Roofs and Condensation:
A Practical Approach for the Design Professional

EXECUTIVE SUMMARY

The steady growth of modern single-ply roofing systems over the past 40 years generated many questions regarding long-term performance. Early in their development, many of the questions were related to the capability of single-ply roofing systems to resist external forces such as wind, fire, ultraviolet radiation, and precipitation in all forms. However, with the advent of “cool” single-ply roofs featuring heat reflective exterior surfaces, new questions have emerged concerning the internal forces at play within the roofing system, especially in regard to vapor movement and the potential for moisture condensation within the roof.

Starting with a brief discussion of the fundamentals of vapor movement in roofing systems, this article reviews current research to gain an understanding of the actual incidence of moisture condensation and the key factors that may lead to the accumulation of moisture within single-ply roofing systems. Based on a review of recent experiments and field studies, the paper concludes that moisture 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:

1) Extremely cold external temperatures;
2) Extremely high internal temperatures and humidity;
3) Unusually low amounts of over-deck roof insulation, and/or
4) Unusually high levels of air movement within the roofing system.

The paper also provides a brief discussion of commonly available tools to analyze moisture in roofs as well as the effect of air barriers and vapor retarders on moisture condensation. In regard to current moisture analysis tools, the paper suggests that these tools may overestimate the potential for moisture condensation in roofs due to the complexity and uncertainty of the variables required. In regard to vapor retarders, the paper suggests that their use involves a number of risks, including the potential for trapped moisture due to external roof leaks as well as reduced air movement within the roofing system to allow drying of the roof over time, commonly referred to as the “self-drying roof” concept.

Based on the review of moisture movement in roofing systems and the tools available to assess and mitigate roof condensation, the paper also provides suggestions for the roofing design professional to deal effectively with moisture movement. These suggestions include:

1) Establish a conservative but realistic estimate for actual interior humidity conditions within the building.
2) Limit unnecessary air movement within the roofing system – both in the design of the roof and in the quality of roof installation.
3) Include a minimum amount of above-deck thermal insulation beneath the roofing membrane.
4) Allow whenever possible the capability of the roof to “self-dry” in the event condensation does occur.
5) Select roofing materials with low perm ratings and high resistance to moisture damage.
6) Use modeling tools, but recognize their limitations.

INTRODUCTION

Over the past 40 years, a dramatic transformation has occurred within the commercial roofing industry. From the beginnings of modern commercial construction methods until the last quarter of the 20th century, commercial rooftops were dominated by a single roofing technology: built-up roofing frequently referred to as “tar and gravel” roofs. Beginning in the1970s, however, a variety of new single-ply roofing technologies emerged to challenge traditional built-up roofing practice. These single-ply systems experienced strong and continuous growth, and by the end of the 20th century, they dominated commercial roofing to the same extent previously enjoyed by built-up roofing.

Compared to built-up roofs, single-ply roofs offered a number of advantages. Single-ply roofs generally require less field labor to install, and the labor conditions themselves are less demanding. Single-ply roofs also tend to be more accommodating to the higher levels of thermal insulation required by today’s energy codes, and their lower overall weight allows for economies in the structural design of the underlying roof deck. Due to these and other advantages, single-ply roofs now account for over three-quarters of the commercial roofing market (Tegnos Research, 2012).

As with any significant change in construction practice, the move to single-ply roofing generated questions regarding long-term performance. Early in the development of single-plies, most of these questions were related to the capability of these new roofing systems to resist external forces such as wind, fire, ultraviolet, and precipitation in all forms. As a result of these and other concerns, single-ply roofing manufacturers made significant investments in product development and testing, which have produced achievements in wind, fire, and weathering performance.

Recently, new questions have been raised regarding the ability of single-ply roofs to resist internal forces within the roofing system, especially air and vapor movement. Some of these questions are related to the use of mechanical attachment of single-ply membranes, which may allow additional air movement within the roof. Other questions are related to the increasing use of “cool,” or highly reflective single-ply membranes in regard to the potential for vapor condensation beneath such membranes and within the roofing system.

In response to these concerns, this paper provides a review of current research in order to understand the actual incidence of moisture condensation in single-ply roofs and to identify the key factors that may lead to the accumulation of moisture within these roofing systems. The paper also discusses the role of related technologies such as air barriers and vapor retarders to control moisture condensation in single-ply roofs. Finally, the paper discusses the role of available building physics modeling tools to help the roofing professional avoid the potential for condensation in roof systems.

