The Effects of Roof Membrane Color on Moisture Accumulation in Low-slope Commercial Roof Systems

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Abstract

The use of highly reflective roof membrane systems is being promoted and in some cases required in energy codes and green building codes and standards. Highly reflective membranes, which typically are light in color, have demonstrated reduced overall energy consumption in cooling dominated climate. These membranes also are theorized to reduce the heat island effect.

Concern has been expressed about using highly reflective roof membrane systems in cool to cold climate zones because they potentially increase moisture accumulation in roof systems. Roof membranes are vapor retarders. The theory is that highly reflective membranes reflect a percentage of the heat that could enter the roof assembly, potentially providing a condensing surface on the cold side of the roof assembly during winter months. The other concern is that roof systems using highly reflective membranes will not get hot enough during the summer months to dry out moisture that may have condensed or otherwise entered the roof assembly.

This study focuses on mechanically-attached, highly reflective, single-ply roof systems installed on low-slope (less than 2:12) structures in cool to cold climate zones. Three sources of data are considered when determining the moisture accumulation potential of these systems.

1. Test roof cuts taken during the winter months
2. Modeling data from a building envelope model specifically designed to evaluate moisture accumulation
3. Data from previous studies to determine the effects of roof membrane color on the drying rate of low-slope roof assemblies

Authors

Mike Ennis has been Technical Director for SPRI , the Association representing Single-Ply Roofing Manufacturers and Component Suppliers for four years. Prior to this he worked for The Dow Chemical Company and was the North American Application Technology Leader for commercial products in Dow's Building Solutions business where he led the development of new products and applications. Mike has 33 years of building and construction experience to his credit. Ennis is a Registered Roof Consultant (RRC) with RCI, Inc. and is Chairman of the Board of Directors of the Roofing Industry Committee on Weather Issues (RICOWI) and the Cool Roof Rating Council (CRRC). He is a member of ASHRAE and ASTM Committees D8 Roofing and Waterproofing, E5 Fire Standards, and E60 Sustainability.

Manfred Kehrer received his Dipl.-Ing., in Technical Physics in 1993 from the University of Applied Science in Munich, Germany. After that, he was working at Fraunhofer IBP, Germany, for 10 years in the laboratory of the department Hygrothermics where he set up, used and maintained several hygrothermal laboratory measurement as well as working on several hygrothermal field tests. After this time he changed to the software development group of the department Hygrothermics, where he started to work on modeling, programming and testing of the transient hygrothermal transport calculation (WUFI). In 2005 he became the Group Manager of that group and was responsible for the development, quality control and sales of the WUFI products and was highly involved in many collaboration projects worldwide.

He recently joined ORNL with the Building Envelopes Research as a Senior Researcher, where he is in charge for hygrothermal investigations.

Introduction

Interest in energy-efficient building design has never been higher. There are many reasons for this, including:

- Rapid escalation in oil, natural gas and electricity rates
- More stringent energy code requirements designed to decrease energy use by a minimum of 30 percent
- Energy code requirements designed to shift peak energy usage to later in the day
- A focus on sustainable and green building practices, which require more energy-efficient buildings

Many strategies can be employed to reduce a building's energy usage. This report focuses on one of the methods being employed to reduce energy usage—specifically the use of highly reflective single-ply roof membranes sometimes referred to as "cool" roofs.

How does a highly reflective roof surface decrease energy use?

The sun generates a tremendous amount of energy in the form of electromagnetic radiation. Part of this energy is absorbed by the earth's atmosphere; the remaining solar irradiance hits the earth's surface. Some of the solar irradiance that hits the earth's surface is reflected back to the atmosphere and some is absorbed. Once absorbed, the energy is emitted back to the sky or released to potentially warm materials below.

All these phenomena occur within a fraction of a micrometer of the impacted surface and are defined as follows:

Absorptance (α)—the fraction of energy that penetrates the surface

Reflectance (ρ)—the fraction of incident radiation that is reflected by the surface

Emittance (ε)—measures how well the surface radiates energy away from itself compared to a black body operating at the same temperature (Miller, et al. 2002)

The amount of energy available to warm materials below the impacted surface depends upon the impacted surface's reflectivity and emissivity. For example, temperature measurements made at Oak Ridge National Laboratories' Buildings Technology Center show that, on a 90 F day, a roof surface with an aged cool roof membrane typically was 40 F cooler than a roof surface with a dark absorptive membrane. (Miller, et al. 2002) This means on a 90 F day, the roof surface of a highly reflective roof would be about 130 F, while the surface of a black membrane would be about 170 F.

This directly affects the amount of heat that will flow into the building. Heat flow is defined by the following relationship:

$$Q = \Delta T/R$$

Where:

Q = heat flow

ΔT = temperature difference between the exterior and interior boundaries

R = resistance to heat flow across the system

Assuming a roof system with a highly reflective roof surfac**e** and one with a black roof surface have the same R-value through the assembly and the same interior temperature, then heat flow will be higher in the assembly with the black surface because the temperature difference between the exterior and interior boundaries will be much greater.

Because a highly reflective roof surface increases energy efficiency by reflecting incident radiation, these roof coverings are most effective in a cooling dominated climate. This is a climate where the bulk of the energy bill to condition the space is used to provide cooling. This would include Department of Energy (DOE)/International Energy Conservation Code (IECC) Zones 1, 2 and 3. (See Figure 1).

