The Thermal Performance of Painted and Unpainted Standing-Seam Metal Roofing Systems Exposed to Two Years of Weathering

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ABSTRACT

Determining how weathering affects the reflectance and emittance of metal roofs is of paramount importance for accelerating the market penetration of metal roofing in both residential and commercial applications. Ultraviolet radiation, atmospheric pollution, microscopic growths, acid rains, temperature cycling caused by sunlight and sudden thunderstorms, moisture penetration, condensation, wind, hail, and freezing and thawing all contribute to the weathering of a roof's exterior surface. However, data describing the impact of weathering are extremely sparse simply because of the time and patience required to collect and interpret the data.

Temperature, heat flow, reflectance, and emittance field data have been electronically cataloged for a full two years for 12 different painted and unpainted metal roofs exposed to weathering on an outdoor test facility. A white-painted metal surface, having a moderate reflectance and high emittance, showed the best thermal performance for predominantly cooling-load climates. For predominantly heating-load climates, a painted metal surface having moderate reflectance and low emittance showed excellent balance for reducing heat gain in the summer and heat loss in the winter.

INTRODUCTION

The Buildings Technology Center (BTC), a National Users facility,[1] is collaborating with roughly 80% of the roofing industry by field-testing each participant's best roof products on an outdoor test facility, the Envelope Systems Research Apparatus[2] (ESRA). The BTC is working with several members of the Single-Ply Roofing Institute[3] (SPRI) and also supports a field study with a consortium of metal roofing industries. The American Iron and Steel Institute (AISI), the GALVALUME Sheet Producers of North America (NamZAC), the Metal Building Manufacturers Association (MBMA), the Metal Construction Association (MCA), and the National Coil Coaters Association (NCCA) are also working with the BTC to test both painted and unpainted metal roofs on the ESRA. The metal industry is keenly interested in documenting whether their products can reduce the energy used for comfort cooling and heating of both residential and commercial buildings.

A building's comfort cooling and heating energy (termed *load*) is directly related to the solar insolation the building receives; the exterior temperature; the level of roof, wall, and foundation insulation; the amount of fenestration; and the building's tightness against unwanted air and moisture infiltration. The solar reflectance and infrared emittance, as well as the air-side convective currents, strongly affect the envelope's exterior temperature. We expect that in moderate to predominantly hot climates, an exterior roof surface with a high

1. The United States Department of Energy (DOE) supports and encourages its DOE-funded laboratories to partner with industry on technical issues that require the research capabilities available at a national laboratory.
2. The ESRA is a one-level, air-conditioned test building oriented east-west for exposing large areas of low-slope roof products to east Tennessee's climate.
3. SPRI represents and supports the sheet membrane and component suppliers to the commercial roofing industry.

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reflectance and high infrared emittance will reduce the exterior temperature and produce savings in comfort cooling. For predominantly heating-load climates, surfaces with moderate reflectance and low infrared emittance will save in comfort heating, although field data documenting the trade-off between reflectance and emittance are sparse.

Field measurements of ten homes by Parker and Barkaszi (1997) showed that reflective white roofing reduced space-cooling energy use by an average of 19% compared to dark asphalt shingles. Measurements made during the summer by Parker and Sherwin (1998) showed that white-tile roofing caused a 76% reduction in the ceiling-heat flux into the house relative to a black-shingle roof. A white-painted metal surface was Parker and Sherwin's second-best performer; it showed a 61% reduction. Rudd and Lstiburek (1998) conducted seasonal simulations for Las Vegas, Nevada. They showed that a white-tile roof decreased the cooling load by 9% and increased the heating load by 3%, compared to a roof with black shingles. The combined effect was an annual space-conditioning load reduction of 2%. Rudd and Lstiburek concluded that the cost reduction in annual space conditioning for the white-tile roof is about half the cooling-cost reduction because of the white-tile penalty in the heating season.

However, field studies conducted by Parker et al. (1998) on several homes in Fort Myers, Florida, showed that the roof, attic, and air-conditioning ductwork accounted for about 25% of the total cooling load. Highly reflective roofs yielded cooling energy savings upwards of 23% of the annual load.

