Long Term Reflective Performance of Roof Membranes

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INTRODUCTION

Today there is a great deal of discussion in the industry, about cool roofs, green roofs, garden roofs, vegetated roofs and other roof systems that are expected to be more ecologically friendly than “conventional roofs”. Cool roofs have received much positive trade press, and some state and federal support for installation where comfort cooling is the dominant building energy load. Some have used the cooling energy savings to promote the use of cool or reflective roofs to areas of the country where cooling requirements are not the dominant energy user. Although we cannot address all of the issues associated with cool roofs, we will address one study that shows how the reflectance of sheet membrane roofs changes over time and how building energy use is affected by reflective roofs. We will not address any product longevity or heat island issues.

Energy Star (a program administered by the US Environmental Protection Agency) requires that low slope roofs have an initial solar reflectance of 0.65 and a three-year aged reflectance of 0.50 to qualify for an Energy Star rating (the requirement for steep slopes is a 0.25 initial reflectance and a 0.15 reflectance after three years). This is the definition of a reflective roof that has been most widely accepted by the roofing and building energy community. Solar reflectance is defined as the fraction of solar flux reflected by a surface expressed as a percent or within the range of 0.00 and 1.00. Therefore all commonly available roofs have some reflectance. However, not all roofs meet Energy Star and, to a large extent, those roofs that meet Energy Star are white or very light colored roofs.

The other common requirement for roofs to be considered “cool” is the requirement for high emittance. Emittance of a surface is defined as the fraction of the maximum possible thermal radiation that the surface emits because of its temperature. The maximum possible thermal radiation is that emitted by a black body at the same temperature. Typical emittance of non-metallic roofing materials, including both black and white membranes is 0.85 to 0.90. Pure metal surfaces such as bare aluminum have a very low emittance of 0.05 to 0.2.

There are three ASTM methods for measuring the reflectance of roofs. They are: ASTM C1549-02, Standard Test Method for Determination of Solar Reflectance Near Ambient Temperature Using a Portable Solar Reflectometer; ASTM E903-96 Standard Test method for Solar Absorbance, Reflectance and Transmittance of Materials using Integrating Spheres, and ASTM E 1918-97 Standard Test Method for Measuring Solar Reflectance of Horizontal and Low Sloped Surfaces in the Field. A consultant is most likely to use ASTM C1549 or ASTM E 1918, while ASTM E903 provides a laboratory standard method to validate the field methods (Petrie, et al. 2001b).

Both ASTM E903 and C1549 test by evaluating a very small area of the material. This can be a general measure of reflectance for new homogeneous materials. If the material is not homogeneous in surface characteristics multiple readings are required and these must be averaged. Neither method produces reproducible results with variegated materials, such as ballasted roofs or shingles. To test a variegated surface ASTM E 1918 must be used. ASTM E1918 must be used with much caution, as it only works in direct sun and with the sun at moderately high incidence angles. If you are to use these test methods be careful that you understand the procedures fully and use them with caution.

Reflecting heat off of the roof reduces the membrane temperature and the amount of heat that is transmitted into the building. The peak temperatures of highly reflective membranes are within 15ºF (8.3°C) of the ambient temperature. This provides little driving force for additional heat to the building from the roof. Therefore the cooling load is lower, and energy cost is saved relative to that for a black roof with the same conventional insulation level.

Two other claims are made for reflective roofs. The first is that the reflective roof being cooler results in greater longevity of roofing materials. The greater longevity makes sense theoretically, but still lacks published data to confirm or deny the claim. The second is that the cooler roof results in less atmospheric heat load, therefore reducing the ambient temperature around the building, and hence less heat island effect. The heat island effect of course does not only involve roofs, but also involves the paving material color on the streets and the exterior wall cladding of the buildings. It also involves the heat thrown off by air conditioners and cooling towers. Cooler roofs should help reduce the heat island effect by keeping the roof surface cooler and by reducing the use of air conditioning at the peak energy use times of the day.

Saving energy when the sun shines is what cool roofs are all about. They do not save energy at night when there is no sun or when it is cold outside. Insulation is an alternative for the energy side of the equation, and may have a positive contribution to mitigating the urban heat island effect by reducing air conditioning heat rejection. Insulation in the form of a protective membrane roof where insulation is exterior to the roofing membrane will contribute to extended membrane life. The DOE Cool Roof Calculator usually recommends very little additional insulation to achieve the same energy savings as adding a cool roof. With insulation being quite inexpensive it is just smart roofing to always install roofs with ASHRAE 90.1 recommended R-value insulation levels or greater.