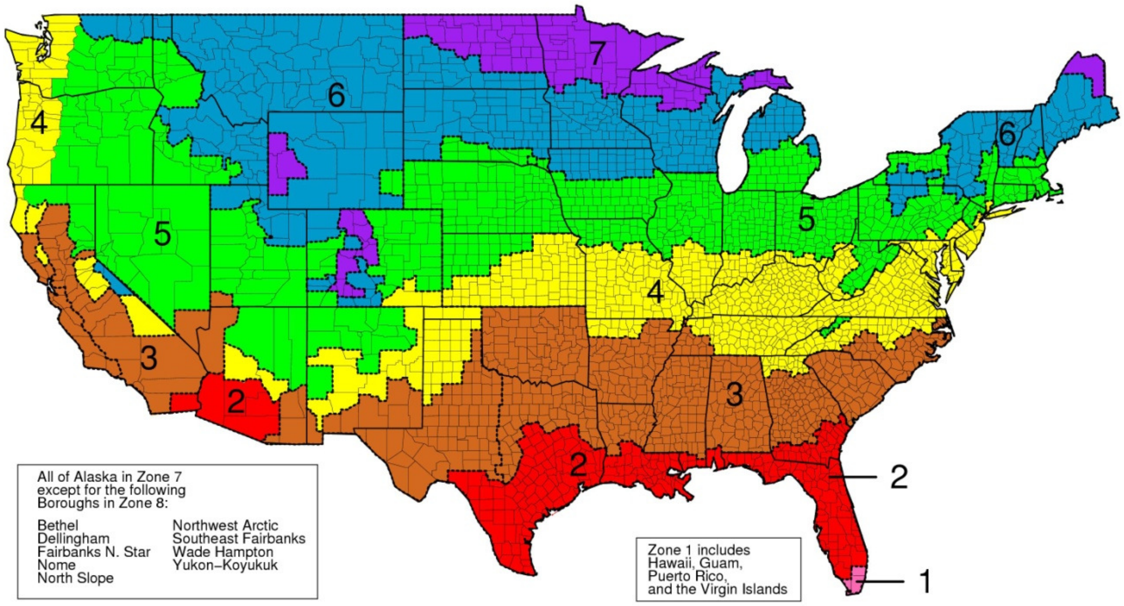

Figure 1 – IECC Climate Zones for the U.S.

What is a highly reflective roof system and what codes or standards recommend its use?

When requirements for the use of highly reflective roof **systems** first began to appear, they were based on their initial reflectivity and emissivity. However, it was noted through general use and research that the reflectivity of these products decreased with time, with the majority of this decrease occurring during the first three years of outdoor exposure until stabilized. (Miller, et al. 2002) Now, in most instances, requirements are based on three-year aged values. Different values are required for steep- and low-slope roof assemblies. This report focuses only on low-slope (less than 2:12) roofs. Some examples of cool roof requirements for low-slope roofs are:

- Title 24, Part 6, of the California Code of Regulations: California's Energy Efficiency Standards for Residential and Nonresidential Buildings defines a reflective roof for low-slope roof systems (less than or equal to 2:12) as one that has a three-year aged minimum reflectivity of 0.55, minimum emissivity of 0.75 or an aged Solar Reflectance Index (SRI) of 64. Cool roofs are prescriptively required in California Climate Zones 2 thru 15.

  SRI is a measure of the surface's ability to reflect solar heat. It takes into account reflectivity and emissivity. It is defined so a standard black surface (reflectivity 0.05/emissivity 0.90) is 0 and a standard white surface (reflectivity 0.80/emissivity 0.90) is 100. (ANSI/CRRC Test Method-1)

- The ENERGY STAR® Program administered by the Environmental Protection Agency (EPA) offers a slightly different definition of a highly reflective roof. The ENERGY STAR Program defines a highly reflective roof as one that has an initial minimum reflectivity of 0.65 and a three-year aged minimum reflectivity of 0.50. The ENERGY STAR program does not currently contain an emissivity requirement.
- The U.S. Green Building Council in its LEED® 2009 rating program for New Construction defines a reflective roof for use on a low-slope roof (less than or equal to 2:12) as one with an initial SRI of 78. The LEED program references the Cool Roof Rating Council as a source of information for reflectivity and emissivity values for various products.
- The International Green Construction Code (IGCC) requires the use of highly reflective roofs, with exceptions, in Climate Zones 1, 2 and 3, for heat island mitigation. In the IGCC, low-slope highly reflective roofs are defined as roofs with a

three-year aged reflectivity of 0.55, emissivity of 0.75 or SRI of 60.

The 2012 IECC contains prescriptive requirements, with exceptions, for using highly reflective membranes in climate zones 1, 2 and 3. IECC defines low-slope highly reflective roofs as roof systems with a three-year aged reflectivity of 0.55, emissivity of 0.75 or SRI of 64.

So, as one can see, there can be several ways to define a reflective roof surface, but many codes and standards require their use. When designing a building with an energy-efficient reflective roof system, it will be necessary to verify the system chosen meets the required performance characteristics.

What are the concerns with using highly reflective roof membranes?

The energy-saving potential of using highly reflective roof systems is well documented, particularly in cooling climates. However, some concern has been expressed with the use of highly reflective roof systems in heating climate zones such as Climate Zones 4 to 8. One of these concerns is moisture accumulation in the roof system during winter months. The concern is that roof systems that use a highly reflective roof membrane are cooler year-round than a system using a noncool membrane. Although this can provide a reduction in energy use, it also may create a situation where the temperatures below the roof membrane remain below the dew point temperature, allowing condensation to occur. With a noncool membrane, the temperature will be above the dew point temperature for a longer period of time, allowing time for the roof system to dry out (Hutchinson, 2009). Roof design is critical and moisture accumulation can occur during winter months under cool and non-cool roof membranes if they are not properly designed.

Hutchinson is not alone in his concern about moisture accumulation in low-slope roof assemblies because of the use of highly reflective roof membranes. To further our understanding of this issue, SPRI, an association representing single-ply membrane manufacturers, component suppliers and design professionals undertook a project to investigate this concern. The project used three data sources in this study:

1. Membrane test cuts
2. Moisture accumulation modeling using the WUFI program
3. Test data obtained during a previous study to evaluate roof recover drying rates.

