Saving Energy by Cleaning Reflective Thermoplastic Low-Slope Roofs

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ABSTRACT

Temperature, heat flow, reflectance, and emittance field data have been electronically cataloged for a full three years for 18 different single-ply membrane roofs exposed to different climates across the U.S. Our results show that the surfaces of the white thermoplastic roof systems lost about 30% to 50% of their solar reflectance after three full years of field exposure. The field data were used to validate a computer code, and simulations were run to determine the trade-off in added insulation and the increase in the cost of building roof energy caused by soiling of the thermoplastic membranes. Simulations also showed what energy costs a building owner would incur before it is economically justifiable to wash a roof.

Washing a high-reflectance thermoplastic membrane roof in Phoenix is clearly justified for roof insulation as high as R-30. In fact, building owners can realize a net savings of about 6¢ per square foot if they wash the roof every other year for a roof with a white thermoplastic membrane and R-15 insulation. In the more moderate climate of Knoxville, the advantage for washing the roof is only about 1¢ per square foot after three years of exposure for a highly reflective thermoplastic membrane with R-15 insulation. Cooling-energy savings are offset by the heating-energy penalty, and it appears that the ratio of cooling degree-days to heating degree-days exceeding 0.4 may roughly represent the boundary for periodically washing cool roof membranes.

INTRODUCTION

Reflective thermoplastic low-slope roofs are the most rapidly growing segment of the United States sheet membrane industry, and they are reducing energy use as building contractors substitute these high-reflectance roofs for the more dark absorptive built-up roof (BUR) and ethylene propylene diene monomer materials (EPDM). The 2000 and 2001 market survey shows that the footprint for installed BUR and EPDM dropped 18% (Good 2001), while the sales for thermoplastic membranes were up almost 20% (SPRI 2003).

The Energy Star initiative developed by the United States Environmental Protection Agency (EPA), the Cool Roof Rating Council (CRRC) rating protocols, state building codes, incentives offered by public utilities, and significant advertising claiming energy savings and mitigation of heat island effects have all helped promote the market penetration of reflective thermoplastic roofing materials. However, historical field data show a significant loss of reflectance as low-slope roofs soil over time from climatic exposure (Wilkes et al. 2000). SPRI Inc., sheet membrane and component suppliers to the roofing industry, partnered with Oak Ridge National Laboratory (ORNL) to document the effect of climatic soiling on thermoplastic membranes (Miller et al. 2002). The research quantified the loss of reflectance as roofs were weathered for three years in several U.S. climates, after which sections of the thermoplastic membrane roofs were cleaned. Key questions answered in the research were the trade-off between reflective roofs and roof insulation (Miller et al. 2002), the ability to effectively wash thermoplastic membranes clean, and the economic justification for periodic roof washing based on increased building energy costs for a soiled roof (Roodvoets et al. 2004).

Saving energy when the sun shines is what cool roofs are all about. Yet despite the simplicity of the cool roof concept,

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testing done under widely varying conditions is confusing industry, regulators, and consumers who do not know how to evaluate marketing claims or decide how test data apply to their situations. State legislators are enacting legislation that allows builders to reduce the insulating R-value of a roof provided the builder finishes the roof with a highly reflective roof membrane or coating. However, the trade-off between roof reflectance and the amount of roof insulation is in debate because a drop in reflectance due to soiling with reduced insulation levels would further exacerbate both cooling loads and operating costs. Further, the Energy Star protocol allows manufacturers to declare reflectance measures for a washed roof after the roof has been exposed for three years to the elements. However, the CRRC requires manufacturers to declare the reflectance of unwashed roofs after the three years of exposure.

Our objective is to document the trade-off between energy savings and first cost of thermoplastic membranes for different levels of roof insulation. The loss of reflectance and the cost penalties associated with the loss are evaluated to justify the economic value of cleaning the roof. This may not settle the debates as to the trade-offs between roof reflectance and insulation or whether the roof should be cleaned, but knowing the potential energy savings for a highly reflective roof will give realistic defensible claims that will give the building industry and practitioners metrics to implement prudent measures.

CERTIFICATION PROTOCOLS FOR REFLECTIVE LOW-SLOPE ROOFING

Prior studies conducted with roof coatings showed that solar reflectance decreases significantly in the first two years of weathering (Byerley and Christian 1994; Petrie et al. 1998). Low-slope membrane manufacturers are therefore keenly interested in documenting the loss in reflectance. They also want to understand the causes for the loss in solar reflectance because the EPA and the CRRC both implemented energy-performance rating protocols. For a manufacturer to obtain an Energy Star® rating, its roof product covering a low-slope roof must have an initial solar reflectance of at least 0.65, and the reflectance must be greater than 0.50 after three years of exposure (whether washed or unwashed). Reflectance data for three existing roofs for three years of exposure must be documented, and one of the roofs must be located within a major urban area. The CRRC provides the consumer with reflectance data only for new material and avoids the issue of washing. However, the CRRC accepts solar reflectance and infrared emittance requirements from state building codes such as California's Title 24 (section 118), which states that a reflective roof in California must have an initial CRRC reflectance rating of 0.70 and an infrared emittance of 0.75.

