# Self-Drying Roofs

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The concept of a self-drying roof has been discussed, tested, and modeled since the early 1960s. The concept is fairly simple: Moisture originating from interior water vapor collects over the colder winter months, when the vapor drive is from the inside to the outside, and can dissipate during the warm/hot summer months when the vapor drive reverses, pushing the moisture down into the building interior and drying the insulation layer. Liquid water can also enter the roof assembly as a result of minor leaks in the roof cover.

The concept was first discussed during a period when insulation layers were thin and R-values were typically in the range of three to eight.[1] The typical insulations of the day were perlite, wood fiberboard, and semirigid fiberglass. Most roof covers were multi-ply, built-up assemblies with an extremely low perm rating—typically 0.01 perms. Little or no diffusion of vapor would take place through the roof cover, resulting in the only path of moisture escape being down into the building interior. A possible direct path could be an open deck joint at the roof-to-wall intersection and an unsealed base flashing.

By the early 1970s, the global energy crisis forced the design and building industry to rethink energy conservation and insulation. This culminated in code mandates to reduce energy consumption by increasing insulation on all planes of the structure. These new demands resulted in innovative insulation materials, manufactured primarily from chemical foams, such as polystyrene, polyurethane, and, eventually in the late 1970s, polyisocyanurate, which is still the primary rigid board stock used today. A number of legacy materials, such as mineral wool, were reformulated and modified as board stock for use in both roofing and exterior wall assemblies. The increase in thickness, change in permeance, and the increase in R-value changed the discussion about self-drying roofs.

Over the years, more variables have entered the discussion, such as light-colored roof covers (typically referred to a "cool roofs"), green roofs, air barriers designed to minimize moisture transport and reduce condensation, and single-ply roof covers that allow for some permeance through the roof cover.[2]

## HISTORY

In the mid-1960s, discussion began about the accumulation of moisture in the insulation layer due to interior moisture defusing through the roof deck into the roof insulation, resulting in wetting of the moisture-sensitive insulating materials such as perlite, fiberglass, and wood fiberboard. Water vapor, which can condensate at dew-point temperatures, becomes resident in the insulation layer, eventually degrading the insulation's thermal performance. Warm, moist interior air that defuses through ceilings and roof deck elements, as well as through breaches in impermeable barriers, typically condenses within the rigid insulation layer. Of course, the extent of the vapor drive and quantity of vapor turning to bulk water is dependent on numerous factors, such as:

- Temperature differential from inside to outside;
- Humidity level within the building interior;
- Thickness and type of insulation;
- Materials forming the ceiling and roof deck;
- HVAC system in use; and
- The use of the space between the ceiling grid and roof deck as a return air plenum.

Construction in the 1960s and early 1970s rarely detailed the roof deck as a sealed structure; warm, moist interior air can easily transfer from the building interior into the compact roof assembly[3] at perimeters, penetrations, and deck joints where gaps exist, especially in wood and steel decks. Unless a vapor barrier was installed and effectively sealed the roof deck plane, the insulation layer was subject to both temperature changes and airflow, resulting in a buildup of moisture within the insulation layer.

In the early editions of the *National Roofing Contractors Association Roofing Manual* (*NRCA Roofing Manual*), the vapor barrier/retarder section clearly stated it was the responsibility of the designer of record to determine whether a vapor barrier was needed.[4] Two options were presented: Add a vapor barrier to the roof assembly to prevent moisture entry from the indoors, or allow the roof to self-dry, accumulating moisture in the winter and releasing it in the summer.

> *The self-drying roof concept offers an alternative to vapor retarders in moderately humid areas. This concept postulates that a roof system may be designed to:*
>
> - *Accept a tolerable amount of winter-accumulated moisture;*
> - *Dissipate this moisture during the spring and summer months when solar radiation heats the roof surface;*
> - *Drive the moisture downward into the building interior, from which it is then vented to the outdoors....*
>
> *...To qualify as a self-drying roof, the system must dissipate enough moisture during the summer drying season to:*
>
> - *Reestablish its equilibrium moisture content (i.e., to show no trend toward long-term accumulation of moisture); and*
> - *Suffer no more than 40 percent average annual loss in thermal resistance.*[5]

A rule of thumb was suggested in the 1983 *NRCA Manual*, stating that a vapor barrier should be considered when the average January temperature was below 40°F.[6] In subsequent editions, more data were provided explaining the science of calculating dew point and evaluating the need for a vapor barrier.[7]

Multiple evaluations of condensation under single-ply roof membranes were carried out in the mid-1980s, gathering field data and computer modeling primarily addressing concerns about the buildup of condensation under EPDM membrane roofs.[8,9]

In the late 1970s, Wayne Tobiasson, attached to the U.S. Army Corps of Engineers Cold Regions Research and Engineering Laboratory (CRREL), began research and evaluation of methods of non-destructive testing and drying of wet insulation caused primarily by breaches in the roof cover. Evaluations and experimentation were carried out with nuclear, capacitance, and infrared equipment to roofs in service. In a 1991 paper, Tobiasson and his coauthors, Alan Greatorex and Doris Van Pelt, followed up on a paper published 12 years earlier with the objective of establishing the effect of thermally induced vapor pressure gradients on insulation materials installed under roof covers.[10] The conclusions of the paper were that all insulations used in roofing, when subjected to thermally induced vapor pressure gradients, will get wet; moisture reduces the insulating value of the insulation, and facers needed to be removed from tested samples to properly determine moisture content. The testing developed a pass/fail criterion, listing the moisture content at which the thermal ratio of the listed insulations equals 80 percent. Tobiasson and his coauthors further conclude:

> *We have found that this is a convenient and useful pass-fail criterion for existing roofing systems. At higher moisture contents, the insulation is considered wet and unacceptable.*[11]

A sketch of the test box created for the testing (*Figure 1*), taken from the 1991 paper, shows the temperature and humidity variation developed for the testing.

