameters that were modeled have a significant impact on the amount of water retained. The variation in results as a function of climate, interior relative humidity, insulation type, insulation thickness, membrane color, and deck permeance ranges by factors of 9, 3, 4.5, 2, 4.5, and 5, respectively.

The composite roof system once again slightly outperformed the monolithic roofing systems. The average overall amount of retained water was 4.0% (compared to 5.8% for the 3-in. monolithic insulation roof systems). Results for the composite systems also are sensitive to all of the parameters that were modeled. The variation in results as a function of climate, interior relative humidity, membrane color, and deck permeance ranges by factors of 10, 3, 6, and 3.5, respectively.

CONCLUSIONS

As part of this program to develop guidelines for designing self-drying roofing systems, the author has developed a list of "requirements" for self-drying roofs, identified the environmental conditions and roof system properties that impact them, and tested these requirements against the results of more than 1,500 computer simulations performed on a validated one-dimensional heat and mass transfer model. Highlights of the initial findings are as follows.

1. There are six requirements that a self-drying roof must satisfy: (a) in the absence of leaks, the moisture content of the roof system must not increase yearly; (b) the winter uptake of moisture must be controlled to preclude the saturation of the insulation layer in contact with the membrane; (c) the roof system must prevent minor failures in the membrane to lead to dripping into the building interior; (d) the roof system must contain some means of controlling moisture transport by convection; (e) water leaking into the roof system must not flow unimpeded through gaps and openings in the insulation; and (f) the roof system must dry as quickly as possible.
2. The first requirement that stipulates that the moisture content of the roof system cannot increase yearly is satisfied for all of the environmental conditions and roof system properties that were simulated. The simulations include environmental conditions that cover the continental United States and include interior relative humidity levels up to 60%. The author found that the overall rate of vapor diffusion into a roofing system is dependent on the roof construction and cannot be specified by simply studying the environmental conditions.
3. An extremely conservative approach has been taken to address requirement 2, the limitation of winter uptake. The author has chosen to limit winter uptake by requiring that the uppermost insulation layer does not saturate. The author found that approximately half of the simulations using monolithic insulation layers (0%, 45%, 72%, and 78% for Miami, Knoxville, Chicago, and Bismarck, respectively) fail this requirement. While all of the parameters that the author evaluated had some impact, it was found that insulation absorptance was the most critical.
4. The author theorized that an insulation that had the combined properties of high absorptance and low permeance might be ideal to prevent condensation under the membrane. Because this material does not presently exist, the author created a composite insulation system to approximate these requirements. Testing this system against requirement 2, the author found that it significantly reduced the number of simulations that exhibited condensation under the membrane; only 3% of the simulations, all with a Bismarck climate, failed to satisfy requirement 2.
5. Requirement 3 requires that condensation does not occur on the deck after the roof has leaked. Approximately one-third of the simulations failed this requirement. Again, the key parameter that controls condensation is the absorptance of the insulation layer; only 16% of the failures were with simulations that contained fiberboard insulation. The composite roof system was able to prevent condensation on the deck for all of the simulations that were performed.
6. Drying times are difficult to quantify because they vary with the timing of the leak and the definition of a "dry" roof. The author used a conservative estimate by initiating the leak early in the winter uptake season. Two alternative definitions of "dry" were used. When employing the procedure that defines "dry" as free from saturation, the author found that climate and insulation type (permeance, in this case) dramatically impacts the results.
7. The author has produced a data base of results that represents a large percentage of roofing systems presently being constructed and the environmental conditions for typical buildings in the continental United States. With this information, the author will develop empirical relations that will enable predictions of whether or not roofing systems satisfy the self-drying roof requirements.

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