The emittance is the other surface property that many state building codes are requiring for roofs to be considered "cool." The emittance of a surface is defined as the fraction of the maximum possible thermal radiation that the surface emits because of its temperature. Therefore, roof emittance is

Figure 1 *Single-ply membranes were mechanically attached to the ESRA and field tested for three years.*

referred to as the infrared emittance because by Wien's displacement law the radiation transfer occurs in the far infrared spectrum. Typical infrared emittance of nonmetallic 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.

ENVELOPE SYSTEMS RESEARCH APPARATUS (ESRA)

The envelope systems research apparatus (ESRA) is a one-level, air-conditioned test building that is oriented east-west for exposing large areas of roof products (see Figure 1). A low-slope roof was built on the ESRA to conduct side-by-side testing under the same solar irradiance and climatic conditions. Roof slope was set for ¼ in. of rise for every 12 in. of run (i.e., 1.2° slope). Approximately half of the ESRA roof was subdivided into ten sections. Each section or lane is part of a roof system that consists of a metal deck, a 1 in. (25.4 mm) thick piece of wood fiberboard laid on the deck, another ½ in. (12.7 mm) thick piece of wood fiberboard placed atop the 1 in. (25.4 mm) thick piece, and a mechanically attached single-ply membrane. Similar membrane materials were overlapped a few inches within a test lane and welded together using a hot air gun. Parapets were used to divide some of the test lanes where the differences in roof material required special techniques to fasten the material to the roof. Further details of the instrumentation used to monitor thermal performance of the single-ply membranes is provided by Miller et al. (2002).

Test membranes were assigned proprietary codes known only by the principal investigators. Manufacturers participating in the study knew their own code but not the identity of others, so each participant could assess their system against

Table 1. Field Sites Selected for Exposing Single-Ply Membranes

Location	Zip Code	Site Climate
Littleton, CO	80127	Cold and dry
Joplin, MO	64801	Moderate
Saginaw, MI	48601	Cold and wet
Fullerton, CA	92832	Humid and warm
Canton, MA	02021	Cold and wet

the field of systems while still keeping the performance of their company's product confidential. A built-up roof (BUR) was used as the base of comparison to determine energy savings. The BUR was made of several layers of alternating bitumen and bitumen-saturated felt paper. The BUR is coded C. The completed assembly for the test membranes exposed on the ESRA is displayed in Figure 1.

Samples of the test membranes were also field tested at different locations across the country to quantify the effect of climate on the soiling of the single-ply membranes. Table 1 lists the different exposure sites, and Figure 2 shows the setup at one site in Saginaw, Michigan. Each sample was attached to plywood backing that was about 1½ ft wide by 4 ft long. All samples at the test sites were simply laid atop a low-slope roof and oriented facing south; slope was set at ¼ in. rise for every 12 in. of run. However, we tested an additional set of membranes at 2 in. of rise for every 12 in. of run at the Saginaw site to judge the effect of roof slope.

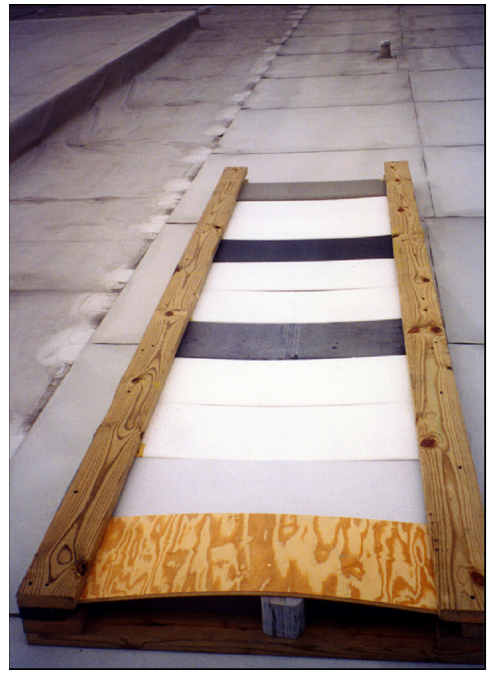


Figure 2 *Membranes at the Saginaw, MI, exposure site.*

REFLECTANCE AND EMITTANCE INSTRUMENTS

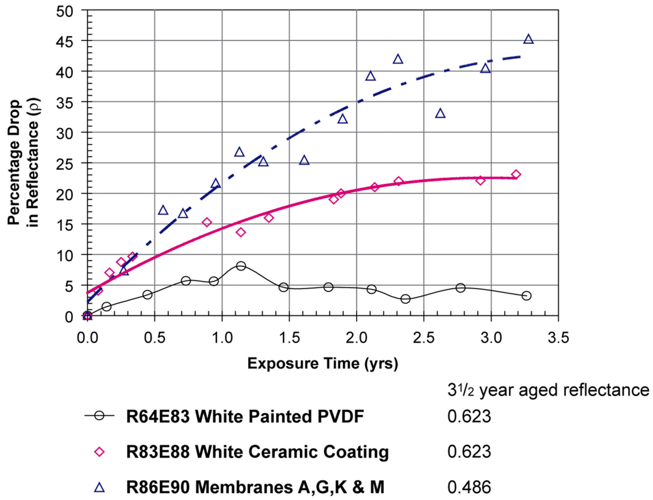
Experimental work included the initial measurement of reflectance and a subsequent measurement every fourth month. Emittance was measured annually. A portable solar spectrum reflectometer was used to measure the solar reflectance of the thermoplastic membranes. The device uses a tungsten halogen lamp to diffusely illuminate a sample. Four detectors, each fitted with differently colored filters, measure the reflected light in different wavelength ranges. The four signals are weighted in appropriate proportions using electronic conditioning to yield the solar reflectance. The device is accurate to within ±0.003 units (Petrie et al. 2001) through validation against the ASTM E-903 method (ASTM 1996).