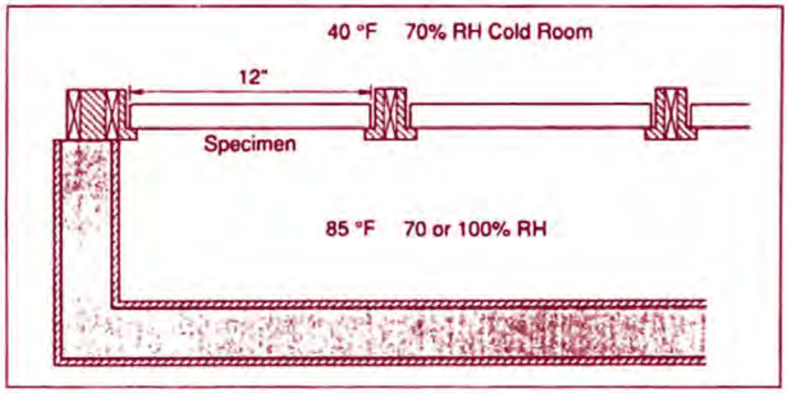


***Figure 1 Sketch of specimens in wetting apparatus.***

*Figure 1 – From Tobiasson, Greatorex, and Van Pelt paper, "New Wetting Curves for Common Roof Insulations."*

In short, Tobiasson's gradients for 15 insulation types developed a "go/no go" criterion to either leave insulation in place and dry it out or remove it because it was too wet and could not be restored to service. A key to these data is the ability to dry out the insulation, which became a focus of Tobiasson and his team in future years.

In a 1983 ASTM article, Tobiasson discussed the ability for insulated, compact roofs (*Figure 2*) to dry out. A portion of his comments included the following:

> *The answer to this question depends on whether or not there is a vapor retarder in the roofing system. If no vapor retarder is present, the wet area will probably dry by giving up water vapor to the building below, since a strong downward vapor drive exists in most wet roofing systems during all or most of the year. This*

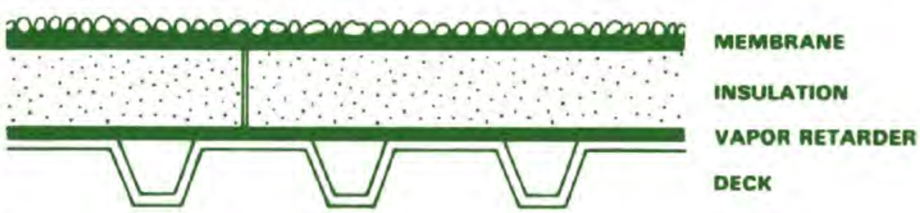


**FIG. 1—*Cross section of a compact roofing system.***

*Figure 2 – From Tobiasson, Korhonen, Coutermarsh, and Greatorex paper, "Can Wet Roof Insulation Be Dried Out?"*

> *promotes drying into the building. Consequently, there is no need to provide external venting features for a compact roofing system that is capable of drying downward. In fact, venting such roofs may do more harm than good, since air leakage paths are created.*[12]

In 1986, Rick Quirouette published an article based on a presentation delivered at the Building Science Insight '86 symposium, which was titled "An Air Barrier for the Building Envelope."[13]

Quirouette introduces the principal functions of an air barrier as a membrane that both prevents the infiltration of outdoor air into a building and the exfiltration of indoor air to the outside. If an air barrier is to perform its intended role, it must meet a number of requirements: continuity, structural integrity, air impermeability, and durability. "An air barrier may consist of a single material or of two or more materials which when assembled together make up an air-impermeable, structurally adequate barrier."[14]

He goes on to state:

> *Continuity means more than being without holes. Because the component that performs the role of the air barrier changes from the wall to the window to the roof, continuity means that all of these assemblies must be connected together so as to ensure that there is no break in the airtightness of the envelope.*[15]

Quirouette states in the close of the paper that air barriers are not a new concept as a separate requirement for the envelope, but concedes it will require an adjustment in the way walls are designed and built and in the types of materials used.

> *It may be unfair to blame the material supplier or the builder; it may be equally unfair to blame the designer. Did he or she have access to all the building science information needed to make design decisions based on sound principles?*[16]

In the 1990s, a major study was carried out at Oak Ridge National Laboratory (ORNL) evaluating six low-slope roof assemblies in a climate simulator. The authors determined that an assembly built with a combination of polyisocyanurate sandwiched between two layers of wood fiberboard, over a slotted steel deck with no vapor retarder, dried faster than any of the other five assemblies.[17] The conclusions noted:

> *The self-drying roofs which had no vapor retarders at all, wetted faster at winter conditions than the systems with liquid-water-permeable but water-vapor-impermeable vapor barriers. However, maximum fiberboard moisture content remained safely below saturation levels in all systems after a month of average winter sunny days.*[18]

The conclusions go on to state:

> *Models of the self-drying roofs and the liquid-water-permeable vapor retarder systems*[19] *both show that a month of drying with average sunny Knoxville [TN] summer days is enough to dry out the average 8.0 lb. (2.9 kg) of water added to the 19.8-$ft^2$ (1.84-$m^2$) cross-sectional area and varying insulation thickness and density in these panels.*[20]

The authors note the water added to the top layers of insulation raised the moisture content of the top layer of wood fiberboard to well above 35 percent, and the wood fiberboard below the polyisocyanurate did not reach saturation after the full test cycle.

Smith A. Funk presented a paper in 1985 detailing the damage to built-up roof membrane installed over aggregate-based lightweight concrete and a method of relieving the roof deck of moisture (*Figure 3*). This method included the use of an impervious layer under the roof cover and drilling holes in the roof deck and lightweight concrete to force moisture out of the system using warm air.[21]

By 2012, the International Energy Conservation Code incorporated the requirements of air barriers into the building enclosure:

> *A continuous air barrier shall be provided throughout the building envelope.... Exception: Air barriers are not required in buildings located in Climate Zones 1, 2 and 3.*[22]

Computer modeling and field data collection in the early part of the millennium have clearly indicated air barriers were essential to reduce condensation in walls and roofs, minimize the loss of conditioned air within the building, and increase building energy efficiency. Thomas Taylor of GAF notes in a 2016 online article:

> *Most people would assume that low-slope roof membranes are air barriers. However, that's not the case, and it's very important to note that:*
> - *The air barrier is the system of materials that controls air leak-*