Berdahl and Bretz (1997) have reported quantitative values of the solar reflectance for a few types of building materials and briefly discussed works by Taha et al. (1992) and Reagab and Acklam (1979), who published some reflectance data from field measurements of test roofs. Petrie et al. (2000) recently completed testing 24 different roof coatings on a low-slope test stand at the BTC. Results revealed a 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 weathering. Infrared emittance of the coating did not change markedly over time, but its effect on thermal performance was intertwined with that of reflectance. To the authors' knowledge, information on the weather's impact on the change in reflectance and emittance of roof materials is limited. Further, the trade-off between climate and reflective roofs has only recently been investigated because of the time and patience required for documenting the weather's impact on exterior roof surfaces.

EXPERIMENTAL FACILITY

Instrumented steep-slope-roof and low-slope-roof test sections were installed in July 1999 and are under field study on the eastern half of the ESRA. The steep-slope section faces directly south and has a slope of 18.4°; the low-slope section has a slope of 1.2°, typical of commercial roofing. The latitude for Oak Ridge is about 36°N, and the ESRA is oriented east-west so that each test roof receives the same intensity of solar insolation. The altitude angle of the sun is slightly south of the ESRA, which eliminates any shading effects on the low-slope test section (see early-morning shading in Figure 1). The following text describes the construction of both the low-slope and steep-slope systems and the setups for the two assemblies.

Low-Slope Roof Test Assembly

The consortium of metal industries is field-testing white-painted polyvinylidene fluoride (PVDF) galvanized steel;[4] off-white polyester; 55% Al-Zn coated steel[5] painted with a clear acrylic dichromate layer; unpainted galvanized steel; and unpainted 55% Al-Zn-coated steel. Material thickness of all roof panels is 24-gage (0.024 in. [0.61 mm]). Three test panels comprise a test lane; each panel is 16-in. (0.38 m) wide to match standard construction set at 48 in. (1.22 m) on center.

Starting from the southeast corner of the ESRA (bottom left in Figure 1), panel layout is three panels of white-painted PVDF galvanized steel, three panels of off-white polyester, three panels of 55% Al-Zn-coated steel painted with a clear acrylic dichromate layer, three panels of unpainted galvanized steel, three panels of unpainted 55% Al-Zn-coated steel, and three panels of black-painted PVDF galvanized steel. The last lane is laminated with photovoltaic cells. Three panels are used per test lane with the center panel for instrumentation guarded by identical panels on either side.

The ESRA's low-slope assembly is made of steel joists and bridging that support a metal deck made of 22-gage, 0.030 in. (0.76 mm) thick galvanized steel. The deck's ribbing

Figure 1 *The Envelope Systems Research Apparatus used for testing painted and unpainted metal roofing.*

4. A zinc-coated steel sheet manufactured by the steel being dipped in continuous coil form through a molten bath of zinc.

5. Processed similarly to hot-dipped galvanized steel. This steel is exposed to a molten bath composed of 55% Al-43.5% Zn -1.5% Si at a temperature of 1100°F (593°C). The coating is solidified rapidly to enhance both the microstructure and the corrosion resistance.

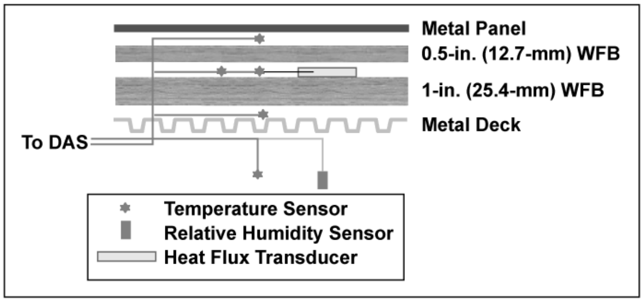

Figure 2 *Instrumentation setup used for the low-slope metal roof assembly being field-tested on the ESRA.*

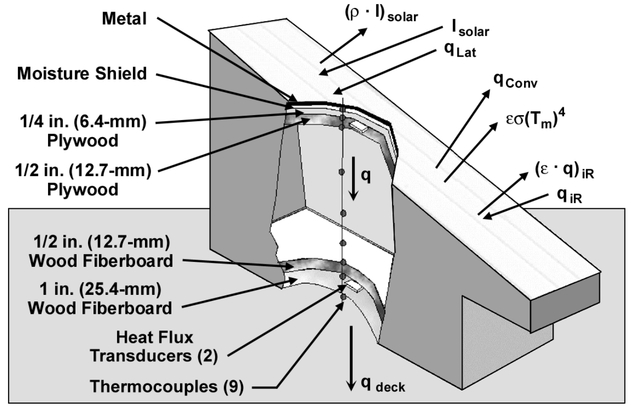

Figure 3 *Instrumentation and design of the steep-slope metal roof assembly being field-tested on the ESRA.*

is narrow, about 1 1/2 in. wide (38.1 mm). Wood fiberboard, 1-in. (25.4 mm) thick, lies atop the deck, and a thinner, 1/2-in.-thick (12.7 mm) piece of wood fiberboard is placed atop the 1-in.-thick (25.4 mm) layer. The test metal roofs are mechanically attached to the metal deck and "sandwich" the 1 1/2 in. (38.1 mm) of fiberboard insulation. A gutter is placed on the south side of the low-slope roof assembly (Figure 1).