The DOE Cool Roof Calculator, which will be further discussed in this paper, can show the difference in the cooling energy saved by a highly reflective roof and one that has become dirty from airborne contaminants. Knowing that roofs did lose reflectance over time SPRI sponsored a study by Oak Ridge National Laboratory to study the loss of reflectance for a three-year period and to attempt to determine the causes of the loss of reflectance. These results and the information that follow will assist in your design decisions.

THE EXPERIMENT

A combined experimental and analytical study was conducted to quantify the energy savings for cool roof membranes. SPRI and several members of SPRI enacted user agreements with ORNL to study the effect of climatic exposure on the surface properties of single ply membranes. SPRI and its affiliates field-tested for three years their single ply low slope roofing systems on the western half of the Envelope Systems Research Apparatus (ESRA) (see Fig. 1). The single ply membranes tested in the study were thermoplastics, bitumen-based membranes, and thermoset membranes covered with 15 lb/ft^2 or 73 kg/m^2 of ballast. The thermoplastics membranes tested were polyvinyl chloride (PVC), polypropylene or thermoplastic polyolefins (TPO). All test membranes were assigned proprietary codes. Participants knew the code only for their own roof product, and could therefore compare their system against the field of systems. The scheme kept the identity of each company's product confidential. A smooth built-up roof (BUR), Code C, was used as the base of comparison to determine energy savings.

Fig. 1. The Envelope Systems Research Apparatus is used for testing roof manufacturer's best products.

Experimental work included the initial measurement of reflectance and a subsequent measurement every fourth month. Emittance was measured annually. Field data of the temperature and heat flux were organized and plotted weekly for comparing the cool membranes against the BUR. Candidate single ply membranes were also exposed at field sites across the country, and reflectance there was measured semiannually to observe the effect of climate.

CLIMATIC EXPOSURE AND CLEANING IMPACTS

Three years of exposure in East Tennessee's climate soiled all white thermoplastic membranes that were field tested on the ESRA. It caused about 30% to 50% loss of surface reflectance, which for the most part occurred within the first two years of exposure (Fig. 2). The reflectance of the membranes A, G, K, and M continued to drop past two years of weathering. From the start, these membranes had the highest initial reflectance; however, the reflectance of the membranes F, I, and J each finished higher than A, G, K, and M after three years of exposure (Fig. 2). Membranes F, J, and I lost about 25% of their original reflectance after the three years of exposure. Neither the variation nor the intensity of precipitation affected the drops in reflectance, as seen by the vertical bars that represent monthly precipitation (Fig. 2). Actually, membranes A, G, K, and M show the largest loss in reflectance when the intensity of the rain was the

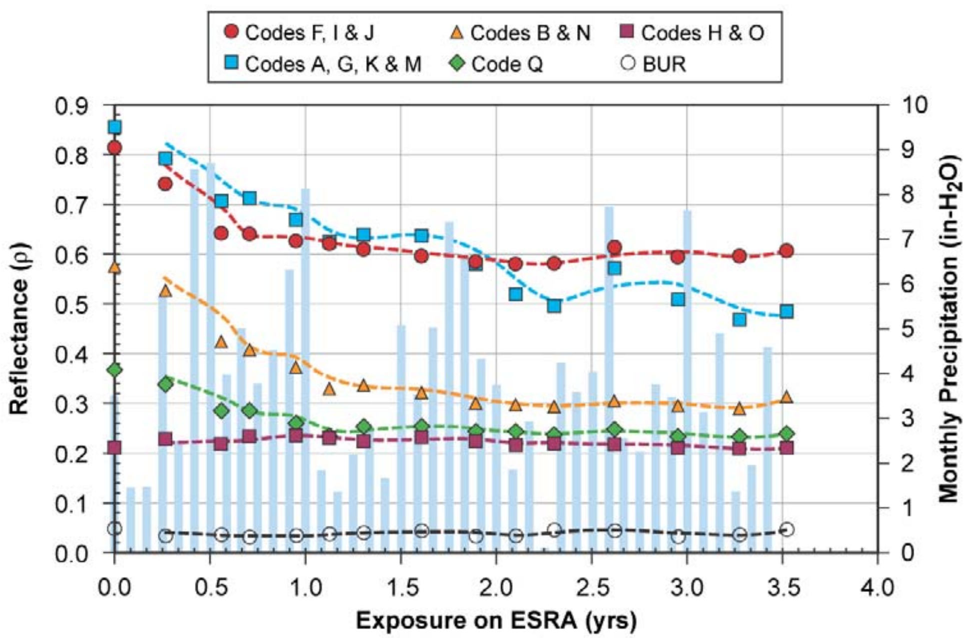

Fig. 2. The amount of precipitation has little effect on the reflectance of the membranes exposed on the ESRA.