ROOFS AND MOISTURE: KEY PRINCIPLES

Before reviewing the research evidence about moisture condensation in roofs, it is important to discuss the complex interplay between roofs and moisture. Such a review can be complicated, especially in terms of the underlying factors; but much of this complexity may be summarized in a few key principles to help guide design decisions.

The science is simple, but the factors are complex.

The basic science of condensation is straightforward and well-established. Moisture in the form of water vapor tends to move from a warm, humid condition to a cold, dry condition as the result of the process of diffusion. Due to diffusion, water vapor tends to move from a warm, humid interior of a building to a colder, less humid external environment. This inside-to-outside water vapor movement is typical for buildings during the winter months, especially in the colder regions of North America. Conversely, in the summer in many North American climates, this vapor movement via diffusion is reversed, with water vapor moving from a warm, humid exterior to a cooler and less humid interior. Figure 1 illustrates this typical winter and summer diffusion of water vapor within a roofing system.

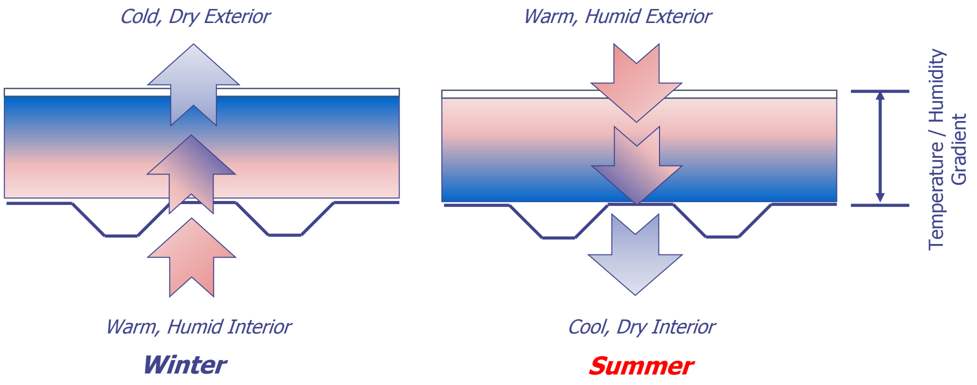


Figure 1. Winter and summer roof vapor drive

It should be noted that the movement of water vapor occurs along a relatively predictable temperature / humidity gradient, with the warmest temperature and highest humidity located close to the interior and the coldest temperature and lowest humidity located close to the exterior in the winter. If at any point along this gradient, the temperature falls below the “dew point” for the associated humidity, the water vapor will condense and become liquid water within the roofing system. Figure 2 illustrates this typical dew point condition and the resultant condensation within a roofing system.

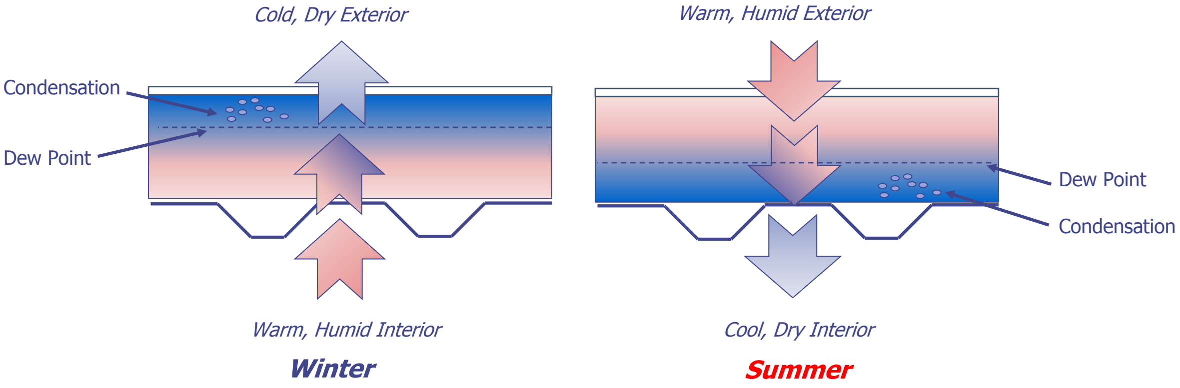


Figure 2. Winter and summer roof dew point condition

Even though this dew point condition may be reached occasionally during the summer in the southernmost climates in North America, the occurrence of condensation in roofing systems is more commonly observed during the winter in the northernmost climates (Griffin & Fricklas, Chap. 6). As a consequence, the findings and recommendations of this article are focused primarily on the potential for roof condensation to occur during the winter heating season, especially in colder climate regions.