Instrumentation. The center panel of each test lane is instrumented with copper-constantan thermocouples for measuring the temperature gradients across the roof insulation (Figure 2). The thermocouples are placed in the ESRA's indoor ambient, attached to the top side of the metal deck, taped between the two layers of fiberboard, and taped atop the surface of the 1/2-in.-thick (12.7 mm) piece of wood fiberboard. A 2-in.-square (50.4 mm) by 0.18-in.-deep (4.6 mm) slot was routed into the top of the 1 in. (25.4 mm) wood fiberboard for the placement of a heat flux transducer (HFT). All transducers were calibrated before being installed into the low-slope assembly. Each HFT was calibrated by being placed in a 12-by-12-in. (0.305-by-0.305-m) guard made from the same lot of wood fiberboard as that used in construction of the low-slope assembly. The sandwich of 1/2-in.-thick (12.7 mm) wood fiberboard, the HFT, and 1-in.-thick (25.4 mm) wood fiberboard was placed in a heat-flow meter calibration apparatus to develop a calibration that corrects for edge effects. The HFT manufacturer states accuracy as ±1% of full-scale reading with a sensitivity of about 1.3 $Btu/h \cdot ft^2$ per mv of signal (4.1 W/m^2 per mv). Our calibrations showed them to be accurate within ±5% of reading.

The two thermocouples taped between the two layers of fiberboard are located 2 in. (50.4 mm) and 4 in. (101.6 mm) away, respectively, from the HFT to check for any horizontal temperature gradients. Using a computational heat conduction code, simulations were made to check the magnitude of horizontal heat flows in the plane of the roof. Predictions showed the effects were small and extend no more than a few inches in from the break between low-slope test lanes. The horizontal heat flow is 2% of the vertical heat flux along the top of the 1/2-in.-thick fiberboard (12.7 mm) at a distance 3 in. (76.2 mm) away from the interface of two adjacent test lanes. The lateral heat flow drops to less than 1% of the vertical flow 6 in. from the interface. Our instrumentation is placed in the center of each three-panel test lane and is about 24 in. (0.61 m) from an adjoining test lane. Therefore, axial effects are judged insignificant. Also, the temperature measures collected 2 in. (50.4 mm) and 4 in. (101.6 mm) away from the HFT show no lateral gradients, and the heat-transfer problem is one-dimensional.

Steep-Slope Roof Test Assembly

Five painted metal panels are being tested on the steep-slope assembly (Figure 1). Material thickness of all roof panels is 24-gage (0.024 in. [0.61 mm]). Three panels of white-painted PVDF galvanized steel, three panels of 55% Al-Zn-coated steel painted with a clear acrylic dichromate layer, six panels of bronze-painted PVDF aluminum, and three panels of black-painted PVDF galvanized steel[6] are being exposed to east Tennessee's weather. The leftmost test lane is an asphalt-shingle roof. The asphalt shingle has a 15-year lifetime warranty and has both Underwriter Laboratory and American Society for Testing and Materials (ASTM) approval for residential roofing.

Three 15-in.-wide panels (0.38 m) compose a test lane. A 3-in.-wide (76.2 mm) parapet is placed between each steep-slope lane so that the test lane matches standard construction, set for 16 in. (0.41 m) on center. The roof deck is made of 1/4-in. (6.4 mm) and 1/2-in. (12.7 mm) thick plywood (Figure 3) nailed to 2-by-6 roof rafters. The exterior surface of the plywood was sealed using a fully adhered moisture shield. The metal panels are of standing-seam design and are attached to the plywood with wood screws along perimeter

6. Black-painted PVDF is laminated with photovoltaic cells.

clips. The attic cavities are also ventilated with both soffit and ridge vents typical of metal roofing with the exception of the center lane. One of the two center roof lanes with a bronze-painted PVDF aluminum exterior is not vented.