The infrared emittance of the different single-ply membranes varies very little; the average emittance for all the membranes is about 0.90. However, the emittance does impact roof temperature and is as important as reflectance in hot climates. We used a portable emissometer to measure the infrared emittance using the procedures in ASTM C-1371 (ASTM 1997). The device has a thermopile radiation detector, which is heated to 180°F (82°C). The detector has two high-ε and two low-ε elements and is designed to respond only to radiant heat transfer between itself and the sample. Because the device is comparative between the high-ε and the low-ε elements, it must be calibrated in situ using two standards, one having an emittance of 0.89, the other having an emittance of 0.06. Kollie et al. (1990) verified the instrument's precision as ±0.008 units and its accuracy as ±0.014 units in controlled laboratory conditions.

CLIMATIC EXPOSURE AND CLEANING IMPACTS

Ultraviolet radiation, atmospheric pollution, microscopic growths, acid rain, temperature cycling caused by sunlight and sudden thunderstorms, moisture penetration, condensation, wind, hail, and freezing and thawing all contribute to the loss of reflectance of a roof's exterior surface. Wilkes et al. (2000) recently completed testing 24 different roof coatings on a low-slope test stand at the ORNL. Results revealed about a 25% decrease in the solar reflectance of white-coated and aluminum-coated surfaces as the time of exposure increased; however, this decrease leveled off after two years of exposure (Figure 3). Field results for thermoplastic membranes exposed on the ESRA showed that the surfaces lost from 30% to 50% of their reflectance after three full years of field exposure (Figure 3). Painted metal roofing was also tested on the ESRA to determine the loss of reflectance as the metal roofs soiled under climatic exposure. After 3½ years, the painted PVDF metal roofs lost less than 5% of their original reflectance (Figure 3).

The results of the three different field studies are very interesting in terms of the absolute reflectance. The white thermoplastic membranes and white ceramic coating with white topcoat had original reflectance measures that were about 20 percentage points higher than the painted metal; however,



Each roof is described generically using an R*xx*E*yy* designation. R*xx* states the solar reflectance of new material; E*yy* defines the infrared emittance of the sample. For example, the thermoplastic membrane is labeled R86E90; its fresh-from-the-can surface properties are therefore 0.86-reflectance and 0.90-emittance.

Figure 3 *Loss of reflectance for single-ply thermoplastic membranes, white ceramic coating, and painted PVDF metal roofs after three years of exposure.*

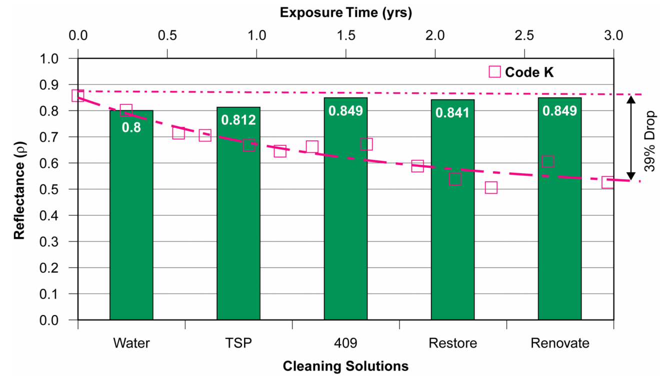


Figure 4 *Code K was almost fully restored after washing.*

after three years of climatic exposure, the reflectance of the painted metal exceeds that of the thermoplastic membrane and equals that of the coating. The reduction is caused by surface contamination that soils the roof. Our findings for the thermoplastic membranes show that airborne particles themselves are responsible for the loss in roof reflectance and 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. Miller et al. (2002) give further discussion on the drivers affecting the loss of reflectance.

Given the findings for the thermoplastic membranes, we washed them and made reflectance measurements to determine whether the surface reflectance could be restored to its original value. Water, 409®, a cleaner-degreaser, trisodium phosphate (TSP), and commercially available cleaning agents (Restore and Rennovate) were applied to small areas of about 1 ft (0.305 m) in diameter on each test membrane. A soft brush was used with the TSP cleaner; all other cleaning agents were applied with a soft cloth. The cleaners were allowed to react with the soiled surface before wiping the surface with another water-saturated soft cloth.