Although a theoretical dew point may be calculated based on simple measures of temperature and humidity within a roofing system, there are several important factors that help determine the exact conditions for condensation and the extent that such condensation occurs. First, the rate of vapor drive is affected by the indoor humidity of the entire building (See Figure 1), which may vary widely depending on type of occupancy and function. While large retail and wholesale storage facilities may rarely exceed 30% to 40% relative humidity (RH) in the winter, other occupancies such as heavy manufacturing and indoor swimming pools may approach 75% to 90% RH (See Griffin & Fricklas, 2006, Table 6.4.). As a result, occupancy tends to play a much more important factor in predicting the potential for condensation than either the indoor or outdoor temperature.

Next, the rate of vapor drive is affected by the permeability of the materials within a roofing system, as measured by their perm rating. As defined by current industry standards (ASTM E-96), the higher the perm rating number, the more readily water vapor (in the gaseous state) can be absorbed and move through the material. Table 1 provides a listing of common roofing materials and compares their perm ratings.

Table 1: Perm ratings of common roofing materials

Source: Griffin & Fricklas (2006) Table 6.2

Material	Perm Rating	Classification
Built-Up Roofing Membrane	0.00 – 0.02	Impermeable (Vapor Proof) ≤ 0.1 Perm
Single-Ply Membrane	0.03 – 0.06	
Polyethylene Film	0.06 – 0.08	
Asphalt Felt	0.3 – 0.8	Semi-Impermeable > 0.1 ≤ 1.0 Perm
Polyiso Roof Insulation	1.0	
Extruded Polystyrene	1.0	
Expanded Polystyrene	1.2	Semi-Permeable > 1.0 ≤ 10.0 Perm
Wood Fiber	3.0 – 5.0	
Gypsum Board	30.0 – 50.0	Permeable > 10.0 Perm

For materials with perm ratings less than 0.1, very little if any vapor can be absorbed or transferred. As shown in Table 1, almost all roofing membranes as well as plastic films such as polyethylene are considered to be impermeable to water vapor. For materials with slightly higher perm ratings between 0.1 and 1.0, the rate of vapor absorption and transfer is significantly reduced, especially if the temperature / humidity gradient is not severe. Examples of semi-impermeable roofing materials include individual layers of roofing felt and foam insulations such as extruded polystyrene and polyisocyanurate. For materials with perm ratings above 1.0, the rate of vapor absorption and transfer begins to increase, and such materials tend to absorb relatively large quantities of water whenever they are subjected to temperature / humidity conditions below the dew point. Examples of common semi-permeable and permeable roofing materials include wood and mineral fiber boards as well as many gypsum products.

In addition to the rate at which water vapor may transfer through a material, the effect of that transfer on the physical integrity of the material may vary significantly. Under some conditions, materials that may absorb moisture to some degree may be suitable for direct exposure to dew point conditions because the condensing moisture has little or no effect on the integrity of the material. One of the best examples of a less-than fully impermeable roofing product intentionally exposed to dew point conditions is the use of extruded polystyrene in inverted roof systems, where the foam insulation is directly exposed to both rain and condensation. Other foam insulations like polyisocyanurate also have low perm ratings, but the use of facers that can be distorted by moisture makes such materials less resistant to overall condensation and other effects.

At the opposite end of the perm spectrum, products with relatively high perm ratings tend to absorb significant quantities of moisture. And frequently, this high level of moisture absorption is associated with significant loss of material integrity. As a result, some common semipermeable and impermeable roofing products such as wood and mineral fiber will effectively be ruined when exposed to prolonged moisture condensation.

So far we have only discussed the movement of water vapor due to diffusion, but there is one additional and very important physical force that drives moisture movement. That force is the movement of air itself within a roofing assembly. And the effect of air movement on moisture transfer can be very significant. In a recent study of the effects of air movement versus diffusion (Lstiburek, 2004) the researcher demonstrated that air movement through a small inch square hole in a 4 foot by 8 foot gypsum board panel may drive almost 100 times as much water vapor than would move through the same panel due to diffusion. Although the effects of air movement in this study were related to wall assemblies, the finding of a relatively high level of vapor movement via a relatively small discontinuity in the wall assembly suggest that similar conditions in roofing systems may trigger similar high levels of moisture movement.