strongest. At about 1¾ years of exposure, months having about 7 in. of rainfall occurred consecutively. Afterward the reflectance of membranes A, G, K, and M dropped an additional 15%, yielding a total reflectance drop of 40%.

Membranes B and N had the largest drop in reflectance. It was nearly 50% after 3 years of field exposure. Hence after three years of exposure in East Tennessee's climate, the loss in reflectance ranges from about 25% to a maximum drop of 50% of the reflectance for new materials.

The reasons for the loss of reflectance are not fully understood, but may very well be caused by the effects of biological growth and for some membranes by the effects of plasticizers formulated into the membranes. Our findings show that airborne particles themselves are responsible for the loss in roof reflectance, and these particles are also the vehicles for delivering microorganisms to the surface as they are deposited on the membrane. Microorganisms grow on the surface forming a biological film-like structure that is hydrophilic. Once formed, the structure forms a net that enhances the continued deposition of dirt onto the surface, which in turn leads to larger drops in reflectance. Without the surface biomass, particles will still deposit on a roof, but the drop in reflectance is less severe over time. A polar lipid fatty analysis confirmed our observations regarding the biomass and revealed a microbial (fungal) indicator prevalent on all the membranes, Miller et al. (2002). Correlating the drop in reflectance also helped substantiate our hypothesis. Regression analysis indicated that the parameters that most strongly influence the decrease in membrane reflectance were relative humidity, average daily temperature change, time, and the number of rain days. All of these parameters promote and stimulate the growth of biomass.

Both solid and liquid plasticizers are used in the formulation of some thermoplastic membranes to keep the material from becoming brittle and tearing. The climatic cycling of temperature is known to cause certain liquid plasticizers to migrate to the surface of the membrane, making the surface tacky; the plasticizers may also be a food source for the growth of the biomass (Griffin 2002). Also some solvents that are used to fully adhere single-ply membranes may after installation migrate over time through the membrane and leave a surface film that is tacky and collects dirt. In each case, the effect of biomass, plasticizer, application materials and their interaction should be investigated to determine their effect on the loss of reflectance of certain white thermoplastic single ply membranes. The results also suggest that manufacturers should check the formulation of certain thermoplastic membranes for ingredients that may promote fungal metabolism and thereby exacerbate the loss of reflectance. A judicious selection of ingredients that hinder the growth of biomass may be a key parameter for optimizing the formulation of white thermoplastic membranes for sustaining high reflectance.

Data from the field sites revealed that the loss in reflectance is similar across the country for some of the test membranes (J, F, and I). The dry climate in Denver, CO, showed similar drops in reflectance as observed in the predominantly heating-load climate of Joplin, MO, as well as in the colder and more humid climate of Boston, MA. However, the loss in reflectance for another family of membranes coded A, G, K, and M was less severe at the field sites than that observed on the ESRA. The field samples were not mechanically fastened to roof insulation and therefore were about 15°F (8.3°C) cooler at solar noon than the same thermoplastic membranes attached to wood fiberboard and tested on the ESRA. We believe the higher peak membrane temperature observed at solar noon is the probable cause of the differences in reflectance loss.

Washing the membranes with commercially available cleaners almost fully restored the reflectance. For example, the highly reflective membrane Code B had developed a splotchy dull gray appearance that caused reflectance to drop about 55% after three years of exposure. However, cleaning almost fully restored the surface reflectance. Similar results were observed for almost all the membranes. In this three-year, time-limited study, the results reveal that the surface opacity of the single-ply membrane limits the photochemical degradation caused by ultraviolet light present in sunlight because manufacturers have formulated the surface of their membranes to include special chemicals and titanium dioxide (TiO_2), a rare earth ceramic material. TiO_2 is used to give color to the material, and is chemically inert, insoluble, and very heat resistant. It increases surface reflectance through refraction and diffraction of the light. The light travels a shorter path and does not penetrate as deeply into the membrane; therefore, less heat is absorbed. Special chemicals that are proprietary information to each manufacturer are also used to weather-protect the membranes and performed well as evident by the restoration of surface reflectance after washing. Signs of weathering may occur after longer periods of exposure but continued discussion is beyond the scope of the reported three-year study.

