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, the threat of structural decay, and the 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.

The requirements of this type of roof system are described. 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 modelling is used to demonstrate the effectiveness of the design. The impact of deck and insulation permeance, climate, leaks, and wintertime water uptake are simulated. A database of simulations is qualitatively described; this database 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, we have 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

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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 appreciably reduce the annually averaged cost of roofing and the amount of roofing debris generated.

In the early 1970s, Robinson and Powell (1971) at the National Institute of Standards and Technology conducted a comprehensive study on the effects of moisture on roof assemblies. They stated that "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 that, at that time, the theoretical basis for understanding combined heat and mass transfer processes was not sufficiently developed and that, 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 twenty-nine computer programs that are capable of analyzing heat and mass transfer. These tools can now 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, we will outline the characteristics that a self-drying roof must possess and, using a heat and mass computer model, test several typical roofing systems to determine under what conditions they meet these requirements. We also will describe 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 comprised of materials that do not rapidly degrade mechanically in the presence of water. The specific requirements of a self-drying roof are:

1) A self-drying roof cannot be used in a climate where the average yearly moisture content increases with time. If the combination of the local climate and the building interior conditions create 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 since 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 are not exceeded. By moisture limit, we mean 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 is still not available. Without it, we choose to conservatively limit the winter uptake so that condensation under the membrane is not allowed to occur.

3) When the roofing system eventually leaks, a self-drying roofing system must passively prevent water from dripping into the building interior. This criteria 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 travelling through the roofing system by convection; a vapor-tight monolithic deck or an air barrier shall 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 all of the above 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 are prohibited because downward drying is all but prevented.

A drawback of Requirement 3 is that leakage into the building interior has traditionally 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. Since 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 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. We assume that
these additions satisfy Requirements 4 and 5; our remaining task is to satisfy the other four basic requirements. They pertain to the effects of water vapor diffusion and are efficiently addressed by computer modelling.

**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? We used a combined heat and mass transfer model to address this question. Rode (1990), Rode (1991), Desjarlais (1993a), Desjarlais (1993b), and Kyle (1994) have described, validated, and used the model on low-slope roofing applications.

We tried to identify all of the important parameters that would impact the performance of a self-drying roof and include these as variables in our simulations. The outside influences and the roof system properties that we identified are listed in Table 1.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Simulation Values</th>
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<tbody>
<tr>
<td><strong>Environmental Conditions</strong></td>
<td></td>
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<tr>
<td>Climate</td>
<td>Bismarck, Chicago, Knoxville, and Miami</td>
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<tr>
<td>Building Interior</td>
<td>40, 50, and 60% Relative Humidity</td>
</tr>
<tr>
<td><strong>Roof System Properties</strong></td>
<td></td>
</tr>
<tr>
<td>Insulation Type</td>
<td>Fiberboard, Polyisocyanurate, and Composite</td>
</tr>
<tr>
<td>Insulation Permeance</td>
<td>High (Fiberboard) and Low (Polyisocyanurate)</td>
</tr>
<tr>
<td>Insulation Absorptance</td>
<td>High (Fiberboard) and Low (Polyisocyanurate)</td>
</tr>
<tr>
<td>Insulation Thickness</td>
<td>25 and 76 mm (1 and 3 inches)</td>
</tr>
<tr>
<td>Membrane Solar Absorptance</td>
<td>0.1 (Black) and 0.7 (White)</td>
</tr>
<tr>
<td>Deck Permeance</td>
<td>36, 57, 290, and 570 metric perms (0.64, 1.0, 5.0, and 10.0 perms)</td>
</tr>
</tbody>
</table>

*Table 1* The environmental conditions and roof system properties that were included as variables in our simulations. Each variable impacts the moisture transport in a roof system.
Environmental conditions were included in our list of parameters because they impact the vapor pressure drives experienced by the roof. The climates of Bismarck (Heating Degree Days or HDD \(65^\circ\text{F base}\) = 8992), Chicago (HDD = 6151), Knoxville (HDD = 3818), and Miami (HDD = 185) were selected because they represent the range of climates that exist in the continental U.S. (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 \((68^\circ\text{F})\).