Roof condensation and roof leakage look the same.

The observation of liquid water within a roofing system does not necessarily indicate that vapor condensation has occurred. Moisture may also enter the roofing system via leakage through cuts, punctures, loose seams, and many other discontinuities in the exterior waterproofing layer of the roof. And because roof leakage continues to be a widely reported phenomenon sufficient to fund thousands of roof service operations across the country, excessive moisture in a roof may be attributed more frequently to exterior leakage rather than interior condensation. In fact, several of the research papers reviewed further in this article include observations of roof leaks that may better explain the presence of moisture for some observations of what initially may have been classified as condensation.

Vapor retarders help, but there are unintended consequences.

Installing an impermeable material as a vapor retarder beneath the dew point in a roof certainly will address many of our concerns regarding condensation, but the protection of a vapor retarder comes at a price. If a roof with a vapor retarder experiences roof leaks, the water entering the roof will be trapped above the vapor retarder within the roofing system. However, because the vapor retarder will prevent the water from entering the building, the leak may be unobserved and left unattended for a considerable time. And during that time, the trapped water may spread for a considerable distance from the point of the leak, making it even more difficult to pinpoint the source of the leak and causing extensive damage to a constantly growing portion of the roof. Figure 3 illustrates how a vapor retarder can reduce the potential for vapor condensation but also increase the potential for trapped water due to roof leaks.

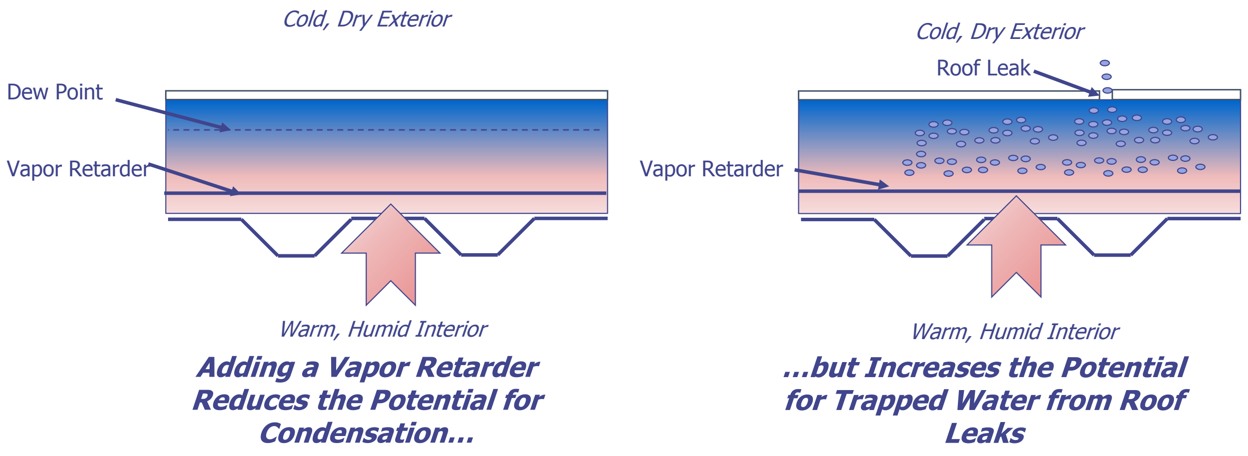


Figure 3: Benefits and limitations of a vapor retarder

Many roofs will “self-dry” if we let them.