This paper will present the test protocol and conclusions from each of these studies.

Membrane test cut program

Test protocol

The objective of this portion of the project was to examine roof systems using highly reflective roof membranes in heating climates by cutting into the roof systems and examining them for moisture accumulation. Following are the requirements that were followed to identify candidate roof systems:

- The roof system must be in a heating climate–the concern about moisture accumulation in the roof assembly would be more pronounced in cold climate zones, which is why the target roof systems were to be located in the heating climates zone. All the roof assemblies evaluated for this study were in Climate Zone 5.
- Test cuts must be taken during the winter months–to maximize the potential for identifying moisture in the roof assembly, test cuts were taken during winter months.

All test cuts were taken in February or early March 2010.

- Test cuts are to be made before 10:30 a.m.–this was included as a requirement to make sure test cuts were made early in the day, before the rooftop warmed to maximize the probability of observing moisture under the roof membrane. In this study, all cuts were made before 10:30 a.m. except for the Erie, Pa., roof system where the cut was made at 11:30 a.m.
- Only light-colored roof systems are tested–for this study, we were targeting light-colored roof systems because the concern dealt with highly reflective roof systems.
- A single layer of insulation is present–single insulation layer assemblies were targeted because we believed this afforded the greatest opportunity for moisture movement through the roof assembly to the back side of the roof membrane. It was further anticipated this would be the most likely condensing surface, allowing for the greatest potential of moisture accumulation in the assembly.
- Only mechanically attached systems were studied–all roof systems were to include mechanically attached single-ply membranes. This is because the installation method for these membranes allows for airspace between the roof insulation or cover board that could allow for moisture accumulation. In situations where the membrane is adhered to the substrate below, there is no space for moisture to condense, greatly reducing the potential for moisture accumulation.
- No vapor retarder is present–the presence of a vapor retarder effectively would limit moisture vapor movement from the building's interior into the roof assembly. To create the most critical scenario, it was decided to only perform roof cuts on roofs that do not contain vapor retarders.

- A roof system that had been in place for at least 5 years. This was to allow time for moisture to accumulate in the roof assembly. Moisture flows in and out of a roof assembly depending upon exterior and interior conditions, which create a vapor pressure differential across the roof system. If the time period during which moisture infiltrates the roof assembly is greater than the time period during which moisture moves out of the roof, then moisture will accumulate in the roof assembly over time. We also wanted to avoid roof re-cover situations because the conditions in the assembly would be unknown, potentially resulting in some reason other than the membrane color to affect the test cut's results.
- The building must be climate-controlled–the building must have a climate-controlled interior to provide a vapor drive across the roof assembly, driving moisture into the roof assembly, particularly in cold weather.

Membrane manufacturers agreed to find roof systems meeting the previously mentioned criteria. Manufacturers' technical representatives or roofing contractors were to cut open a roof system, examine it for condensation on the membrane, and determine the status of the facer and insulation and report back. The test cut was to be made across an insulation joint and in an area that shows no history of leaks such as near patches, etc.

Figure 2 provides an example of the test data collection sheet provided to the representative doing the sampling.

SPRI White Membrane Moisture Study

Roof Inspection Checklist -- Test cuts must be made before 10 a.m.

Roof System Information

Membrane Type/Color	
(TPO or PVC)	TPO / White
Insulation Type/Thickness	
(single layer of polyisocyanurate only)	2.75-inch ISO 95+GL
Mechanically Attached Membrane (only)	MAS 10-foot Seam Spacing
No Vapor Barrier	NO
Type of Building – Warehouse, Office, Retail	
(must be heated & air conditioned)	Retail
How old is the roof (must be at least 5 years old)	Installed 12/07/02
Building Location (City & State)	Erie, Pa.
Time of Sampling	11:30 a.m.

Investigation Details (please provide electronic pictures for each item below, where applicable, No samples are required)

Make a small cut in two separate areas of roof membrane across insulation joints (About an 8-inch by 8inch cut). The cut should be large enough to determine the following items and be in an area that shows no history of leaks: (Note the relative location of cut on roof–roof edge, center of roof)

- Is there condensation on the bottom of the membrane?

Please describe (small beads, heavy water film, etc.) NO

- Is the Insulation facer wet?

  Please describe (moist, soaked, etc.) NO

- Is the facer damaged? Please describe

  (facer plies separating, facer delaminating, etc.) NO

- Any moisture in or visible damage to the insulation foam core or the steel deck? NO

- Additional comments.

  There was evidence of moisture migration through the joints in the center roof cut; however, this appears to be dry and probably occurred during building construction.

Figure 2 – Example of completed test cut evaluation form

Figures 3, 4, and 5 are examples of test cuts that were completed on the roof systems. These pictures were taken on the roof system located in Erie. Figure 3 shows the back side of the TPO membrane; Figure 4 shows the surface of the polyisocyanurate foam insulation; and Figure 5 shows the core cut taken from the polyisocyanurate foam insulation.