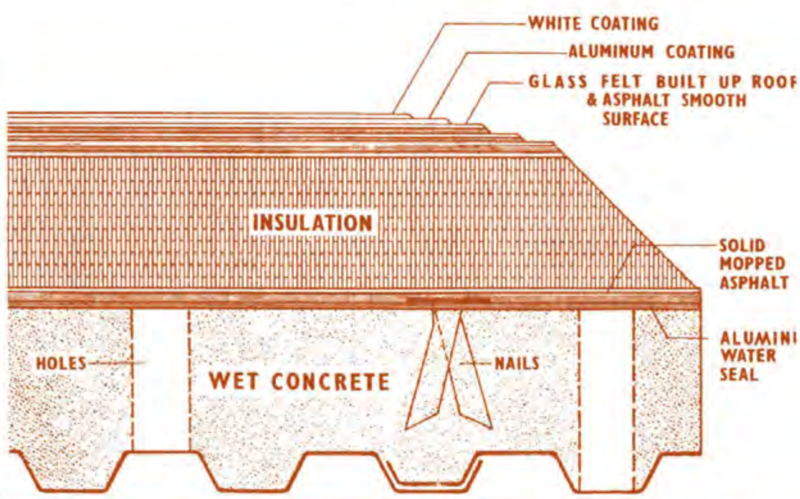


*Figure 6 Glass felt built-up roof*

*Figure 3 – From Funk paper, "Suggested Repair Specifications for Built-Up Roofs Over Wet Lightweight Concrete Decks."*

*age/convection heat flow through the building enclosure; and*

- *The air barrier is not one material but instead is an integrated system of many different materials/components."*[23]

Taylor goes on to state that roof membranes are very good at blocking airflow, but unless they are properly tied into the other parts of the building enclosure, the building will still leak air. He further states there are three ways to achieve compliance:

- *Use of International Energy Conservation Code (IECC)-approved decking materials that have shown an air permeance of < 0.004 cfm/$ft^2$ under a pressure differential of 0.3 in. of water;*[24]
- *Assemblies of materials and components (sealants, tapes etc.) that can be built and tested and proven to demonstrate air permeance of < 0.004 cfm/$ft^2$; and*
- *Employment of building air testing under ASTM E779.*[25]

Of course, the roof is only a component of the air barrier system. For continuity, the rooftop air barrier must be tied into the wall system's air barriers to form a continuous system. The roof air barrier cannot be considered on its own.

One of the IECC-approved air barriers is a fully adhered, built-up, modified, or single-ply roof material; however, the inclusion of all fully adhered systems has been contested by both the American Society of Heating, Refrigeration, and Air Conditioning Engineers (ASHRAE) and the NRCA.[26]

In 2015, "Roofs and Condensation: A Practical Approach for the Design Professional," was published by James Hoff, president of TEGNOS Research, Inc., for *Building Enclosure*.[27] The paper primarily discusses the internal forces at play within the single-ply roof system. The author concludes that condensation in all roofs is a relatively rare phenomenon that tends to occur only in the presence of one or more severe design conditions. These conditions include:

- Extremely cold external temperatures,
- Extremely high internal temperatures and humidity,
- Unusually low amounts of over-deck roof insulation, and/or
- Unusually high levels of air movement within the roof system.

Hoff moves from diffusion to air movement, referencing work carried out by Joseph Lstiburek in 2004 that demonstrated that air movement through a small square-inch hole in a 4- x 8-ft. gypsum panel may drive almost 100 times a much water vapor as would move through the same panel due to diffusion.[28] While the research was addressing walls, the same concepts can be attributed to the roof plane.

The Hoff paper concludes, among other things, that a vapor barrier may stop vapor from entering the system and condensing, but the installation comes at a price. If the roof experiences a leak, the water entering the roof will be trapped and unobserved, causing extensive damage to the roof. Additionally, Hoff concludes the concept of self-drying has been documented as a viable approach to evacuating water, from the referenced Oak Ridge study to the writing of C.W. Griffin and Richard Fricklas in their 2006 *Manual of Low-Slope Roof Systems*.

> *Self-drying roof systems use the sun and summer heat to evaporate moisture that may have accumulated in the roof due to condensation over winter. The external heating of the roof reverses the vapor drive and transfers the condensed moisture back into the building where it originated. The self-drying roof is not only an accidental discovery but also a sometimes-overlooked benefit for the roofing industry. Although under some conditions, roofs may experience moisture condensation in the winter, the dynamics of summer heat and sun help to mitigate any potential long-term damage from this winter condensation. However, the self-drying process may only be effective for roofs installed over vapor-permeable decks such as metal or wood, and only if a vapor retarder has not been installed as part of the roofing system.*[29]

With the development of (no-longer-available) MOIST modeling software[30] and subsequently developed WUFI® modeling software,[31] more data have been produced and combined with data collection from the field. WUFI is a collaborative product of ORNL and the Fraunhofer Institute for Building Physics and includes solar reflectance and reflectivity in the modeling input, allowing for the variation in performance of assemblies employing dark- and light-colored roof covers. Field data generated from a wide range of industry-recognized investigators have identified both design and installation flaws as the primary cause of water accumulation in light-colored roofs, initially suspected as the result of the lower surface temperatures resulting from a light-colored membrane.

In 2020, Rockford Boyer published an article titled "Theory of a Self-Drying Roof" in *Construction Canada*.[32] In the article, Boyer concludes:

- 60 to 70 percent of moisture-related roof issues are the result of poor construction methods and workmanship,
- 20 to 25 percent were caused by poor design, and
- The remaining 10 percent were due to material failure.

He further concludes that moisture ingress into the roof enclosure typically occurs through three conditions:

- Physical bulk water entry,
- Roofing material moisture content (construction moisture and through interior vapor diffusion), and
- Air leakage.

The article followed four physical models after simulation of 78 models using WUFI software. Two physical models were self-drying roofs with both black and white roof covers installed in Toronto. The undersides of the decks were ventilated to move moisture out from the underside of the deck. The black-surfaced roof cover dried in half the time when compared with the white roof cover. The author concluded the drying was effective when a single wetting event took place and noted that if several wetting events took place, the results would be different.

The remaining two physical models were in Edmonton, which is a much colder climate. The models included a smart vapor retarder[33] and no venting at the underside of the deck. The author reported that even with a black membrane, there was insufficient energy to diffuse the moisture to the interior, and further, the white roof cover "does not have adequate energy to move all of the moisture out of the system before the interior moist air reverses and diffuses back into the system (around mid-September)." The author concludes that he does not believe a self-drying roof with a white membrane "will be an acceptable approach" (in the colder environment).

After the 78 simulations, the author concludes the models prove the potential for a self-drying roof enclosure is suitable in almost every location, with several outliers in very cold climates. Note, the assemblies were created with "vapor-open" materials and utilized a steel deck that was demonstrated to have relatively high permeability due to joints, gaps, and screw holes.