The emittance of the membrane systems did not vary much from year to year. In fact, the variation in emittance was less than 5% of the average emittance for all the white thermoplastic membranes. The results are consistent with the observations of Wilkes, et al. (2000) for roof coatings. The average emittance for all the white thermoplastic membranes was about 0.90 and the average standard deviation for all the membranes was about ±0.04.

THERMAL PERFORMANCE

Energy simulations have shown that the heat transmission through the roof of a warehouse having a dark BUR with R-5 insulation was about one-half of the cooling loads for the whole building. The more reflective the roof membrane remains, the lower will be its surface temperature and the less will be the load supported by the cooling plant. Therefore, the thermal performance of low slope roofs is determined by the roof's exterior temperature, which in turn is affected by the soiling of the roof's surface. The soiling caused a drop in reflectance and caused the measured peak membrane temperature to increase from year to year as shown below in Table 1.

Table 1. The measured peak membrane temperatures for Code A, J, and C membranes exposed on the ESRA for three years to the climate of East Tennessee

	Aug. 14–20, 1998	Aug. 6–12, 1999	Aug. 11–17, 2000	Aug. 31–Sep. 6, 2001
Code A	106.1	132.9	133.6	140.2
Code J	110.0	130.5	121.5	119.1
BUR	169.2	168.6	159.0	162.8

The peak temperature for the BUR was a measured 169°F (76.1°C) in August 1998 and decreased slightly during the project as a result of some "graying" of the black BUR surface. The maximum outdoor air temperature was about 97°F (36.1°C). The Code A and Code J membranes are only about 9°F (5°C) warmer than the outdoor air temperature for measurements made in August of 1998. They soil with time and their peak temperatures increase. After three years, the surface temperature of Code A increased by about 34°F (19°C), which in turn caused the measured roof heat flow entering the building to double. On August 18, 1998, the measured daytime heat flux entering through the Code A membrane was 28 Btu/ft^2 (88 Wh/m^2). Three years later, on September 4, 2001, the heat flux had increased to 56 Btu/ft^2 (176.6 Wh/m^2). After one year of exposure, for measurements taken in August 1999, a 30% drop in reflectance caused the membrane temperature to increase by 27°F (15°C). The soiling of the single ply membranes caused by climatic exposure is therefore significant because after only one to three years of field exposure, the “highly reflective” membrane (Code A) has a surface temperature that is only 22.6°F (12.5°C) lower than a BUR. As a result, the heat flux penetrating Code A increased from 25% to 50% of the flux penetrating the BUR after three years of field exposure in Oak Ridge, TN.

As previously stated, the soiling of the Code J membrane was not as severe as that observed for Code A, and initially, Code A had a higher reflectance than Code J. However, the reflectance of membrane Code J exceeded that of Code A after three years of exposure. The soiling of the membrane J caused about a 30% loss in reflectance, which caused the peak membrane temperature to increase from 110°F (43°C) in August 1998 to about 119°F (48.3°C) in August 2001. The surface temperature of Code J was therefore almost 21°F (11.7°C) cooler than that of the Code A membrane, which in turn reduced the heat flux entering the roof. Overall, the membranes F, I, and J showed less soiling than did the membranes A, G, and K. Therefore, they performed better thermally than did membranes A, G, and K.

COOL ROOF CALCULATOR

Oak Ridge National Laboratory’s Simplified Transient Analysis of Roofs or STAR computer code was validated against the ESRA field data. The code predicts the membrane temperature within about ±5% of field measurements and predicts the daily heat flux within about ±10%. Petrie et al. (2001a) used STAR to formulate a roof calculator for predicting the heat flow solely through the roof. STAR generated the annual heating and cooling roof loads for different geographic regions within the United States. Typical meteorological year (TMY2) data (NREL 1995) was used by STAR to generate the loads for different climates. The loads data were formulated into empirical curve fits and programmed into an algorithm. The algorithms were used for estimating the loads and the amount of energy cost savings for a reflective roof as compared to a smooth, dark BUR with the same amount of insulation but with a solar reflectance of only 0.05 and an infrared emittance of 0.90. The calculator computations have no interaction with the characteristics of the building and therefore eliminate the confounding building variables that can confuse measuring the performance of a roof.