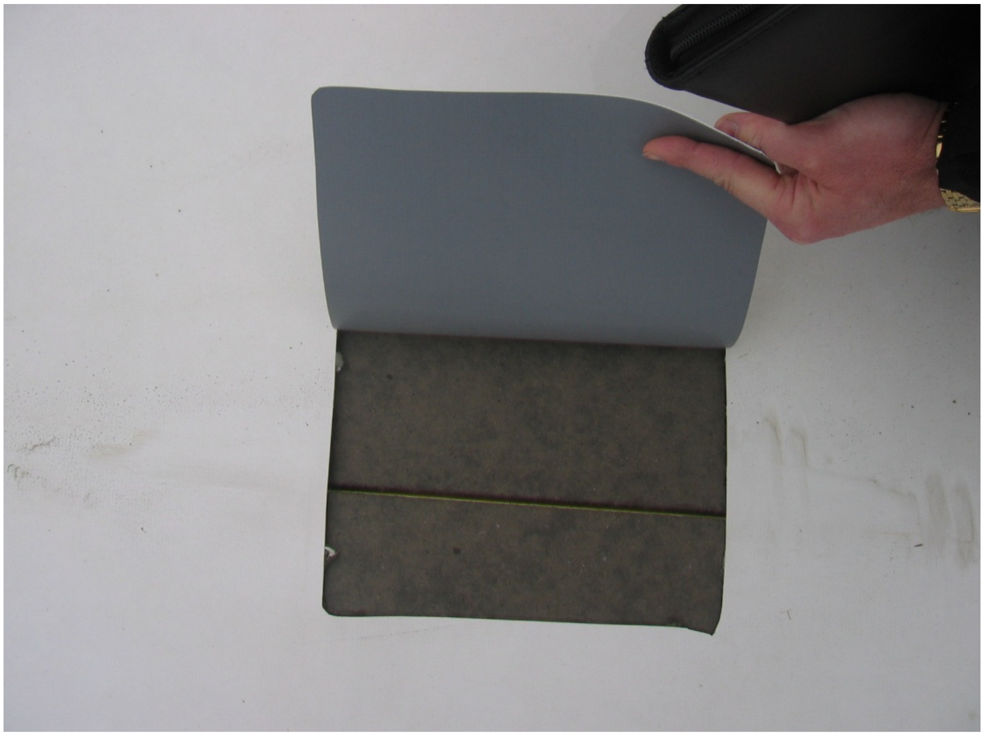

Figure 3–Back side of TPO membrane above insulation joint in Hartland, Mich.

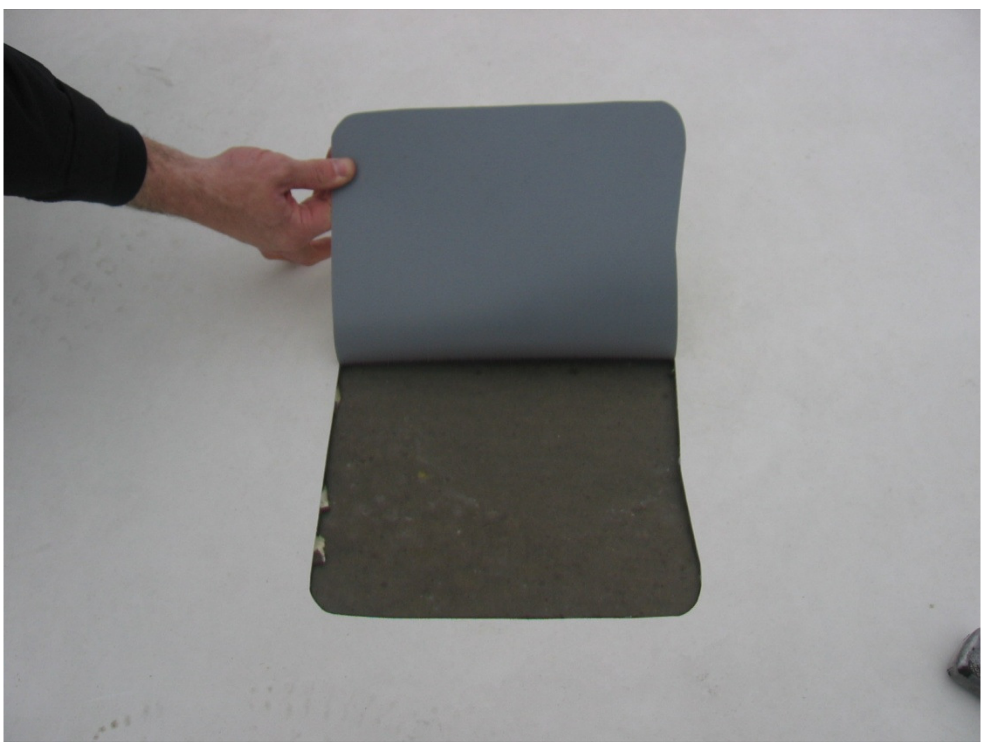

Figure 4–Example of polyisocyanurate foam facer in Hartland, Mich.