In 2018, a paper by Jonathan Smegal, John Straube, and Christopher Schumacher, titled "Measured Drying Ability of Compact Low-Slope Roofs," was published in conjunction with the Canadian Building Envelope Technology Symposium.[34] The authors constructed three roof assemblies, all with two layers of 3-in. "stone wool" insulation, a two-ply modified-bitumen membrane roof cover, and metal decking. Panels 1 and 2 both had self-adhered air/vapor barriers but Panel 1 had the addition of a diffusion roof vent. Panel 3 had a smart vapor control retarder. The mock-ups were field-exposed in a test facility located in Waterloo, Ontario (Climate Zone 5-6).[35]

Water was introduced into the assemblies at specified rates and times. Moisture movement and diffusion were measured and recorded. The authors concluded:

> *Installation of the smart vapor retarder over the metal deck instead of a vapor-impermeable membrane demonstrated measurable improvement of drying ability. This enhanced drying could improve long-term durability and avoid moisture-related issues within the roofing assembly. The diffusion vent port design did little or nothing to improve performance in this field exposure test.*[36]

The authors further noted more extensive testing should be carried out with both stone wool and polyisocyanurate insulation. The conclusions from the limited testing focused on the greater durability of a roof assembly that could take in limited quantities of water and express the water through a natural drying process.

## LESSONS LEARNED

The discussion about the feasibility of self-drying roofs has been ongoing for more than 50 years. The concept, when first addressed, considered black roofs with low R-value insulation layers with primarily moisture-absorbing insulation materials. Air barriers were yet to be mandated and all vapor barriers were just that—vapor-impermeable. The science that identified the causes of condensation and the computer modeling capabilities were yet to come.

The issues of "poor construction" and "deficient design" are regularly raised with minimal guidance as to how to avoid these pitfalls. Virtually every learned paper identifies both design and construction as a major cause of moisture accumulation within a roof assembly.

Tobiasson and his team in their 1983 article acknowledged insulation could get wet from both external and internal factors and could dry out for re-use, provided the wetting was not extensive; and also acknowledged drying down was the easiest way to eliminate moisture. Area one-way vents became the focus of attention, attempting to dry up by flashing a vent into the roof cover. S.A. Funk tested out his theory of drying lightweight concrete in a number of school systems in Florida and developed for market a durable protective layer that shielded the roof cover from water damage from below.[37]

Roof system manufacturers developed products to better manage water within the roof assembly and water from below that could damage the compact roof. Some European manufacturers developed base layer materials to allow for the lateral movement of moisture below the insulated roof. Also, the use of vented base sheets became a common practice in the United States to separate old roofs from new and allow for lateral moisture movement.[38]

The impact of air flow through all elements of the building enclosure became a focus in the 1980s, with the recognition of its significant impact on moisture accumulation within walls and roofs. While much of the early research focused on exterior wall assemblies, the research and code-mandated changes in construction relate to roofs as much as to the four walls. These changes in construction methods (continuous air barriers and insulation) resulted in the additional step of field testing of completed work to determine performance.[39] This highlights one of the big differences between roofs and walls: Most walls are clad in discontinuous air-permeable systems with a secondary air and water barrier placed between the cladding and exterior sheathing. Low-sloped roofs are continuous weathertight barriers with multiple discontinuous layers below the roof cover and, in some cases, a second continuous layer that may be either a vapor/air barrier or an air barrier. The results of a successful air barrier test of the walls cannot simply be transferred to the performance of the roof cover as an air barrier.

It is a given that a white roof increases reflectivity and reduces the heat load of the insulation layer, but the change in reflectivity and emissivity changes how moisture moves within the assembly itself. This has been demonstrated in computer modeling, small-scale testing, and field analysis. It has been concluded by field data, such as those published by Phil Dregger[40] and Tom Hutchinson,[41] that deficient design and construction play a significant role where moisture accumulation occurs in cool roof assemblies.

We have also learned that even relatively small quantities of water within a roof system, from external or internal sources, can impact the wind resistance of the system by degrading the cellulose on the facers of polyisocyanurate core insulation. Both adhesive and cohesive failure of the paper facers reduces the uplift performance, resulting in warnings and internet conversations responding to blogs.[44,43] This is supported by a joint Single Ply Roofing Industry (SPRI)/ORNL study that concluded three out of ten roof assemblies had some level of moisture buildup under conditions that normally would not suggest the need for a vapor or air barrier. The primary impact is to the underlying insulation components and not necessarily the roof cover.[44]

New materials have entered the market that can play a significant role in the way roof assemblies are now designed—some of which can enhance the method and speed of drying compact assemblies. These include closed-cell foam, smart vapor retarders, self-adhered and partially adhered layers, and vapor-permeable self-adhered air barriers. As new products have been developed to meet an identified need, roof assemblies are tested with both dark and light roof covers to determine performance in varying climatic conditions. Some new materials, such as vacuum insulated panels,[45] which are very new to the market, are air- and water-impermeable except at joints. These panels will result in much thinner low-sloped roof, and eliminate the potential of water uptake into insulation, but they will challenge designers and installers with other issues, such as difficulty in sloping and cutting, as well as post-construction openings for new roof penetrations.

New materials have entered the market that can play a significant role in the way roof assemblies are now designed—some of which can enhance the method and speed of drying compact assemblies. These include closed-cell foam, smart vapor retarders, self-adhered and partially adhered layers, and vapor-permeable self-adhered air barriers.

While the inclusion of a vapor barrier will retard vapor flow into the roof assembly in colder climates, it also can trap incidental exterior water coming from minor leakage through the roof cover. Field data and modeling suggest that properly designed and installed roof systems only require a vapor barrier in the most extreme of climates where moisture cannot be dried out of the system during warmer months.[46] We must also consider the warnings about even minimal quantities of moisture buildup impacting paper-faced rigid insulation and possible reduction in wind uplift resistance.[47]

The 2018 Smegal, Straube, and Schumacher testing conclusions were that the assembly with a smart vapor barrier allowed "some moisture diffusion into the interior space, resulting in a drier assembly following the first winter."[48] Their reference assembly (vapor barrier on metal roof deck and vapor diffusion venting ports) showed the interior moisture dried slowly over 18 weeks. The assembly with the smart vapor retarder over metal deck allowed for a quicker drying time within five weeks. The authors concluded vapor diffusion ports did not appear to increase the drying rate of the assembly.