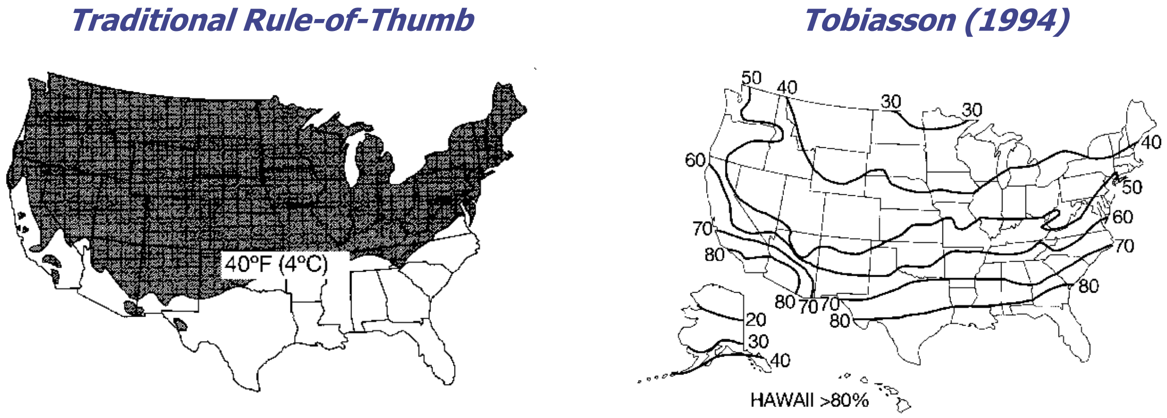
The self-drying roof concept may be traced to field accounts of roof systems observed to have been wet in the winter but dry by the following summer. This condition of wetting in the winter and drying in the summer has now been documented in numerous research studies (see Desjarlais et al., 1998, and Griffin & Fricklas, 2006, Chap. 6). And a considerable body of knowledge has been developed to understand how the phenomenon operates. Self-drying roof systems use the sun and summer heat to evaporate moisture that may have accumulated in a roof due to condensation over the 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.

PREDICTING ROOF CONDENSATION: FROM RULES OF THUMB TO COMPUTER MODELS

Due to the effects of the perm rating of materials, the potential for condensation-related damage, and the inadvertent movement of air within a roofing system, the initial scientific simplicity of diffusion-driven vapor movement becomes significantly more complicated – and risky. And the adverse implications of underestimating the potential for condensation within roofing systems may influence roofing professionals to take a conservative approach when assessing the impact of these additional factors. At the same time, addressing the risks of condensation by installing a vapor retarder may result in increased damage from roof leaks and eliminate the self-drying potential of the roof. Because of these risks and consequences, building researchers and roofing professionals have expended considerable effort to develop useful tools to aid in the analysis of condensation in roofs and select the best designs to address the effects of condensation.

One of the earliest approaches to roof condensation was a simple rule-of-thumb: If the roof is located in a climate with an average January temperature of 40°F or less, condensation should be assumed and a vapor retarder should be installed. A more sophisticated approach was developed by Tobiasson (1994) who identified the minimum average January temperature that would require a vapor retarder based on the interior humidity of a building. Figure 4 provides two U.S. maps to illustrate these two approaches. The map on the left illustrates the geographic extent of the traditional 40°F rule-of-thumb, while the map on the right illustrates the maximum interior humidity allowed before a vapor retarder is recommended.



Traditional Rule-of-Thumb

Tobiasson (1994)

Average January Outdoor Temperature (≤40°F Shaded)

Maximum Humidity @ 68°F Indoor Temperature (Percent)

Figure 4: Simplified approaches for recommending a roof vapor retarder

(Source: Oak Ridge National Laboratories)

As illustrated by the two maps in Figure 4, the 40°F January temperature cut-off is more conservative than Tobiasson's indoor humidity approach. As an example, the 40°F map locates Cincinnati, Ohio within the area requiring a roof vapor retarder. However, the indoor humidity approach would recommend a roof vapor retarder only if the indoor humidity in January exceeds 50% RH for a roof in Cincinnati. This is an important difference because many building occupancies, from residences to stores and warehouses, will rarely develop an average humidity above 50% in the winter.

Recently a more sophisticated approach to predicting roof condensation has been developed. This approach is called WUFI and was the result of a cooperative effort between cooperation with Fraunhofer Institute for Building Physics (IBP) in Germany and Oak Ridge National Laboratory (ORNL) in the United States. WUFI is a free software program available from ORNL[1], which allows modeling of heat and moisture over time in complex roofs and wall assemblies. WUFI incorporates the newest findings regarding vapor diffusion and liquid transport in building materials and has been validated by comparison with field observations. Because WUFI can provide a day-by-day analysis of moisture movement based on actual weather data, it can be used to plot the characteristics of roof self-drying so that the analysis of condensation may be viewed as a long-term phenomenon. WUFI also allows the inclusion of the effects of solar radiation, which may be an important factor in roof self-drying.

Although WUFI obviously marks a significant step forward in building moisture analysis, it still may be subject to some of the same conservative, rule-of-thumb principles that characterized previous simplified approaches. As an example, the WUFI user must make assumptions regarding air movement within the building; and as discussed previously, the amount of air movement can have a dramatic effect on moisture transfer and the potential for condensation. As a result, it may be very easy to overestimate the amount of air movement and in turn overemphasize the potential for long-term condensation within a roof or other building assembly. In addition to issues regarding air movement levels, the current WUFI tool contains only limited data for popular North American roofing system components such as polyiso foam insulation.