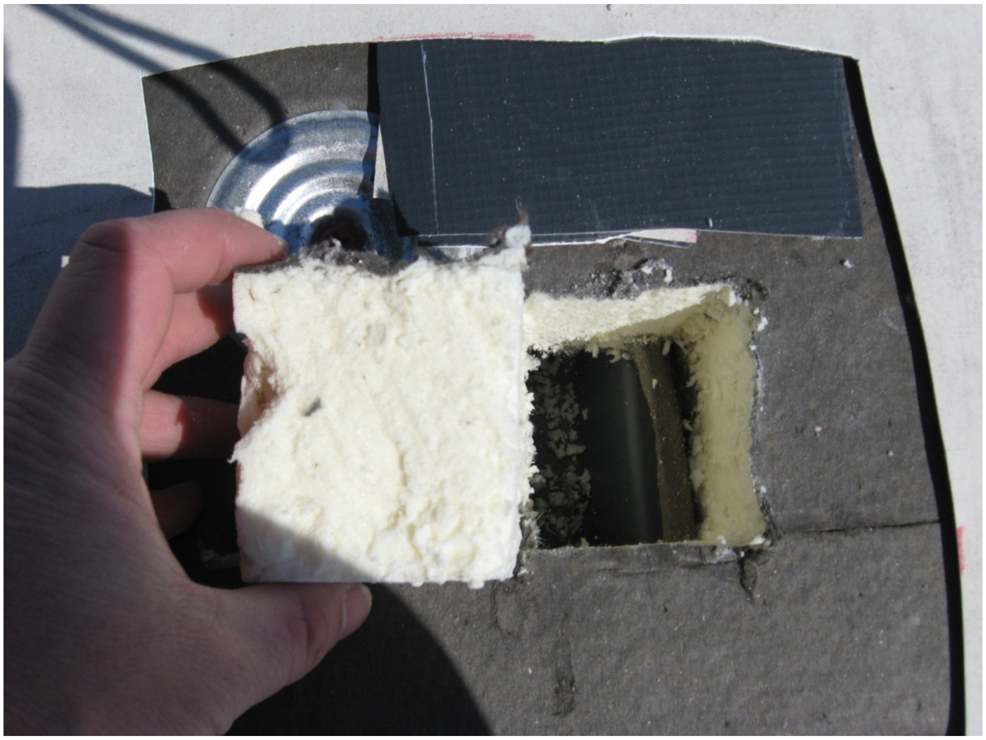

Figure 5–Example of foam test cut in Erie, Pa.

Table 1 provides a summary of the test results.

Membrane type/color	Insulation type/thickness	Method of attachment	Vapor barrier (Y/N)	Location of cut	Building type	Roof age (years)	Location	Describe condition below membrane	Describe insulation facer condition	Describe insulation core condition
TPO/ white	Polyisocyanurate/ single 3-inch-thick layer	Mechanically attached	N	Next to HVAC unit above office area	Office & garage	6.5	Southbridge, Mass.	Damp	Slight stain/ no damage	Insulation dry/no rust on steel deck
TPO /white	Polyisocyanurate/ single 2-inch-thick layer	Mechanically attached	N	Center of the roof	Retail	9.5	Holyoke, Mass.	Wet	Wrinkled but still laminated to the insulation	Insulation dry/no rust on steel deck
TPO/ white	Polyisocyanurate/ single 3-inch-thick layer	Mechanically attached	N	Southwest corner, insulation joint was 1-inch from cut	Retail	12	Manchester, N.H.	Damp	Slight stain on facer	Insulation dry/ deck in excellent condition
TPO/ white	Polyisocyanurate/ single layer	Mechanically attached	N		Cable station	2	Chicago	No moisture	No damage	Insulation dry
TPO/ white	Polyisocyanurate/ single layer	Mechanically attached	N		Conditioned	3	Chicago	No moisture	No damage	Insulation dry
TPO/white	Polyisocyanurate/single layer 2.75-inch thick	Mechanically attached 10-foot seam spacing	N		Retail	7.5	Erie, Pa.	No moisture	No damage(1)	Insulation dry
PVC/grey	Polyisocyanurate/ single layer 3-inch thick	Mechanically attached	N		School	5	Lake Fenton, Mich.	No moisture	No damage	Insulation dry
TPO/white	Polyisocyanurate/ layers 1.5-inch thick each	Mechanically attached	N		Office	3	Springfield, Mass.	No moisture	No damage	Insulation dry
TPO/ white	Polyisocyanurate/ single layer 3-inch thick	Mechanically attached	N		Grocery	2	Hartland, Mich.	No moisture	No damage	Insulation dry
TPO/ white	Polyisocyanurate	Mechanically attached	N		Retail	4	Round Lake, Ill.	No moisture	No damage	Insulation dry

Conclusions From the Test Cut Study

Ten roof systems were investigated. In seven of the cases, no moisture or damage to the polyisocyanurate foam insulation or facer was noted. In three of the cases, condensation was apparent on the backside of the highly reflective membrane. The level of condensation as described by the observer was “damp” to “wet.” Minimal damage had occurred to the polyisocyanurate foam insulation. Consequential impact was limited on the facer of the product and described by the observer as “stained,” and in one case “wrinkled,” but still laminated to the insulation. The foam itself was dry, with no rust on the steel roof deck.

The conclusion from this portion of the study is that although there were signs of moisture condensation in three of the 10 roofs observed, minimal effect had occurred to the roofing assembly that would affect its integrity, insulating value or performance. No detrimental effect to the roof system was noted.

WUFI modeling study

Hygrothermics

Besides a building component’s thermal properties and their effects on heating losses, its hygric behavior has to be considered, too. Permanently increased moisture content in the component may result in moisture damage. For example, elevated moisture levels in a roof assembly can lead to premature degradation of roof system components and ultimately the system’s failure. In addition, a building component’s thermal and hygric behavior are closely interrelated: Increased moisture content increases heat losses; the thermal situation affects moisture transport. Therefore, both have to be investigated together in their mutual interdependence; the research field of hygrothermics is handling these problems.

When modeling these phenomena, a tool must be used which is capable to model heat and moisture transport in a transient simulation under real boundary conditions. Long-wave radiation must be considered; otherwise nightly overcooling cannot be achieved in the simulation. In order to accurately calculate the temperatures of exterior surfaces, which are a key point to estimate the condensation risk, a detailed radiation model was developed based on physical fundamentals. This model was integrated into the well established hygrothermal software (Künzel, H.M., 1995) for the calculation of the coupled heat and moisture transport in building components and validated many times for instance in (Kehrer, M., 2008).

The most common method of evaluating a building assembly's moisture performance assumes steady state conditions. This does not accurately portray the changing water vapor drive conditions that occur in the actual building environment.

WUFI (Wärme und Feuchte instationär - Transient Heat and Moisture) addresses this issue. It is a menu-driven PC program developed by IBP [What does this stand for?] and validated using data derived from outdoor and laboratory tests. It allows realistic calculation of the transient hygrothermal behaviour of multilayer building components exposed to natural climate conditions.

WUFI is based on the newest findings regarding vapor diffusion and liquid transport in building materials and only requires standard material properties and easy-to-determine moisture storage and liquid transport functions. The program can use measured weather data--including driving rain and solar radiation--as boundary conditions, allowing realistic investigations on the behavior of the component when exposed to natural weather.