History has also shown us that roofs are installed "in the weather." Both stored and partially installed roofing materials are subject to wetting due to humidity, freezing temperatures, and rain. Moisture can become trapped in the newly installed roof assembly and sealed into the system if both top and bottom layers of the system are impermeable. While some roof covers have some vapor diffusing capability, they are minimal. Trapped moisture will result in the moisture cycling within the assembly as temperatures and other factors change. Experience has also shown that wet and even damp materials are disposed of in reroof applications, due to the same concern of trapping both vapor and water in a roof system.[49]

What we have learned is:

- Reducing air flow into the system will significantly reduce the potential for condensation.
- Solar reflective roofs (cool roofs) reduce heat load but can also alter the moisture movement within the assembly.
- Residual moisture in roofing materials can be expected.
- While newer insulation materials may be less susceptible to water than insulation materials of the past, damage can still occur to paper facers if subjected to prolonged high humidity and moisture.
- Assemblies will perform differently in different climatic conditions, resulting in no one single assembly that will fit all needs.
- The energy code has mandated greater thermal performance; therefore, thicker insulation layers are required with the current materials available. New insulation materials, such as vacuum insulated panels (VIPs), may reduce the thickness of the insulation layer but, again, may change the moisture movement within the roof assembly.

Many roofs have been installed with air/vapor barriers as a base layer over "non-permeable" metal decks under the pretense that in order to hold out liquid water, underlayment must be non-vapor-permeable in order to function as a "temporary roof" during the construction phase. These vapor barrier underlayments are often poorly detailed or installed incorrectly to properly function as "air barriers," and consequently, they allow moisture-laden air flow to enter the roofing assembly. This moisture cannot be eliminated by the "self-drying process" because the non-vapor-permeable nature of the materials won't allow diffusive drying except the limited areas of breaches.

Breaches or gaps in the vapor or air barriers clearly play a major role in uncontrolled air flow and formation of condensation. The Lstiburek 2004 publication, comparing the impact of a hole in a gypsum board with the diffusion through an entire 4- x 8-ft. gypsum board, clearly demonstrated the importance of the need for continuity when closing off air flow. The many inspections by forensic engineers of walls and roofs in service have shown that the transitions from roof to walls are breaches, and penetrations are not fully sealed. Vapor barriers do not extend high enough up walls and are not adequately sealed at walls and penetrations, pumping warm, moist air into the very space they were designed to protect.

A review of "standard details" published by the roofing industry provides minimal guidance, especially where vapor retarders tie to walls. Things "get in the way," such as bar joints, shelf angles, and the like, that do not get detailed. Multiple trades are involved with the transition, compounding the problem.

## LOOKING FOR SOLUTIONS

If vapor barriers are not needed in the majority of the climatic zones—other than extreme cold regions—air barriers are still needed as a component of the roof to minimize airflow into the roof assembly. The roof cover is above the insulation layer, and while the roof cover keeps exterior air and water from entering the assembly, if unsealed,[50] conditioned air flow from the interior can enter the assembly. In some structures, the interior pressure is positive, pushing the conditioned air into the roof assembly. An effective air barrier is needed to protect the assembly and limit air flow into the insulation layer(s). The industry provides little detailing for the installation of air barriers, most of the time relying on the list of decks or insulation layers that, when installed correctly, act as air barriers. These products, provided in the IECC, include:

- Minimum ⅜-in. plywood or oriented strand board (OSB) with taped or sealed joints;
- Minimum ½-in. polystyrene with sealed joints;
- Minimum ½-in. polyisocyanurate with sealed joints;
- Closed-cell foam;
- Minimum 4½-in.-thick open-cell foam;
- Precast concrete with grouted joints or cast-in-place concrete; or
- Sheet steel or aluminum.

Rarely do we encounter decks that have been sealed at penetrations, wall transitions, and joints. Recall the testing Boyer did of metal decks where the perm rating of the profile metal deck ranged from 0.25 perms at side laps to 0.2 perms at end laps. Boyer was testing for vapor transmission under ASTM E96[51] and not for air transfer through the many gaps typically encountered in a steel deck.

An air barrier that is perforated with screw holes is already compromised, and it is further compromised by incomplete flashing and termination details. Note, FM Global approves vapor barriers in Class I systems that are screwed or nailed to the deck; however, FM Global is not testing for air or vapor flow, focusing instead on wind, hail, and fire resistance.

Recently, FM Global has approved a vapor barrier that is self-adhered and typically has insulation mechanically attached to the deck through the modified-bitumen layer. The vapor barrier is installed directly to a substrate and sealed. The fastener holes are sealed by the modified-bitumen matrix, minimizing the vapor flow through the holes. This eliminates one traditional component of the assembly—a thermal barrier board—which is mechanically attached to the deck with a vapor barrier bonded to its surface. The perm rating of the product is 0.03 perms.

The cost of effectively sealing a deck can be significant and, in some cases, impractical. Sealing steel decks at welds, screws, and overlaps is difficult and even more so at wall transitions. Sealing plywood joints and gaps at penetrations is rarely achieved. Moreover, the perm rating of these decking materials is very low, minimizing diffusion of moisture once they have been sealed against air flow.

Another product that is self-adhered is a vapor-permeable air barrier. Though it is vapor-permeable, it can be flashed to walls and penetrations and still forms an air barrier. The product can bond to most substrates, including profiled metal decks, and achieve greater than a 90-psf uplift rating when tested under FM Global Test Standard 4470.[52] The perm rating, including the adhesive layer, is 30 perms.

The self-adhered vapor barrier product will create an effective barrier, stopping water vapor from rising into the roof assembly; yet, like all vapor barriers, it will not allow vapor to flow downward through the sheets to eliminate any moisture in the system.

*Figure 4 – Test chamber with two panels installed on top.*

*Figure 5 – Non-woven polyester fabric and test panel. The panel box is fully coated in a vapor-impermeable paint.*

The self-adhered vapor-permeable barrier product, if not punctured when the roof assembly is installed, will allow vapor from the building interior to rise into the assembly, yet it will not allow air flow into the insulation layer(s). Residual moisture can pass as vapor back into the building interior where it will be absorbed into the interior environment.

As noted in the "Measured Drying Ability of Compact Low-Slope Roofs" paper, small-scale modeling was carried out with two "stone wool" panels and one polyisocyanurate panel, but they did not test the combination of polyisocyanurate and a smart vapor barrier and suggested that further testing should be carried out with more variables.

## TESTING

No ASTM standard has been developed to evaluate moisture movement within a compact roof assembly. A test standard was developed, basing the concept on the chambers designed by Tobiasson and his CRREL team in the 1980s (*Figure 1*). The test panels were designed and built in the Trinity | ERD laboratories in Seattle and New Orleans. The test setup consists of two test panel boxes positioned over a conditioning chamber that maintain a constant temperature (*Figure 4*).