RECENT ROOF CONDENSATION RESEARCH

Because of new tools like WUFI, research into roof condensation has increased dramatically within the last few years. And because WUFI can incorporate solar radiation effects and the solar reflectivity of the roof surface, much of this research has been directed at how moisture movement is affected by a cool, highly reflective roof compared to a darker roof with low solar reflectivity. One of the first research studies to be published (Bludau et al. 2008) introduced two concepts regarding cool roofs. The first involves the reduction in internal heat gain caused by a highly reflective roof during the day, and the second involves nighttime radiation effects that can cool the roof surface below ambient air temperature. Modeling conducted in this study suggested that a white reflective roof installed over a layer of thermal insulation (in this case, polyisocyanurate) and a permeable (i.e. self-drying) metal deck in an extreme cold climate zone like Anchorage, Alaska may accumulate moisture in the winter in excess of the amount of moisture that can be removed in the summer through self-drying. Modeling conducted on the same roof assembly in a less severe climate (Chicago Illinois) suggested that the amount of moisture in the roof system would tend to increase in the winter, but the self-drying process in the summer would still return the roof to its original moisture condition. A similar modeling study (Saber et al., 2011) which included a layer of wood fiber instead of polyisocyanurate foam suggested that excessive moisture accumulation would occur under white reflective roofs in northern locations such as Saskatoon, Saskatchewan and St. Johns, Newfoundland. However, modeling for a similar roof in Toronto, Ontario showed no long-term moisture accumulation.

In the same time period of these modeling studies, several professional consultants began to investigate field reports of excessive moisture accumulation in cool roofing systems. Hutchinson (2009) summarized a number of anecdotal reports of roof condensation in cool roofs in and around Chicago, Illinois. In all cases, the observation of condensation was associated with one or more roof design problems such as the use of a single layer of roof insulation or workmanship practices that allowed excessive air movement. In a similar manner, Dregger (2012) reported field observations of three cool roofs installed in California which also showed excessive moisture accumulation. All of these roofs were installed over plywood or OSB decks with no insulation above the deck; and Dregger concluded that the moisture accumulation observed could be attributed to a combination of a lack of thermal insulation above the roof deck and excessive air movement within the roof assembly. Dregger also suggested that the addition of a layer of insulation above the roof deck and under the roof membrane would have corrected this problem by moving the dew point below the roof deck and reducing air flow within the roofing system.

As a result of these initial modeling studies and field observations, a new level of experimental research was started to better understand the potential for excessive moisture accumulation in cool roofs. Ennis and Kehrer (2011) conducted a study of mechanically-attached single-ply roofs installed in Chicago, Illinois (the same location as Hutchinson's field observations), and used the results of the observations to conduct a modeling study using WUFI. In all cases, both black and white roofs modeled dried out completely by the summer even if small levels of moisture may have accumulated during the winter. In addition, Ennis and Kehrer observed that the WUFI modeling tended to predict a higher level of moisture accumulation in the white roof than actually observed during field observations. The researchers suggested that the difference between predicted and actual moisture accumulation may be due to a relatively high air exchange rate selected in the modeling to account for possible air movement due to billowing of the mechanically attached roof membrane.

In an effort to better quantify the amount of air intrusion in mechanically attached single-ply systems, the National Research Council of Canada (NRC, 2104) conducted an experimental observation of air movement using a large pressurization apparatus typically used for wind uplift testing of roofing systems. After measuring actual air leakage of various mechanically-attached single-ply systems, the NRC study concluded that leakage was negligible and well below the minimum ASTM and ICC standards for a building air barrier. As a result, the NRC research tends to confirm previous suggestions that the assumed air infiltration rate for mechanically-attached single-ply roofs is much higher than the amount of air infiltration that actually occurs.

Finally, a large-scale field study of cool single-ply roofs was conducted by Fenner et al. (2014). This study looked at cool mechanically attached single-ply roofs installed on 26 Target stores, all in colder climates, all more than 10 years old, all direct to steel deck, and half with only a single layer of insulation. Based on roof test cuts conducted at each store location, visible moisture was observed in only one roof; and this moisture was attributed to an observed external leak rather than internal condensation. A follow-up by this author, conducted using a portable humidity sensor in several Midwest Target stores during December, 2014, suggests that the actual humidity in the stores in the winter may be lower than assumed in previous modeling studies. These anecdotal observations indicated that the average humidity in these stores in the winter month of December ranged from 25% to under 35% during outdoor temperatures from 25°F to 30°F.