The insulation materials in the roofing system play a complex part in the transport of water vapor. The rate that the vapor transfers through the insulation is controlled by the insulation’s permeance; their absorptance (or hygroscopicity) dictates what level of water vapor is required for condensation to occur while their thermal resistance (which is a function of the material type and its thickness) affect the temperature distribution through the roofing system. When considering traditional roofing insulations, the material’s key moisture properties can be classified in three categories. One group of insulations are hygroscopic and highly permeable and consists of the organic roof insulations such as fiberboard and perlite. A second group of roof insulations has low permeance and are non-hygroscopic; this category is made up of all of the closed cell foam products currently in use. The final category consists of products that are permeable and non-hygroscopic with fiberglass roof insulation being the only material in this category. Since there is not a significant amount of fiberglass roof insulation being used in new construction (NRCA 1993), we chose fiberboard and polyisocyanurate foam as our representatives from the two widely used categories of roofing insulation. We expect 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 1994).

The rates of moisture migration into and out of roofing systems are affected by the permeance of the deck. Metal decks, that presently dominate the market, have permeances that have been estimated to range between 36 metric perms or 0.64 perms (Kyle 1994) to 57 metric perms or 1.0 perms (Sheahan 1989). 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.

For modelling purposes, the roofing system was divided into a series of layers. A schematic of the simulated roof is shown in Figure 1. 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 modelled 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.

For each of the four climates, a total of 120 roofing configurations were analyzed. Each roofing configuration was simulated three times. An initial 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 twenty-four months (January, Year 1 to December, Year 2). December, Year 2 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 require 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 2 results from the first simulation were used as initial conditions and we performed an additional one-year simulation. To determine if the moisture content of the roof increased, we compared the moisture contents computed for the final month of the simulation with the initial moisture contents of this simulation. This comparison yields a quantitative assessment of whether any additional water resides in the roof system at the end of the simulated year. To determine if condensation occurs under the membrane, we 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, we assumed that a roof leak occurred on 1 January 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/m² (0.35 lbs/ft²) of water to the roof system. We added this amount of water to the December, Year 2 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, we examined the results for the bottom thin layer of insulation and totalled 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, we performed two separate analyses. First, we examined the monthly relative humidity of all of the layers in the roofing system and identified the first month when all of 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, we again compared the final month’s computed
moisture content for the total roof system to the initial conditions after the leak; their difference indicates quantitatively how much water was dissipated to the building interior.

Does the amount of water that we added to the roof system accurately represent a real leak? We wrestled with this question for some time. The amount of water added is equivalent to a 0.8 mm (0.03-inch) 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, our addition was uniformly distributed over the entire surface area of the roof. If the guidelines for the design of self-drying roofs are followed, we recommend 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 we have modelled can be considered as appreciable.

We have noted that the time required to dry is a function of when a leak occurs. All four climates that we have modelled 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 of time. By selecting January for the leak to occur, the roof systems 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.

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 comprised of a 76 mm (3-inch) 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 whose interior is maintained at 60% relative humidity. We are testing this roof system for conformance with Requirement 2, condensation under the membrane during winter uptake. The symbols (□, +, ◊, and △) 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 lbs/ft² (to convert to kg/m², multiply by 4.88).

At the beginning of the simulation (1 January), the moisture content of the top insulation layer increases dramatically, peaking approximately on Day 65 (6 March) and then decreases rapidly until Day
135 (15 May) where it stabilizes for the duration of the summer. On approximately Day 285 (12 October), the moisture content begins to rise and continues this process through the remainder of the calendar year. The saturation moisture content for fiberboard is 36.5 weight percent. Therefore, this simulation fails to satisfy Requirement 2 because between Days 29 and 83 (29 January and 24 March), the moisture content of the top insulation is above saturation and water has condensed below the membrane.

The bottom insulation undergoes a dramatically different moisture content cycle. The moisture content of the bottom insulation layer slowly increases throughout the winter and spring seasons and, around Day 150 (30 May), surpasses the moisture content level of the top insulation layer. This condition continues until approximately Day 260 (17 September) when the moisture driving forces have reversed and water vapor is being driven into the roof system. At this time, the moisture content of the bottom insulation layer is decreasing and is surpassed by the upper layers.