WUFI has been used to assess the drying time of masonry with trapped construction moisture; danger of interstitial condensation; influence of driving rain on exterior building components; effect of repair and retrofit measures; and hygrothermal performance of roof and wall assemblies in different climate zones.

Modeling protocol

For the hygrothermal simulation the following input data have been used:

Assembly (interior to exterior)

- Traditional metal deck
- 2” to 3” polyisocyanurate insulation boards, thickness is depending on the specific roof cut.
- White TPO / PVC Membrane

Material properties from the hygrothermal model database are utilized except for the metal trapezoidal construction where a permeance of 0.75 [perm] is used supposed to be representative for the metal deck including the leakages due to screws, according to investigations done by ORNL.

Outdoor Boundary Conditions

Climate files from the hygrothermal model database on an hourly basis closest to the observed objects have been used (The locations are Boston, Albany, Chicago, Cleveland and Detroit). These used climate files represent the 10% coldest climate conditions according to IEA Annex 24. To study the impact of the less absorptive "cool color", one set of simulation has been carried out with a solar absorptivity of 30% except one simulation with a gray surface and therefore a solar absorptivity of 50%. Another set of simulation has been carried out with a solar absorptivity of 90%, which represents a black color of the exterior surface.

Indoor Boundary Conditions

Indoor Design Temperature and RH on an hourly basis according to the simplified method (ASHRAE Standard 160, 2009) as shown in Figure 6 have been used.

Initial Conditions

The simulation started with an initial moisture content of EMC80 (ASHRAE Standard 160, 2009) on October 1st and was carried out for one year.

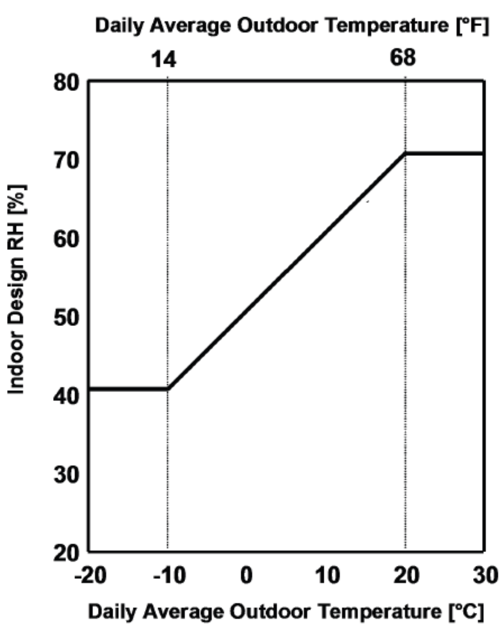

Figure 6: Indoor Desigh RH, simplified method, according to (ASHRAE Standard 160, 2009).

Simulations have been carried out for all observed objects. Moisture content of the most exterior 2 mm (80 mil) of insulation for every simulation has been evaluated to receive the layer thickness of condensate [mm].

Modeling results

Figure 7 shows the calculation results of the roofs with white exterior surface (cool roof). Yellow curves are simulations correlating with a wet/damp result of the visual observation and each black curve correlates with a dry observation result. The following can be stated:

- All roofs accumulate water underneath the exterior TPO/PVC-membrane during the winter and dry out completely in summer.
- The layer thickness of condensing water is roughly 0.2 mm (8 mil) for all roofs.
- The impact of the specific climate location and the exact insulation thickness is minor.
- Appears to be no significant correlation between the simulation results and the observations.

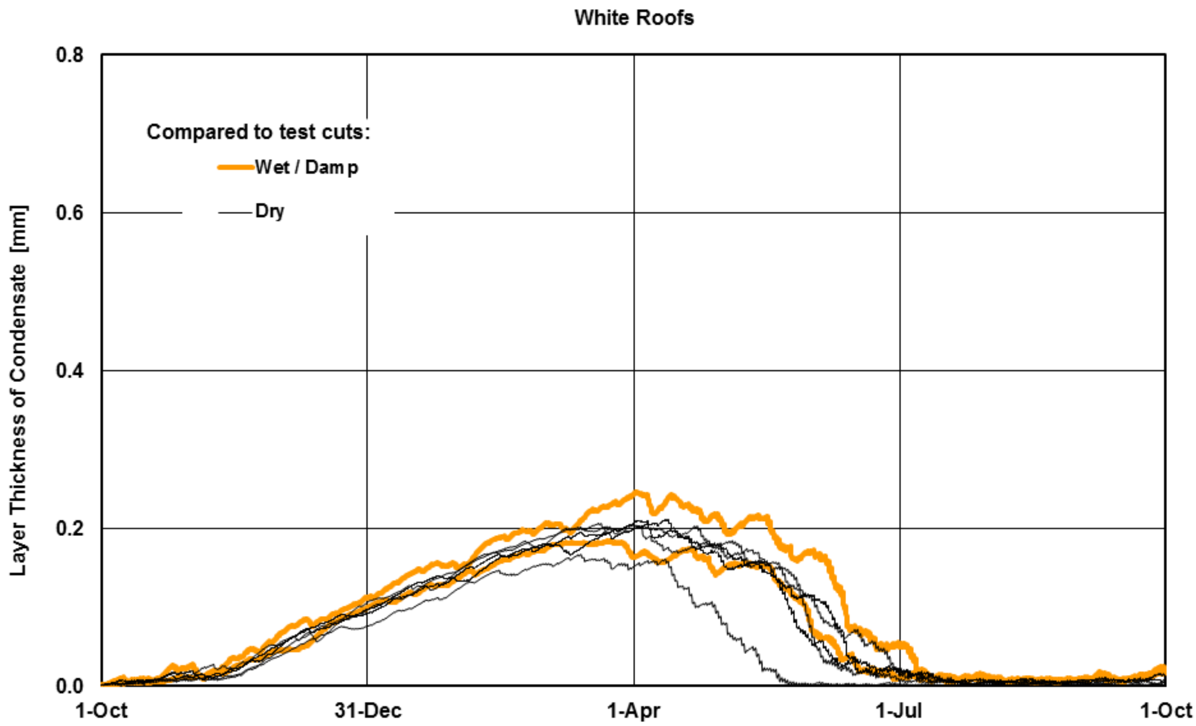

Figure. 7: Layer thickness of condensate depending on time of all simulated roofs with white exterior surface. The Legend describes whether the test cut associated with this calculation showed dry or wet conditions**.**