Cleaning almost fully restored the surface reflectance of all the thermoplastic membranes as typified by Code K (Figure 4). Table 2 lists the restoration of reflectance after cleaning all thermoplastic membranes field tested on the ESRA. The average restoration in reflectance for all

Table 2. The Restoration of Reflectance (%) for the Membranes Exposed on the ESRA

	A, G, K, M	B, N	F, I, J
Water	77.1%	60.6%	57.7%
Trisodium phosphate (TSP)	92.6%	89.6%	85.0%
409 cleaner • degreaser	94.7%	94.9%	95.0%
Restore (2 min)	97.1%	95.6%	91.5%
Renovate (5 min)	98.3%	95.5%	92.8%

membranes (Table 2) is about 95% of the original reflectance for each sample. The results are significant and show that the thermoplastic membranes are impervious to the effects of solar irradiance within the first three years of climatic exposure. Ultraviolet light has had little short-term effect on the solar reflectance. Manufacturers have formulated their membranes with titanium dioxide (TiO_2), a rare earth ceramic material. Titanium dioxide is processed from rutile and is the most important white pigment currently used in the manufacturer of paints, plastics, and roof membranes. TiO_2 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 and the membrane is more durable to the climatic elements.

The EPA requires field testing at three different building sites; however, the results for the thermoplastic membranes show the loss of reflectance to be very similar across the country (Figure 5). The dry climate in Denver, Colorado, showed similar drops in reflectance as observed in the predominantly heating-load climate of Joplin, Missouri, as well as in the colder and more humid climate of Boston, Massachusetts. The exception is the data for Fontana, California; here the data are skewed because the test membranes were accidentally left in ponded water atop a low-slope roof. Also, solar reflectance measures collected from the fence post exposure sites in Denver, Saginaw, and Joplin are very similar to the reflectance

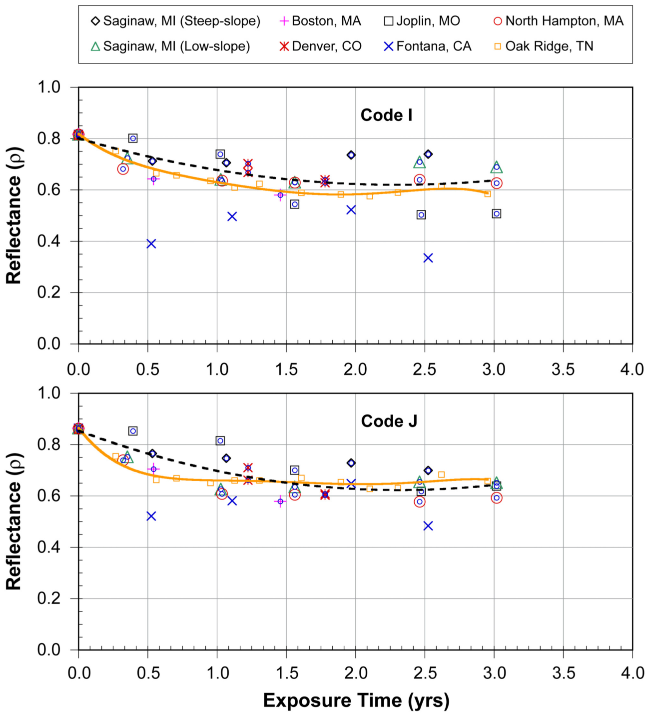


Figure 5 *The loss of reflectance is similar for field samples J and I exposed to various climates across the United States.*

measures recorded for the test roofs exposed on the ESRA in Oak Ridge (Figure 5). The changes in solar reflectance of the thermoplastic membranes appear independent of climate! The results show that fence post data are a viable alternative for certifying thermoplastic membrane roofs as Energy Star® compliant because they yielded similar trends as the identical roofs exposed on the ESRA.

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 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.

EFFECT OF ROOF SOILING ON BUILDING ENERGY LOAD

The field study of the thermoplastic membranes showed that the surfaces could lose as much as 50% of their initial reflectance after three years of field exposure for tests conducted at Oak Ridge, Tennessee; North Hampton, Massachusetts; Canton, Massachusetts' Littleton, Colorado; Joplin, Missouri; Saginaw, Michigan; and Fullerton, California. To determine the increase in the building roof heat transfer and the subsequent cost of the energy increase caused by soiling of the thermoplastic membranes, a numerical computer code named STAR was used to solve for the heat flow entering or leaving the roof. STAR models the transient one-dimensional heat flow through the exterior roof cover, through multiple layers of roof insulation, and through the supporting subframe (e.g., a metal deck). The code supports specified boundary conditions at the inside and outside surfaces of a roof and can also handle boundary conditions coupled to the outdoor weather and indoor environment. It also accounts for temperature-dependent thermal properties observed in insulation.

STAR was validated against temperature and heat flow data acquired from the field tests conducted on the ESRA. Miller et al. (2002) give further detail of the formulation and validation of STAR and show the code accurate within an average predictive error of about 4% of the measured membrane temperatures. The total heat flow through the roof was predicted to within about 5% of the heat flow experimentally measured in the roof insulation. In earlier work, Wilkes et al. (2000) input typical meteorological year (TMY2) data (NREL 1995) into STAR and showed excellent agreement between prediction and annual heat flow through low-slope roof coatings.