Note that the total moisture content of the roof has not appreciably increased. On Days 0 and 365, the total roof system moisture contents are 1.81 and 1.83 Kg/m² (0.370 and 0.375 lbs/ft²) respectively. By updating the initial boundary conditions and rerunning this simulation, we found even closer agreement between the initial and final moisture content; 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 we performed, we discovered that there were no instances where there was a buildup of water in the roofing assemblies. Even in the simulations where we 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. We 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 percent). Additional simulations would eventually eliminate any differences.

These data are in conflict with a previous study (Tobiasson 1986) where it was determined that certain portions of the continental U.S. climate created net vapor drives into the roofing system. In these locations, moisture levels in the roof would increase 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 (1994) reported that the exterior vapor pressure is roughly independent of ambient temperature. We 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 our results, the recommendation for using a vapor retarder in a roof system to prevent moisture buildup in the roof system is unwarranted for any continental U.S. climate (given our modelling 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 strongly influenced by climate, insulation material, and deck permeance. A summary of these results is depicted 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 inch and "3" for 76 mm or 3 inches); 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 "0" indicates that condensation occurred under the membrane during the simulation; "--" indicates that the simulation was not performed.

Our 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. Since 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 increases to 36 (out of 48 simulations). With the exception of the simulations with the lowest interior relative humidity and deck permeance, all the simulations yield 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 exhibit condensation. As the winter climate becomes more severe, simulations with lower levels of deck permeance and lower interior relative humidity begin to exhibit condensation.
A summary of the total moisture content of the simulated roof systems at the end of the simulated year (December) is depicted in Figure 3. The moisture content of the roof system is most 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 to 76 mm (1 to 3 inches) 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. What does appear surprising is the fact that, when analyzing the fiberboard and PIR simulations separately, the impact of deck permeance is very 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.

Probably the most surprising result that we obtained from this family of simulations was the onset of condensation was insensitive to moisture content. Based on our simulations, the key parameter that controls the onset of condensation is the absorptance of the insulation material. We postulated that a composite insulation material comprised of a vapor resistive core (PIR) and an absorptive outer layer (fiberboard) could reduce the probability of condensation. We have demonstrated that PIR significantly reduces the total roofing system moisture content. 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.

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

Only three composite simulations yield condensation under the membrane (see Table 2). These three simulations are for the Bismarck climate and include a 60% relative humidity interior and a relatively permeable deck. In addition, the composite roof system reduced the overall roof system moisture content. The average moisture content of the composite roof systems was only 67% of the monolithic roof insulation systems if only the 76 mm (3 inch) insulation simulations are compared. Except for the harshest combination of environmental and roof component combinations, all composite
roof systems satisfy Requirement 2. We anticipate 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 non-monolithic (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, we 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. These results are also 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 yield very similar results. For both climates, there are 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 modelled 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-inch) thick insulation layers and appear to be most strongly influenced by the interior relative humidity. In addition to the 24 PIR simulations that failed to satisfy Requirement 3 in the Knoxville climate, seven additional PIR simulations indicate that condensation occurs on the deck. These additional simulations are primarily limited to the thinner insulation layer and to the next to the lowest level of deck permeance that we modelled.

Using the Bismarck climate, condensation on the upper surface of the deck occurs in only 3 additional simulations; these simulations include 25 mm (1 inch) fiberboard insulation and the higher levels of interior relative humidity and deck permeance.

We also modelled our composite roof system to determine if it would preclude the onset of condensation on the upper surface of the deck. Again, we limited these simulations to just a 76 mm (3 inch) overall insulation layer thickness. We found that none of the simulations performed on the composite insulation system indicated that condensation occurred on the deck.
<table>
<thead>
<tr>
<th>CODE</th>
<th>WFB</th>
<th>PIR</th>
<th>COMP</th>
<th>WFB</th>
<th>PIR</th>
<th>COMP</th>
<th>WFB</th>
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**Table 2** Summary of results assessing the satisfaction of Requirements 2 (is there condensation under the membrane?) and 3 (does water condense on the deck?) of a self-drying roof. A "•" 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.
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 what is a dry roof plays a role in how we assess the time required to dry. We propose two alternatives:

1) A roof can be considered "dry" when there is no liquid present in the roof system. From a modelling perspective, we could address Requirement 6 by measuring how much time is required to reduce the relative humidity in each layer of the roof system below 100%. In this analysis, we simply monitor the relative humidity of each layer of the roofing system on a monthly basis until all layers have a relative humidity below 100%.