Figure 8 shows the calculation results of the roofs with black exterior surface where we can note:

- Generally similar behavior compared to white roof calculations of for all roofs.
- The maximum layer thickness of condensate is with roughly 0.08 mm (3 mil) which is less than half compared to the white roof results.

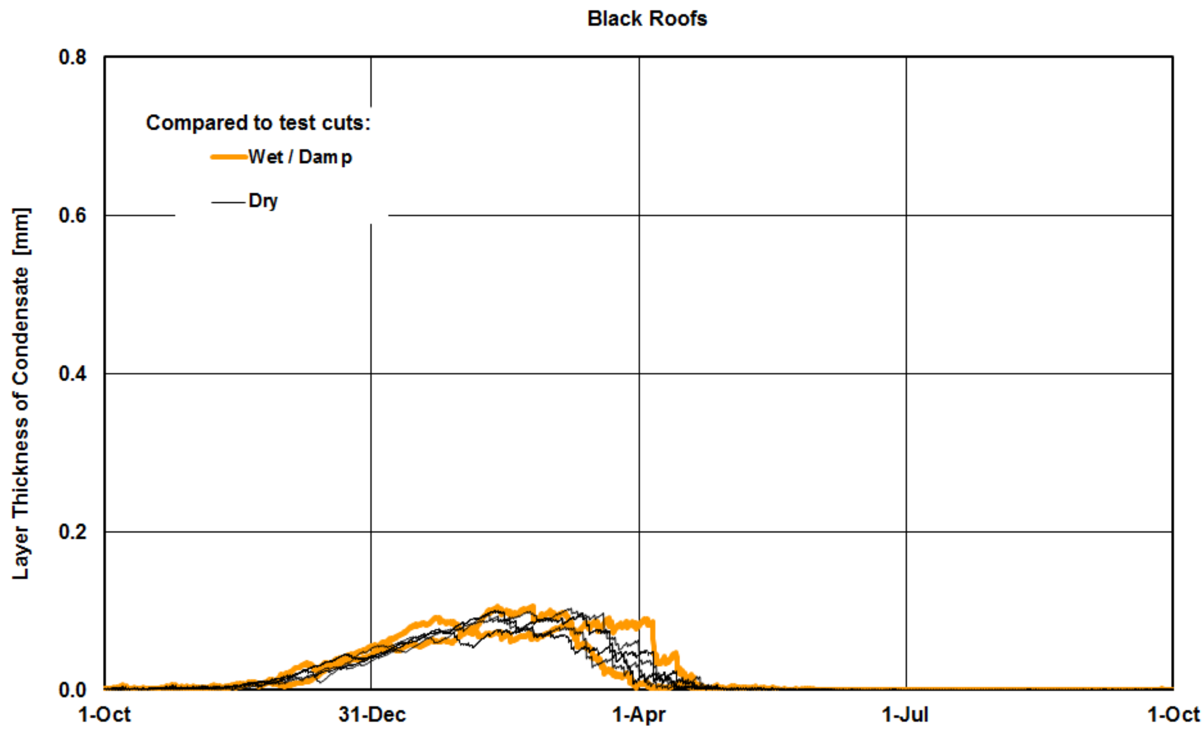

Figure 8: Layer thickness of condensate depending on time of all simulated roofs with black exterior surface. The Legend describes whether the test cut associated with this calculation showed dry or wet conditions.

Conclusions

The results show that the solar absorptivity of the surface and thus surface color impact the condensation risk of the investigated type of roof in climate zone 5. The exact climate location within the climate zone 5 as well as the exact insulation thickness has only a minor influence on the condensation risk. Modelling showed that the amount of condensation for white roofs is more than twice the amount for black roofs due to less gained solar energy needed for the dry out process. However, in within the parameters used in this study, both roofs returned to a dry condition during the course of the year, which is consistent with filed test cut observations.

Roof re-cover drying rate study

Background

In 1997, SPRI initiated a project to evaluate the drying potential of failed roof systems containing moisture that were re-covered by single-ply roof membranes. Two buildings were evaluated. The subject of the paper referenced in this report was a building located in Rossville, Ill. One of the variables evaluated was the effects of roof membrane color on the roof system's drying rate. This study is pertinent to the current topic because the effects of roof membrane color on the roof system's ability to dry will contribute significantly to long-term moisture accumulation.

Test protocol

Building selection

The subcommittee was searching for a building that met the following criteria:

- The size of the building should be large enough to represent a typical building but small enough to control the cost. Ideally, the building should be between (3,000 and 10,000 square feet (280 and 930 m^2).
- The building ideally should be located in a northern climate and have a conditioned interior. The roof system must be contaminated with an appreciable amount of water.
- The roof system must have the potential to dry downwardly (no vapor retarder).
- The roof system should be as "typical" as possible—i.e., have a metal deck, some insulation and a traditional membrane.
- The deck must be structurally sound.

- Access to the roof, edge detailing and all other aspects of reroofing should be considered to minimize the overall project cost.
- The building owner must be willing to allow performance of an experiment on his building
- Ideally, the building should be owned by a nonprofit organization that would benefit from the reroofing project.