Weather databases for Phoenix, Arizona; Knoxville, Tennessee; and Minneapolis, Minnesota, were derived from the TMY2 data (NREL 1995) to contain three years of hourly data of the ambient dry-bulb temperature and relative humidity, wind speed and direction, solar insolation, cloud cover, and precipitation. STAR read the data and calculated the hourly heat flux entering or leaving the conditioned space. Simulations were run for a low-slope roof with an insulation level of R-15, the minimum level of insulation recommended for nonresidential low-slope roofing (ASHRAE 1999). Membrane soiling data for the SPRI field study was formulated into an algorithm and used within STAR to forecast the loss of reflectance over time for exposure at Phoenix, Knoxville, and Minneapolis.

An annual roof load was calculated by summing the cooling load and the heating load roof energies (Miller et al. 2002). The annual roof heat transfer for a soiled membrane was then scaled by the annual roof heat transfer for the identical clean membrane. Therefore, subtracting one from the scaled factor represents the percentage increase in roof energy as compared to the same clean membrane whose reflectance remains constant (Figure 6). A scaled roof energy factor of one represents no net change in energy, trends exceeding one represent penalties in increased roof energy, and trends falling below one represent decreases in roof net heat transfer.

For a roof having R-15 insulation in Phoenix, the results show significant increases in roof heat transfer. One year of soiling causes a 24% increase in the annual energy penetrating the roof of a Code A membrane with R-15 insulation. After two years, the roof incurs a 51% increase. The increase in energy levels out through three years of exposure, and the net increase in annual roof heat transfer plateaus at about 60%. Integration of the curve for Code A in Figure 6 and scaling by

Table 3. Cumulative Cost Penalty $/(ft²·yr) for the Building Roof Energy Observed as the Highly Reflective Membranes Code A and Code I Soil with Exposure Time*

R-Value (h·ft²·°F)/Btu	Code A Membrane Exposure Time (Years)			Code I Membrane Exposure Time (Years)		
	1	2	3	1	2	3
Exposure in Phoenix, AZ, climate						
5	–$0.067	–$0.219	–$0.400	–$0.057	–$0.162	–$0.266
10	–$0.037	–$0.120	–$0.218	–$0.031	–$0.088	–$0.145
15	–$0.021	–$0.068	–$0.123	–$0.018	–$0.050	–$0.082
20	–$0.014	–$0.043	–$0.077	–$0.012	–$0.031	–$0.051
30	–$0.008	–$0.027	–$0.048	–$0.007	–$0.020	–$0.032
Exposure in Knoxville, TN, climate						
5	–$0.023	–$0.070	–$0.125	–$0.019	–$0.052	–$0.083
10	–$0.011	–$0.035	–$0.062	–$0.010	–$0.026	–$0.041
15	–$0.004	–$0.013	–$0.023	–$0.004	–$0.010	–$0.015
20	–$0.001	–$0.004	–$0.006	–$0.001	–$0.003	–$0.004
30	–$0.001	–$0.002	–$0.004	–$0.001	–$0.002	–$0.002

* The negative currency values reflect the cost the building owner pays in increased utility services because the thermoplastic membranes soil the roof and increase the annual roof energy. $/m²·yr = 10.764*{$/ft²·yr}.

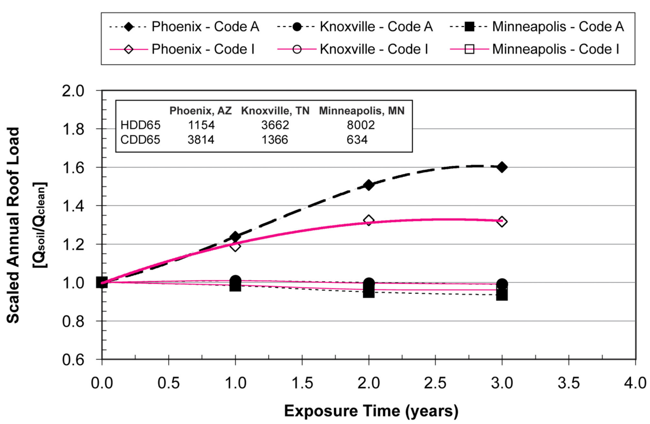


Figure 6 *Scaled annual energy transmitted through a low-slope roof having R-15 insulation and different thermoplastic membranes.* Q_{soil} *represents the annual energy transmitted through a soiled membrane with R-15 insulation.* Q_{clean} *represents the same membrane with no loss of reflectance.*

the three years of exposure yields an annual average heat gain in roof energy of 35%. For the Code I membrane compared against a clean Code I membrane, a 31% increase is observed after three years of exposure in Phoenix (Figure 6). Integrating the Code I membrane over time and again scaling by the exposure time yielded an annual average roof heat gain of 23.1%.