2) 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, we monitor 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, we simplified this comparison to how much of the original leak water has been removed by the end of the one-year simulation. Our comparison generates results that suggest relative drying rates.

A summary of our data to test the first alternate definition of drying is presented in Figure 4. We 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 impact the time most appreciably 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 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. Since our 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 5¾ 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.
Our second alternate definition of drying time compares how much of the leak water is retained in the roof system after a full year of simulation. Our 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. We find that all of the parameters that we modelled 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 range 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 inch monolithic insulation roof systems). Results for the composite systems also are sensitive to all of the parameters that we modelled. The variation in results as a function of climate, interior relative humidity, membrane color, and deck permeance range by factors of 10, 3, 6, and 3.5, respectively.

CONCLUSIONS

As part of our program to develop guidelines for designing self-drying roofing systems, we have 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 over 1500 computer simulations performed on a validated one-dimensional heat and mass transfer model. Highlights of our initial findings are:

1) There are six requirements that a self-drying roof must satisfy: (1) in the absence of leaks, the moisture content of the roof system must not increase yearly, (2) the winter uptake of moisture must be controlled to preclude the saturation of the insulation layer in contact with the membrane, (3) the roof system must prevent minor failures in the membrane to lead to dripping into the building interior, (4) the roof system must contain some means of controlling moisture transport by convection, (5) water leaking into the roof system must not flow unimpeded through gaps and openings in the insulation, and (6) 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 we simulated. Our simulations include environmental conditions that cover the continental U.S. and include interior relative humidity levels up to 60%. We find 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. We have chosen to limit winter uptake by requiring that the uppermost insulation
layer does not saturate. We find that approximately half of our 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 we evaluated had some impact, we found that insulation absorptance was the most critical.

4) We theorized that an insulation that had the combined properties of high absorptance and low permeance might be ideal to prevent condensation under the membrane. Since this material does not presently exist, we created a composite insulation system to approximate these requirements. Testing this system against Requirement 2, we found that we 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 a third of our simulations fail 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. Our composite roof system was able to prevent condensation on the deck for all of the simulations that we performed.

6) Drying times are difficult to quantify because they vary with the timing of the leak and the definition of a "dry" roof. We used a conservative estimate by initiating the leak early in the winter uptake season. We used two alternate definitions of "dry." When we employ the procedure that defines "dry" as free from saturation, we find that climate and insulation type (permeance, in this case) most dramatically impact the results.

7) We have produced a database of results that represents a large percentage of roofing systems presently being constructed and the environmental conditions for typical buildings in the continental U.S. With this information, we will develop empirical relations that will enable us to predict whether or not roofing systems satisfy the self-drying roof requirements.

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REFERENCES


FIGURE CAPTIONS

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.

2) An example of a typical simulation output. The simulation depicted in this figure is for a roof system comprised of a 76 mm (3-inch) 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 whose interior is maintained at 60% relative humidity. See text for a description of the results.

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.

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.

5) The average amounts 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.
Figure 4

Simulation Parameter

Deck
- 0.64 Perms
- 1.0 Perms
- 5.0 Perms
- 10.0 Perms

Color
- White
- Black

Thickness
- 3 inch
- 1 inch

Material
- PIR Fiberboard

RH
- 60%
- 50%
- 40%

Climate
- Miami
- Knoxville
- Chicago
- Bismarck

Drying Time, Months
Figure 5

Simulation Parameter

- Deck:
  - 0.64 Perms
  - 1.0 Perms
  - 5.0 Perms
  - 10.0 Perms

- Color:
  - White
  - Black

- Thickness:
  - 3 inch
  - 1 inch

- Material:
  - PIR
  - Fiberboard

- RH:
  - 60%
  - 50%
  - 40%

- Climate:
  - Miami
  - Knoxville
  - Chicago
  - Bismarck

Leak Water Remaining in Roof, %