Many of the selection criteria are similar to the criteria used to select roof systems for test cuts in this study. Figure 6 shows the building selected for the re-cover study, which is located in Climate Zone 5. The roof system had a 1:12 slope with an existing BUR roof assembly, which had been re-covered at some point with an asphalt base sheet with a liquid-applied aluminum coating.

Test step up

After removing any loose coated felt and sweeping off loose aggregate, a re-cover board consisting of either ½-inch (13-mm) wood fiberboard in 4- by 8-foot (1.2- by 2.4-m) sheets or nominal 2-inch (5-mm) polyisocyanurate foam in 4- by 8-foot (1.2- by 2.4-m) sheets were mechanically attached to the roof deck.

About half the roof area was covered with a black or white mechanically attached TPO single-ply membrane. White membrane was used on the western half of the roof system and black membrane was used on the eastern half. Because two manufacturers donated membrane, the roof was further split to accommodate the inclusion of their membranes. Figure 7 depicts the layout of the insulation and membranes.

The building was reroofed in this manner because of the interest in examining the effects of roof color and re-cover insulation R-value on the roof system's drying rate. The black and white ethylene propylene membrane had solar reflectances of about 0.05 and 0.8, respectively. These solar reflectance values approximate the limits of membrane color used in roofing applications.

Instrumentation was installed in the roof system during the reroofing. Six temperature sensors were installed directly under the membrane and two sets of temperature and relative humidity sensors were installed inside the building. These sensors would be used as the boundary conditions of the modeling efforts; the sensors below the membrane effectively would define the climate side of the roof system while the sensors below the deck would monitor the indoor conditions. All the instrumentation was connected to a data acquisition system (DAS) installed in the building. The DAS sampled the output of each sensor every minute and computed 15-minute averages that were stored in memory for subsequent analysis.

When the re-cover was completed, the roof was marked off in a grid pattern on 5-foot (1.5-m) centers. Each intersection of the gridlines was given a two-number ID; the two numbers identified the location of all the intersections from the southwest corner of the roof system. The first digit identified the intersection's distance (in feet) from the southwest corner in the north/south direction and the second digit identified the same parameter in the east/west direction.

A major goal of this project was to determine how rapidly the existing roof system would dry after it had been re-covered. To assess the roof system's drying rate, it was essential to accurately determine the initial concentration and distribution of moisture in the existing roof system. To accomplish this, a nuclear densometer moisture survey of the entire roof on a grid with nodes 5 feet (1.5 m) apart was completed. Seven core samples were taken at the same time and were used to calibrate the output of the nuclear densometer. The relationship between the nuclear densometer's output and moisture content of the core samples (determined gravimetrically) was obtained by linearly regressing the data. Coefficients of fit for these regressions exceeded 0.95. Separate relationships were developed for the different re-cover insulation areas; those relationships then were employed to determine the moisture content for each location sampled with the nuclear densometer. The average moisture content for the total roof system was determined by an area-weighted sum. Additionally, area weighted moisture contents of the roof areas covered by different re-cover insulations and different membrane colors also were determined. Nuclear densometer surveys were repeated 4, 12 and 25 months after reroofing. These data are presented in Table 2.

Roof Area	Average Moisture Content, Weight Percent, After			
	0 Months	4 Months	12 Months	25 Months
Entire Roof	14.2	13.4	11.1	9.0
WFB Re-cover	17.6	16.3	12.8	9.6
PIR Re-cover	10.8	10.5	9.5	8.3
Black Membrane	14.6	13.6	10.8	8.6
White Membrane	13.7	13.1	11.1	9.3

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Table 2 – Drying rate of various test roof sections included in roof re-cover study

Conclusions from roof recovery study

1. The drying rate for the section of the test roof system covered with a black roof membrane was slightly greater than the drying rate of the test roof system section covered by the white membrane—6 percent by weight vs. 4.4 percent by weight.
2. This difference in drying rate did not affect the performance of the fasteners or insulation over the two-year period of the study.

Overall conclusions from the study

1. Situations where moisture accumulation occurs are design issues.
2. When designing a roof system membrane color, in addition to other variables such as building conditions, insulation levels and local weather conditions must be considered in order to prevent moisture condensation and subsequent accumulation within the assembly.
3. Within the parameters used in this study, roof systems with white membranes and those with black membranes both went through wetting and drying periods throughout the year, with both systems returning to a dry state during the course of the year.
4. Reports referenced in this paper, have concluded that moisture accumulation in the roof assembly does occur and can be severe, impacting the long-term performance of the roof assembly. However, this was not observed during this study, with only 3 of the 10 roofs studied showing only minimal signs of condensation.
5. Modeling using transient moisture models such as WUFI can and should be used by design professionals to assess the tendency of various roof designs to allow for moisture accumulation and determine how to design a roof assembly to prevent

such problems. Corrective measures may include the use of vapor retarders, double layer insulation and sealing penetrations, to name a few. It is recommended that further investigation should be conducted in climate zones 6, 7, and 8.

6. It is also recommended that the effect of possible ventilation effects due to wind pressure and hence uplift of the exterior membrane be investigated. Using the WUFI model to simulate this effect indicates that introducing interior air into the roof assembly via this mechanism increases the potential for condensation within the roof assembly.
7. Specifically further investigations should be done to determine the maximum allowed air leakage depending on the climate zone.
8. It is also recommended that the effect of possible ventilation effects due to wind pressure and hence uplift of the exterior membrane be investigated. Using the WUFI model to simulate this effect indicates that introducing interior air into the roof assembly via this mechanism increases the potential for condensation within the roof assembly. Specifically further investigations should be done to determine the maximum allowed air leakage depending on the climate zone.

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