Two 2- x 2-ft. test panels were constructed as detailed further—one with a self-adhered vapor barrier applied directly to the top flanges of the profiled metal deck as a base layer (Panel 1), and the other with a self-adhered vapor-permeable barrier as a base layer (Panel 2).

After conditioning for 24 hours, a layer of 16-oz.-per-sq.-yd., non-woven polyester fabric ("polyester") was applied dry over each base layer (*Figure 5*). The polyester was weighed and recorded prior to installation. A 2-in. layer of coated, fiberglass-faced polyisocyanurate insulation, with a single joint at mid-span, was installed over the polyester in both panels. Over the insulation layer was installed a water-resistant, ½-in. gypsum cover board with a fiberglass face. Another layer of 16-oz. polyester was applied over the gypsum board. The polyester was saturated prior to installation.

The polyester was weighed both before and after saturation to determine the quantity of water resident in the polyester layer. On average, the polyester absorbed 1.936 lb. of water, which equates to 29.68 fluid oz. A single layer of 60-mil, non-reinforced EPDM membrane was installed over the polyester layer and sealed to the panel box perimeter with EPDM bonding adhesive. The panels were sealed to the top of a 4- x 8- x 4-ft. insulated plywood chamber that was gapped at the base to allow for air escape. A 550-BTU air conditioner was installed into the chamber, set to maintain a temperature of 65°F.[53] A temperature/humidity meter

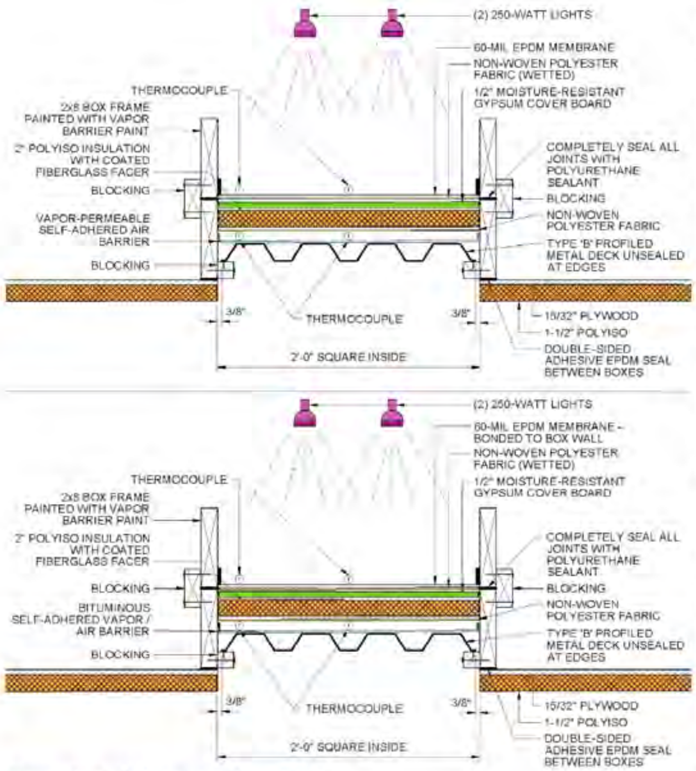


*Figure 6 – Initial test panel assembly.*

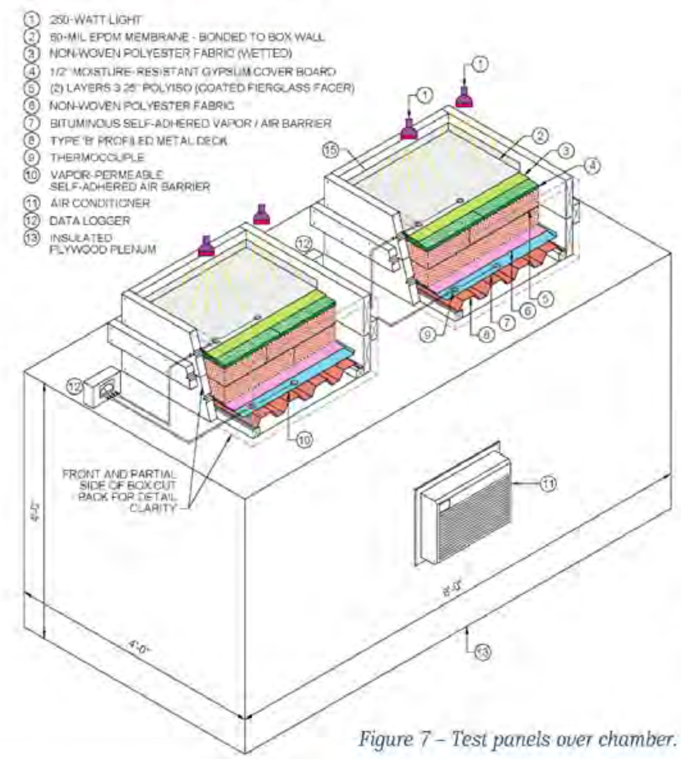


*Figure 7 – Test panels over chamber.*

was set inside the chamber to record temperature and humidity every 15 minutes.

Two infrared, 250-watt heat lamps were set 30 in. above the membrane surfaces of each panel. The lights were set on a 12-hour timer, heating the surfaces of the EPDM membranes to 150-155°F for 12 hours; then turned off for 12 hours, cooling the EPDM surfaces to an ambient temperature of 72°F. Two thermocouples were placed on each of the membrane surfaces, and two additional thermocouples at the vapor/air barrier surfaces (*Figures 6* and *7*).

The test panels were cycled for 36 24-hour periods, after which the panels were opened, and the polyester and insulation layers examined. In both panels, the top polyester layers under the EPDM membrane were dry. The weights of the polyester were within 0.02 oz. of the dry weights before wetting. The insulation layers were weighed, recording similar weight in the vapor-permeable air barrier chamber, and a 2.2 percent increase by weight in the vapor barrier chamber, compared to pre-testing weights. The bottom side of the insulation was wet in the vapor barrier chamber. The base polyester layers were removed and weighed. The base polyester layer in Panel 1 over the vapor barrier was saturated, with 27.55 oz. of water absorbed into the polyester. Some residual water remained on the surface of the vapor barrier. The base polyester layer in Panel 2, over the self-adhered vapor-permeable air barrier, was dry to the touch. The polyester weighed 2.4 percent more than when initially installed dry. The base layers were removed from both chambers to expose the decks, and no moisture was observed in the deck low points.