The predominant heating in Minneapolis causes the annual roof heat transfer for the membranes to drop slightly because the soiling of the Code A and I membranes lessens the heating-energy penalty. Knoxville's climate is moderate, and despite the fact that Code A and I membranes soil, the net effect on annual roof heat transfer is small (Figure 6). For the Code A and I membranes with insulation levels exceeding R-10, the cooling energy savings are offset by the heating-energy penalty.

Cost of Building Energy Incurred Due to Soiling of Roof

Cost estimates for the increase in building load were calculated by subtracting the roof heat transfer for a thermoplastic membrane that soils with time from the roof heat transfer for the same membrane that remains clean. Service charges for electricity and natural gas were gleaned from the Energy Information Administration (EIA). The field COP was set at 1.75 and the efficiency of the gas furnace was assumed moderate at 0.85.

The cost data are listed in Table 3 for different levels of roof insulation for exposure in the climates of Knoxville and Phoenix. The negative currency values represent the cost of energy that the building owner incurs as the roof soils. The data directly compare the thermoplastic membrane with soiling to the same thermoplastic membrane without soiling, which allows a direct assessment of the benefit and frequency for washing the roof.

Table 4. Annual Energy Savings and the R-Value of BUR with Equivalent Energy Costs of Reflective Roofs* $\$/m^2 = 10.764*\{\$/ft^2\}$

	Net Annual Savings ($ per ft^2) vs. R05E90 (BUR)			BUR Equivalent R-Value for Net Savings = 0		
	Code A R865E928	Code I R813E947	Code H R245E805	Code A R865E928	Code I R813E947	Code H R245E805
Phoenix, AZ						
R-5 $(h{\cdot}ft^2{\cdot}°F)/Btu$	$0.366	$0.344	$0.069	R-15.6	R-14.3	R-6.2
R-10 $(h{\cdot}ft^2{\cdot}°F)/Btu$	$0.211	$0.199	$0.040	R-30.7	R-28.0	R-11.2
R-15 $(h{\cdot}ft^2{\cdot}°F)/Btu$	$0.129	$0.121	$0.024	R-34.7	R-34.1	R-16.7
R-20 $(h{\cdot}ft^2{\cdot}°F)/Btu$	$0.095	$0.089	$0.018	R-35.7	R-35.4	R-26.1
R-30 $(h{\cdot}ft^2{\cdot}°F)/Btu$	$0.075	$0.070	$0.014	R-36.3	R-36.1	R-32.0
Knoxville, TN						
R -5 $(h{\cdot}ft^2{\cdot}°F)/Btu$	$0.128	$0.119	$0.027	R-10.3	R- 9.8	R-5.9
R-10 $(h{\cdot}ft^2{\cdot}°F)/Btu$	$0.073	$0.069	$0.015	R-16.0	R-15.3	R-10.9
R-15 $(h{\cdot}ft^2{\cdot}°F)/Btu$	$0.045	$0.042	$0.009	R-30.3	R-29.2	R-16.2
R-20 $(h{\cdot}ft^2{\cdot}°F)/Btu$	$0.033	$0.031	$0.007	R-33.6	R-33.3	R-23.6
R-30 $(h{\cdot}ft^2{\cdot}°F)/Btu$	$0.026	$0.024	$0.005	R-34.9	R-34.7	R-31.5
Minneapolis, MN						
R-5 $(h{\cdot}ft^2{\cdot}°F)/Btu$	$0.030	$0.028	$0.010	R- 5.8	R- 5.8	R- 5.3
R-10 $(h{\cdot}ft^2{\cdot}°F)/Btu$	$0.017	$0.016	$0.006	R-10.8	R-10.8	R-10.3
R-15 $(h{\cdot}ft^2{\cdot}°F)/Btu$	$0.011	$0.010	$0.003	R-16.1	R-16.1	R-15.3
R-20 $(h{\cdot}ft^2{\cdot}°F)/Btu$	$0.008	$0.008	$0.003	R-23.5	R-23.2	R-20.8
R-30 $(h{\cdot}ft^2{\cdot}°F)/Btu$	$0.006	$0.006	$0.002	R-31.4	R-31.3	R-30.5

* These simulations do not include soiling of the membranes.

An independent contractor would charge about 1¢ per square foot to wash a roof with a power washer. The cost of additional roof energy for Phoenix clearly justifies power washing a roof with insulation as high as R-30 for the Code A membrane. In fact, the building owner can realize a net savings of about 6¢ per square foot if he washes the roof every other year for a roof with Code A membrane with R-15 insulation. The cost advantage is not as great for the Code I membrane because Code I loses only about 25% of its original reflectance as compared to the 50% loss observed for Code A membrane. Yet the building owner can still save about 4¢ per square foot by washing the Code I membrane that has R-15 insulation every other year. Washing every third year increases the savings to about 11¢ and 7¢ per square foot of the Code A and Code I membranes, respectively.

In the more moderate climate of Knoxville, the advantage for washing the roof is only about 1¢ per square foot after three years of exposure for the Code A membrane with R-15 insulation. Once again, cooling-energy savings are partially offset by the heating-energy penalty. A slight cost penalty is observed in the Knoxville climate because of the difference in costs of electricity as compared to cost of natural gas. However, as discussed earlier, washing shows no clear cost advantage to the building owner in a moderate climate such as Knoxville.