OBSERVATIONS FROM RECENT RESEARCH AND FIELD STUDIES

Although frequently discussed in recent research and reports, moisture accumulation in roofs appears to be a relatively rare phenomenon tending to occur only in the presence of one or more severe conditions. These severe conditions may include:

- **Extremely cold external temperatures**. It is possible that such extreme temperatures may exist only in the northernmost areas of North America.
- **Extremely high internal temperature and humidity**. The observations of the complete lack of moisture accumulation in 26 roofs over Target stores suggests that actual winter humidity in typical retail, office, and warehouse occupancies may be significantly lower than assumed in several recent moisture modeling studies.
- **No insulation or a single layer of roof insulation above-deck**. The Dregger (2012) study of uninsulated roofs in California certainly suggests that some level of above-deck insulation should be used with any single-ply roofing membrane. In a similar manner, the Hutchinson (2009) reports of condensation associated with only a single layer of roofing insulation may suggest that two or more staggered layers of insulation should be installed under all single-ply roofs.
- **Unusually high levels of air movement within the roofing system.** Some of the modeling studies reviewed in this article suggest that high levels of air movement within a roofing

system will contribute to moisture accumulation. However, recent NRC (2014) air barrier testing of mechanically attached single-plies suggests that modeling tools may easily overestimate the amount of air infiltration affecting the roof. As a result, they also may overestimate the potential for moisture condensation in roofs.

In addition to this brief review of the key conditions that may contribute to condensation and moisture accumulation in most if not all roof assemblies, it would be important to restate the benefits and risks of vapor retarders within roofing systems. Although a well-designed and installed vapor retarder can remove many of the concerns associated with moisture accumulation, they add new risks of allowing moisture accumulation from roof leaks and may severely limit important self-drying roof properties.

RECOMMENDATIONS FOR THE DESIGN PROFESSIONAL

Based on the review of moisture movement in roofing systems and the tools available to assess and mitigate roof condensation, the following strategies are recommended for the concerned design professional:

- **Establish a conservative but realistic estimate for actual interior humidity conditions within the building.** Although underestimating humidity conditions may lead to moisture accumulation within a roofing system, overestimating anticipated humidity conditions may unnecessarily point to the need for a vapor retarder and the loss of self-drying roof benefits.
- **Limit unnecessary air movement within the roofing system – both in the design of the roof and in the quality of roof installation.** The bad news here is that poor design and installation practices – like installing only a single layer of roof insulation and failing to close obvious gaps at penetrations and transitions in the roof assembly – will cause a high level of unwanted air infiltration that may lead to moisture accumulation. But the good news from the recent NRC (2014) study is that mechanically attached single-ply roofs using reinforced membranes significantly reduce air movement – even to the point that they could be considered air barriers by current building code criteria.
- **Include a minimum amount of above-deck thermal insulation beneath the roofing membrane**. The Dregger (2012) study of uninsulated roofs in California suggests that some minimal level of above-deck roof insulation should be installed with every cool single-ply roofing system, even in moderate climates. Dregger further suggests that above-deck insulation be installed even when not required by the building code.
- **Allow whenever possible the capability of the roof to “self-dry” in the event condensation does occur.** It’s not that often that building designers are given a free gift like the self-drying roof concept, and it should not be discarded without considerable analysis.
- **Select roofing materials with low perm ratings and high resistance to moisture damage.** As illustrated in Table 1, there are many roofing materials available with low perm ratings, especially critical roof insulations that must resist moisture for many years. Using low perm materials can reduce the consequences of moisture accumulation in the event other factors fail to remain within your design assumptions.
- **Use modeling tools, but recognize their limitations**. In the case of the simplest tools, recent research clearly suggests that the answers they provide will almost always be overly conservative. In the case of more sophisticated tools like WUFI, it is vital that the designer understand the underlying assumptions and adapt these assumptions to actual expected conditions.

FOOTNOTES

1. Additional information about WUFI including a free software download may be obtained from Oak Ridge National Laboratory at http://web.ornl.gov/sci/btc/apps/moisture/index.html

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