The test panels were not disturbed for the total testing period; therefore, it is unknown when during the cycling the permeable layer substantially dried. The temperature in the cooling chamber varied between 61° and 70°F over the test period, averaging 68°F. Surface temperatures of the membranes remained relatively constant during the heating period, with variations from 152° to 166°F after one hour of heat lamp activation. While not fully controlled, the cycle (variations in surface temperature and a constant cooler temperature under the chamber) demonstrated that conditions drove the moisture down, bypassing the insulation layer to the underlying base layer. The vapor barrier base layer stopped bulk water transfer to the cooled interior space, and the self-adhered vapor-permeable air barrier allowed the moisture to pass through, as water vapor, into the deck flutes and finally, at the perimeter gaps, into the cooled space below.[54]

Additional panels were assembled as Panels 3 and 4, with identical materials to Panels 1 and 2, but with increased insulation, adding two layers of 3½ -in., coated, glass-faced insulation. A joint in each layer of insulation was installed over the dry polyester layer (*Figure 8*). Panels 3 and 4 were tested for 48 24-hour cycles, following the same protocol detailed above.

Panels 3 and 4 were disassembled, first removing the roof cover, exposing the top layer of polyester. In both panels, the top layers of polyester were dry after exposure to ambient conditions for 24 hours. The insulation layers were dry; however, the bottom side of the insulation in the vapor barrier panel was damp to the touch. The base polyester in the vapor barrier panel was saturated. Weighing of the base polyester confirmed the majority of the water in the top polyester layer was now in the base polyester layer with some water resident on the top face of the vapor barrier. The polyester layer in Panel 4, over the vapor-permeable self-adhered layer, was dry. Comparison with the original dry weight confirmed a marginal increase in weight and no water in the low points of the steel deck.

The increased insulation thickness increased the moisture migration time to around 48 cycles. Again, it is not known when the polyester was fully dried since there was no metering for moisture in the lower polyester layer. Based on preliminary testing, full drying of the assembly took place somewhere between 42 and 48 cycles. The configuration of the test panels did not allow for moisture measurement during the cycling period since the roof assembly was sealed.

To allow for monitoring of the moisture levels during cycling, the panels were reassembled with new components, with manually operated moisture meters installed at the interfaces of the base insulation layer and the base non-woven fabric layer to record moisture changes at the interfaces. To avoid the potential of interference of the steel deck to the accuracy of the capacitance meter, a plastic plate was attached to the high flange of the deck (*Figure 9*). The meter was read daily to determine the moisture levels at the interface of the bottom of the base insulation and the base polyester layer.

The increased insulation, to a level consistent with current codes, slowed the drying process in the controlled environment. The results of the first 48-cycles confirms moisture resident in the compact roof assembly can be driven down into the interior space within a summer drying cycle. This was predicted by Tobiasson and offered as an option by the NRCA for drying a compact roof as early as 1983. What has changed is the availability of vapor-permeable air barriers that can inhibit air flow and still allow vapor transmission in both directions. The importance of air barrier continuity must be stressed for the assembly to perform as intended.

The newly constructed Panels 5 and 6,

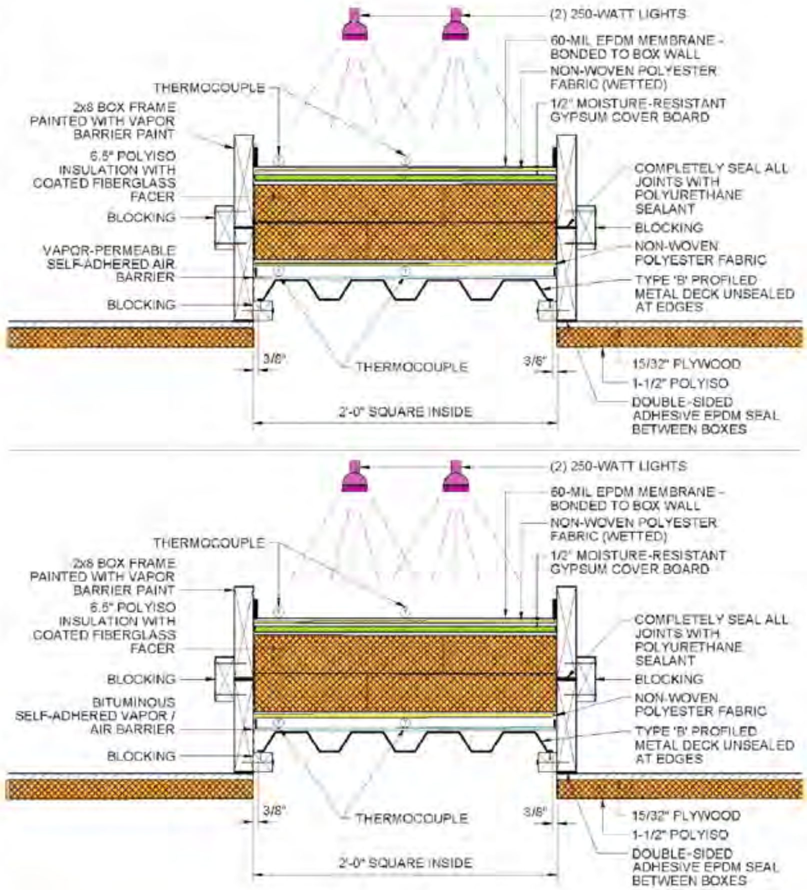


*Figure 8 – Second test assemblies.*

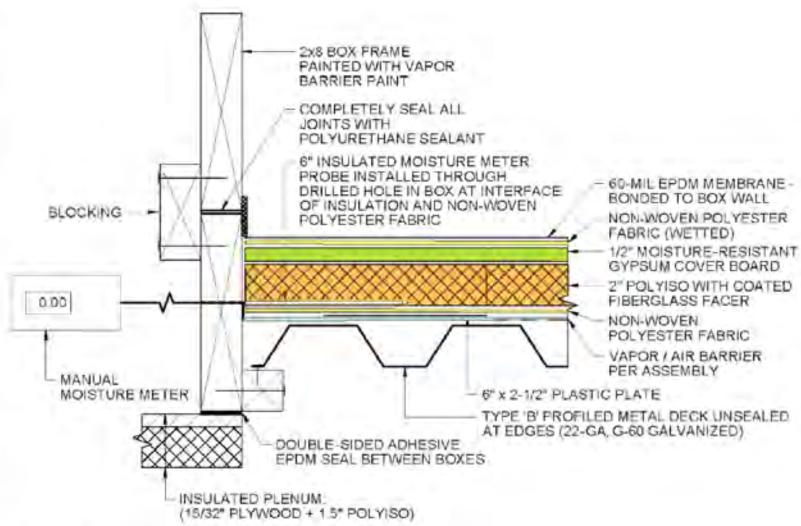


*Figure 9 – New test panel assembly.*

*Figure 10 – Existing substrate after removal of metal roof at Tampa Airport.*

*Figure 11 – Installed air barrier at Tampa Airport.*

with the additional metering, should provide better data as to the timing of the moisture migrating from the top to the bottom polyester layers with current insulation levels mandated by code.