COOL ROOF PREMIUMS AND ROOF INSULATION TRADE-OFFS

The monetary value of energy savings for a low-slope roof covered with membranes coded A, I, and H was calculated relative to a dark BUR. We opted to not include the soiling effects of the membranes as discussed in the previous section. Only fresh-from-the-factory reflectance measures were used for the results shown in Table 4. The data reflecting soiling effects in Table 3, however, can be used to adjust Table 4 data for the effects of soiling. To use Table 3 data with Table 4 results over, for example, a three-year exposure period, simply triple the Table 4 value for the respective coded membrane and level of roof insulation and subtract the Table 3 value in the three-year column to determine the cost savings for three years of exposure of a soiled membrane over a BUR. We adopted this approach of keeping the soiling results separate because a manufacturer's representative would use the reflectance of new thermoplastic material according to the manufacturer's specifications in a proposed bid to highlight the potential energy and cost savings attributable to the thermoplastic membrane. A practitioner or building owner would also want to know how much insulation is needed in a dark absorptive roof to have the same energy savings as offered by a cool roof. We answer both questions based on the information the manufacturer's representative would have available.

Cool Roof Premiums as Compared to a BUR

For the cooling-dominated climate of Phoenix and the mixed climate of Knoxville, the highly reflective membrane Code A with a roof insulation level of R-5, yielded energy cost savings of about $0.37/ft^2 ($3.98/m^2) per year and $0.13/ft^2 ($1.40/m^2) per year, respectively. When the R-value level is increased to R-15, energy savings are reduced to $0.13/ft^2 ($1.40/m^2) per year in Phoenix and $0.05/ft^2 ($0.54/m^2) per year in Knoxville. Increasing the insulation level reduces the cost savings produced by the reflective roof (Table 4). None of the reflective membranes offers an energy cost savings ≥ $0.05/ft^2 ($0.54/m^2) per year for the heating-dominated climate of Minneapolis (Table 4). The results help demonstrate the regions where reflective roofing is profitable and can make significant market penetration.

Roof Insulation Trade-Offs

Almost 70% of new roofing in 2001 for the western U.S. was finished in dark absorptive BUR, ethylene-propylene-diene-terpolymer (EPDM) and bitumen-based single-ply membranes (Dodson 2001). Table 4 shows the level of insulation needed by the dark roof to have the same annual heat load as a high-reflectance roof having less insulation. In Phoenix, a dark absorptive BUR would need an R-Value of 15.6 compared to an R-5 roof covered with the reflective membrane Code A. In the more moderate climate of Knoxville, the BUR would need R-10 as compared to the R-5 covered with Code A. From Table 4 one sees that ignoring radiation control causes the amount of insulation to significantly increase for the cooling-dominated climate of Phoenix and the mixed climate of Knoxville.

Our study shows a trade-off between the material costs for reflective roofing as compared to the material cost for additional insulation needed to offset the increase in annual roof energy if the roof cover is a dark absorptive BUR. Wholesale costs for polyisocyanurate insulation sold in Phoenix, Knoxville, and Minneapolis were used to help demonstrate the trade-off (Miller et al. 2002). These cost data were used along with the equivalent R-value data from Table 4 to compare material costs for two roof systems—one having a cool roof membrane with polyisocyanurate insulation and the other having a dark, absorptive BUR with the equivalent R-value of polyisocyanurate insulation that would force both roofs to have the same annual operating cost for

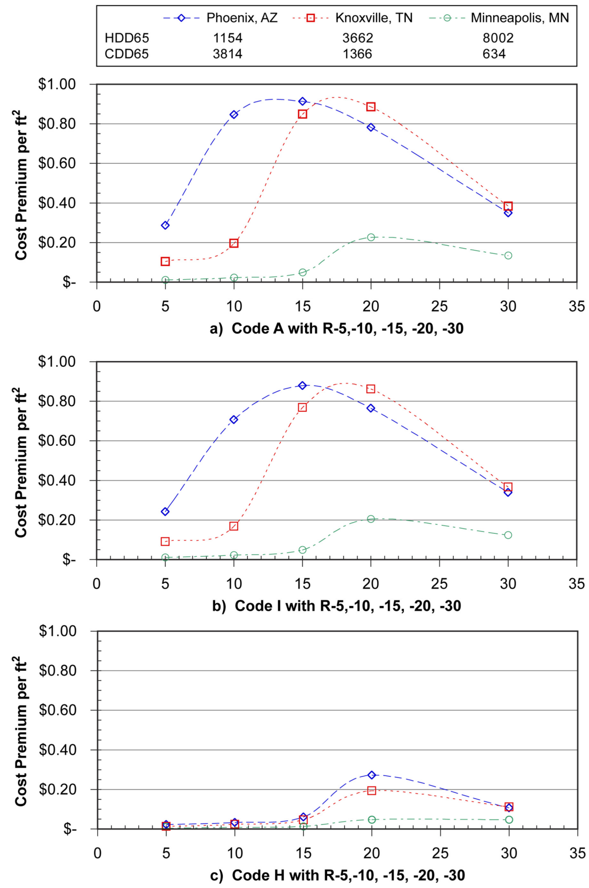


Figure 7 *Cost of additional insulation needed for a smooth BUR roof to have the same annual operating cost as a cool roof membrane, $/m^2 = 10.764*{$/ft^2}.*