The relative effects of different surfaces and different amounts of thermal insulation are generally the same using the calculator and the STAR code. The average error in heating load is about ±15% for the Codes A, I, and H membranes simulated with insulation levels ranging from R-5 through R-30. Results also showed that the roof calculator predicted the cooling load of an R-5 roof in Phoenix, Knoxville, and Minneapolis within about ±5% of the STAR output for the membranes coded A, I, and H. Therefore, validations against

STAR data showed that the calculator predicts the cooling and heating loads of roofs exposed to cooling-dominant and also heating-dominant climates within about ±10%. The calculator is also accurate for insulation levels ranging from about R-5 through R-35.

Examples of the use of the calculator are depicted in Table 2. For the cooling-dominated climate of Phoenix, AZ, and the mixed climate of Knoxville, TN, a highly reflective membrane yielded the maximum energy savings. With a roof insulation level of R-5, energy savings are about $0.37/ft^2 per year and $0.13/ft^2 per year for Phoenix and Knoxville, respectively. Increasing the R-value to R-15 drops the annual energy savings from the highly reflective membrane to $0.13/ft^2 for Phoenix and $0.05/ft^2 for Knoxville. Of course, energy use is less for both the reflective and black R-15 roofs compared to the respective R-5 roofs.

Table 2 also shows the level of insulation needed by a smooth BUR to have the same annual operating cost as a high reflectance roof. In Phoenix, AZ, a dark absorptive BUR would need an R-value of 15.6 as compared to an R-5 roof covered with the reflective membrane Code A. In the more moderate climate of Knoxville, TN, the BUR would need R-10 as compared to the R-5 covered with the Code A membrane. Hence, not taking advantage of solar radiation control almost doubles the required R-value to get its energy cost savings for the cooling-dominated climate of Phoenix and the mixed climate of Knoxville.

Table 2. The net cost of annual energy savings and the R-value of BUR with equivalent energy costs of reflective roofs*

	Net savings ($/ft^2) Vs R05E90 (BUR)			BUR equivalent R-value for net savings = 0		
	Code A	Code I	Code H	Code A	Code I	Code H
Phoenix, AZ	R865E928	R813E947	R245E805	R865E928	R813E947	R245E805
R-5 (h·ft^2·^{o}F)/Btu	$0.366	$0.344	$0.069	R-15.6	R-14.3	R-6.2
R-10 (h·ft^2·^{o}F)/Btu	$0.211	$0.199	$0.040	R-30.7	R-28	R-11.2
R-15 (h·ft^2·^{o}F)/Btu	$0.129	$0.121	$0.024	R-34.7	R-34.1	R-16.7
R-20 (h·ft^2·^{o}F)/Btu	$0.095	$0.089	$0.018	R-35.7	R-35.4	R-26.1
R-30 (h·ft^2·^{o}F)/Btu	$0.075	$0.070	$0.014	R-36.3	R-36.1	R-32.0
Knoxville, TN						
R-5 (h·ft^2·^{o}F)/Btu	$0.128	$0.119	$0.027	R-10.3	R-9.8	R-5.9
R-10 (h·ft^2·^{o}F)/Btu	$0.073	$0.069	$0.015	R-16	R-15.3	R-10.9
R-15 (h·ft^2·^{o}F)/Btu	$0.045	$0.042	$0.009	R-30.3	R-29.2	R-16.2
R-20 (h·ft^2·^{o}F)/Btu	$0.033	$0.031	$0.007	R-33.6	R-33.3	R-23.6
R-30 (h·ft^2·^{o}F)/Btu	$0.026	$0.024	$0.005	R-34.9	R-34.7	R-31.5

* These simulations use initial solar reflectance, which do not include soiling of the membranes, and are based on typical energy costs from the Energy Information Administration (EIA 2001). A COP of 1.75 was used for the rooftop air-conditioner and an efficiency of 85% for the furnace.

SUMMARY

Long-term field exposure of a variety of single ply membranes has led to the development of a database of information that was employed to validate a calculation tool that can be used to estimate the economic benefits of deploying cool roof strategies. Understanding how the reflectance of these membranes changed with time and the causes of the changes has been explored. The financial impact of these changes was also estimated, and savings in predominantly cooling and some moderate climates justify periodic washing of cool roof membranes.

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