## DISCUSSION

Field research and computer modeling over the years have identified both diffusion and air transport as the primary carriers of moisture into walls and roofs. Air transport has been identified as a primary cause of moisture migration, with a significant level of research beginning in the 1980s and continuing into the early 2000s. Roof decks are in many cases porous, allowing air transportation of moisture into the roof assembly without the addition of diffusion. The IECC recognized the need to seal decks at joints and transitions to form an air barrier—a step that rarely happens in most roof deck assemblies. Even with attempts to seal the deck—especially a profiled metal deck—

joints, overlaps, screw holes, and weld burns allow moisture transport through airflow into the roof assembly without a barrier layer. In many cases, especially in reroofing conditions, which form the majority of roofing projects today, sealing the deck to form an air barrier as defined in the IECC is a difficult and expensive process.

Field studies have documented that roofs outside of the extreme temperature zones, when properly constructed, can absorb migrating moisture in the winter months and dry out during the summer months without damage to the insulating layers. As noted above, the level of moisture absorption must not reach the level of irreparable damage (Tobiasson set the pass/fail at 80 percent of thermal value) or where damage to a paper facer may result in cohesive or adhesive failure of the facer. There have been limited studies as to the impact moisture might have on paper-based insulation facers. Recent hurricanes have provided more field data, which should provide greater insight. The increased thermal requirements of today's codes also change the moisture movement and the drying times during the summer months.

Good design and construction of roof assemblies have been shown to play a major factor in moisture transport, and their absence to be a primary cause of roof failures. Where a vapor/air barrier or air barrier is applied, it must form a complete, homogeneous layer that integrates with the air barrier of the rest of the enclosure. Failure to do so leads to unanticipated moisture flow and reduction in insulation performance, accelerated corrosion, and, in some cases, roof assembly failures. Better detailing of the installation of both vapor and air barriers is needed to guide the installation community in good practices. This will require coordination with other trades and specialties that participate in the building enclosure.

New air barrier products are now being deployed in assemblies to assist in drying out existing materials that have been marginally impacted by moisture for re-use in new assemblies. A recent project at Tampa International Airport has included a self-adhered vapor-permeable air barrier layer to dry out existing insulation in a new metal roof assembly (*Figures 10* and *11*). A layer of a vapor-permeable air barrier was installed over existing mechanically attached insulation. The layer provided temporary protection of the building and drove any moisture in the insulation down into the building interior. While the ideal placement of the vapor-permeable layer would be at the deck interface, this would require the complete removal of the existing insulation.

Advances in products such as self-adhered bituminous vapor barriers and self-adhered air-permeable barriers provide new tools to tackle moisture transport and diffusion issues. More work is needed to better understand how roof cover colors can impact moisture flow so that guidelines and recommendations can be provided to the design community.

Highly moisture-permeable air barriers can rehabilitate both existing and new roof decks to create the air barrier contemplated in the IECC without the time-consuming process of taping and sealing. Moreover, the air barrier can extend beyond the roof plane, forming an airtight connection with the exterior wall air barrier system. In the same way, self-adhered bituminous vapor barriers can create an effective air and vapor seal, again connecting to the wall assemblies. How the newer vapor-permeable

Under development for over 50 years, the advancements in new materials, combined with continued research and field testing, have now made it possible for self-drying roofs to become a standard in the industry.

air barriers can be used with the many roof covers on the market will be better known as the products come into more general use in varying climate regions. Ongoing testing and field evaluation will help determine drying times with current code-mandated insulation layers commonly in use.

The building industry in the United Kingdom rethought its approach to ventilation requirements for wood-framed construction after careful evaluation of vapor-permeable air barriers. Further research and testing in North America could bring about clearer design guidelines, better detailing and integration of the vapor/air barrier assemblies into the enclosure, and clearer installation instructions to assist the installing community.

## CONCLUSIONS

The many steps in the evolution of self-drying roofs have been a collaboration of scientists, field engineers, material developers, and membrane manufacturers—all of whom have contributed to the understanding of moisture movement within a compact roof and the avenues to evacuate moisture—whether from external or internal sources. The development of insulating materials that absorb less water was an initial key step to rehabilitating existing insulation for an additional roofing cycle. Tobiasson and his team provided a pass/fail method to determine re-use, which was never fully incorporated into the nondestructive testing methods used for evaluation of roofs in service.

The limitations created by a smaller materials palette and a lesser concern for the contribution to waste disposal took the focus away from more sustainable and durable roofs—even when there was minor water infiltration into the assemblies.

While white roofs were available as early as the 1970s, their value to energy conservation was not fully understood until around 20 years later. White roofs instead of black roofs changed the way moisture moved through compact roofs, requiring better modeling tools and field engineering analysis to understand new problems associated with moisture movement and accumulation.

The recognition of the importance of air barriers in the reduction of condensation brought additional focus to sources of water in our walls and roofs.

As is almost always the case, laboratory and field research spawn invention. This work over an extended period of time expanded the palette of available materials, which in turn has expanded the options in design.

There are still missing elements that would better assist the design and installation community:

- Better evaluation protocols for non-destructive testing methods to optimize the use of existing insulation;
- Better detailing of air and vapor barriers and developing continuity with other air barrier elements making up the enclosure; and
- Additional testing and system design by membrane manufacturers to take advantage of newly developed materials.

Under development for over 50 years, the advancements in new materials, combined with continued research and field testing, have now made it possible for self-drying roofs to become a standard in the industry. Provided clearly defined protocols and design guidelines are established, this assembly can successfully perform even after it has been partially compromised, allowing materials—typically bound for the landfill—to be re-used and exemplify the tenets of environmentally sound design.

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