roof energy. For example, a BUR cover needs an R-34.7 to have the same annual operating cost as a Code A membrane with R-15 insulation (Table 4). The difference in R-value (R-34.7 minus R-15) is translated into the cost of additional insulation and is then plotted in Figure 7 against a cool membrane with different R-values of polyisocyanurate insulation. The curves for Phoenix, Knoxville, and Minneapolis, therefore, represent the cost of additional insulation for a BUR or they can also be viewed as the affordable cost premium for cool membranes as compared to the material cost for the additional insulation on a BUR roof. This affordable cost premium reaches a maximum as R-value increases but then diminishes with further increase in R-value (Figure 7). Hence, a synergy is observed between R-value and reflective roofing as R-value increases from R-5 up to about R-20; however, continuing to increase R-value beyond R-20 (along the x-axis) causes the effect of insulation to mask the effect of the reflective roof. Also, the peak in cost premium shifts to higher R-values as the climate changes from a hot to a cold climate. Note that we did not constrain the annual operating cost of heat transferred across the roof; it drops as R-value increases and is at its lowest value at R-30 (Figure 7).

For Phoenix and Knoxville, the maximum affordable cost premium of \$0.90 per ft^2 (\$9.70/m^2) occurs at about R-15 and R-18, respectively (Figure 7a, 7b). According to ASHRAE Standard 90.1 (1999), the minimum level of insulation for nonresidential, low-slope roofing is R-15. Also, single-ply membranes of about 40 mil thickness cost about \$0.40 per ft^2 (\$4.30/m^2); a thicker 80-mil membrane costs about \$0.75 per ft^2 (\$8.07/m^2). Therefore, based solely on material costs, a consumer in Phoenix or Knoxville could easily afford a cool membrane (Code A or Code I) with R-15 level of polyisocyanurate insulation. However, in Minneapolis, the membrane with R-20 insulation would have to cost less than about \$0.20 per ft^2 (\$2.15/m^2) to have the same material cost as a BUR with about R-23. The state energy code in Minneapolis requires R-30 for low-slope commercial roofs, which makes the cost-effectiveness of cool roofing even more prohibitive in Minnesota. The Code H membrane has a low reflectance and shows that the membrane must cost less than \$0.30 per ft^2 (\$3.23/m^2) to economically justify its use over a BUR with additional polyisocyanurate insulation (Figure 7c).

CONCLUSIONS

Simulations were conducted to determine the increase in cost of building roof energy caused by soiling of white reflective thermoplastic membranes. Weather databases for Phoenix, Knoxville, and Minneapolis were input to a numerical code for simulating the heat flow through a low-slope roof with insulation levels ranging from R-5 through R-30. Membrane soiling was forecast using algorithms predicting the loss of reflectance.

Field testing of the thermoplastic membranes showed that the surfaces lost from 30% to 50% of their reflectance after three full years of exposure. Yet despite the loss of reflectance, the thermoplastic membranes were cleaned within 95% or more of their original reflectance. The finding is important based on the current requirements of Energy Star®, which allows cleaning after three years of exposure, and the Cool Roof Rating Council (CRRC), which does not allow cleaning after three years. The premise of the CRRC is that roofs are rarely cleaned; however, results for predominately cooling-load climates showed economic justification for periodically cleaning the roof. The cost of additional roof energy clearly justifies washing roofs with insulation as high as R-30 in predominantly cooling-load climates, although washing shows no clear cost advantage to the building owner in moderate climates such as Knoxville.

The field data also show that the loss of reflectance is fairly uniform among the various test sites. The dry climate in Denver showed drops in reflectance similar to those observed in the predominantly heating-load climate of Joplin, Missouri, as well as in the colder and more humid climate of Boston. Further, the loss of reflectance for materials on the ESRA were very similar to those observed at the field sites. The changes in solar reflectance of the thermoplastic membranes appear independent of climate and show that fence exposure data are a viable alternative for certifying the thermoplastic membrane roofs as Energy Star® compliant because they yielded similar trends as the identical roofs exposed on the ESRA.

A trade-off occurs between the use of reflective roofing and the use of additional insulation needed to offset the increase in annual roof energy if the roof cover is a dark absorptive BUR. The results show that around the R-15 minimum insulation level for low-slope roofing specified by ASHRAE Standard 90.1 (ASHRAE 1999), a maximum affordable premium results for thermoplastic membranes. A consumer in Phoenix or Knoxville can easily afford a thermoplastic reflective membrane with R-15 level of polyisocyanurate insulation because the cost of additional insulation needed by the dark absorptive BUR exceeds the cost of the manufacturer's best reflective products. Hence, thermoplastic membranes when compared to the market standard BUR roof have their largest cost advantage at about ASHRAE's minimum specified levels of roof insulation.

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