The attic truss is of conventional design and is made of 2-by-4 and 2-by-6 wood materials. The soffit for the steep-slope roof assembly is 1 1/2-ft (0.46 m) wide and includes a perforated metal plate for venting the attic. A gutter is also installed on the steep-slope assembly to prevent runoff onto the low-slope assembly.

The test lanes have their own unique attic cavities, and each cavity is about 4 ft (1.22 m) wide with a footprint of about 16 ft (4.88 m). Holton and Beggs (1999) measured an attic air temperature of 108ºF (42.2ºC) in testing a light-colored, plastic-shake roof. They later tested the identical house with asphalt shingles. For field-testing recorded at the same outdoor temperature, the attic temperature rose to 126ºF (52.2ºC). Therefore, it is entirely possible for temperature differences of about 20ºF (10ºC) to occur between adjacent attic cavities.

For the ESRA testing, Type II expanded polystyrene foam insulation[7] of 11 in. thickness was installed between test cavities (Figure 3) to minimize any lateral heat flows to less than about 0.5% of the solar-flux incident on a roof panel. To further minimize any lateral heat flow effects, we arranged the test roofs by grouping light-color roofs separately from dark-color roofs (Figure 1).

Instrumentation. A 2 in. (50.4 mm) square by 0.18 in. (4.6 mm) deep slot was routed from the 1/2-in. (12.7 mm) plywood, an HFT and a thermocouple were emplaced, and the 1/4-in. (6.4 mm) plywood was nailed atop the thicker piece of plywood. Because of natural convection forces, the temperature gradient from the surface of the test roof to the attic cavity may vary from the soffit to the ridge vent. We therefore placed an averaging thermopile[8] between the two pieces of plywood and on the underside of the 1/2-in. (12.7 mm) plywood to measure the average temperature gradient across the roof deck. The local heat flux, measured by the HFT, and the temperature difference measured near the HFT yield a check of the plywood thermal conductivity. The thermopile placed across the plywood will then enable the total energy transmitted through the test roof to be calculated. We also installed thermopiles across the expanded polystyrene foam insulation to measure the strength of any lateral heat flows between adjacent cavities.

All cavities have an instrumented area in the sub-roof for measuring the heat flows into the conditioned space under them. The setup is identical to that used for the low-slope assembly. The attic floor consists of a metal deck, a 1 in. (25.4 mm) thick piece of wood fiberboard lying on the metal deck and a 1/2 in. (12 mm) thick piece of wood fiberboard placed atop the thicker piece.

Reflectance and Emittance Instruments

We used a portable solar spectrum reflectometer to measure the total hemispherical reflectance[9] of the painted and unpainted metal roof panels. 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 to yield the total hemispherical reflectance. The device is accurate to within ±0.003 units (Petrie et al. 2000) through validation against the ASTM E-903 method (ASTM 1996).

The emittance[10] of the different painted and unpainted metal roofs varies from about 0.15 to 0.90. The impact of emittance on roof temperature is as important as that of reflectance. We therefore used a portable emissometer to measure the total hemispherical emissivity 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.

Weathering of Painted and Unpainted Metal Roofing

The Environmental Protection Agency (EPA) has implemented the Energy Star® Roof Products Program to help consumers identify energy-efficient, cost-effective roofing. Manufacturers can enter a memorandum of understanding with the EPA and display the Energy Star® logo provided their product meets Energy Star® specifications for low- and steep-slope roofing. Low-slope roofing must have an initial solar reflectance ≥ 0.65, and the reflectance must be maintained ≥ 0.50 for three years after installation. Steep-slope roofing must have an initial solar reflectance ≥ 0.25, which must be maintained ≥ 0.15 for three years after installation. Three years of reflectance data must be documented for three exist-

7. Type II polystyrene foam has a density of 1.25 lb/ft^3 (20 kg/m^3); therefore, its transport properties are not as strongly temperature-dependent as foam, which has a density ≤ 0.94 lb/ft^3 (15 kg/m^3).

8. The thermopile was made of a series connection of thermocouples, which yields an average temperature.

9. Reflectance used here is the solar hemispherical reflectivity and is defined as the fraction of energy, incident from all directions of an enclosing hemisphere with wavelengths ranging from 0.25 to 2.5 μm onto a surface, which is reflected diffusely over all wavelengths.

10. Heat loss is in the infrared spectrum. However, for this study, the measured emittance is the infrared hemispherical emittance, defined as the fraction of radiation emitted from a surface over wavelengths ranging from 4 to 40 μm and in all directions as compared to a blackbody, (i.e., a perfect emitter).

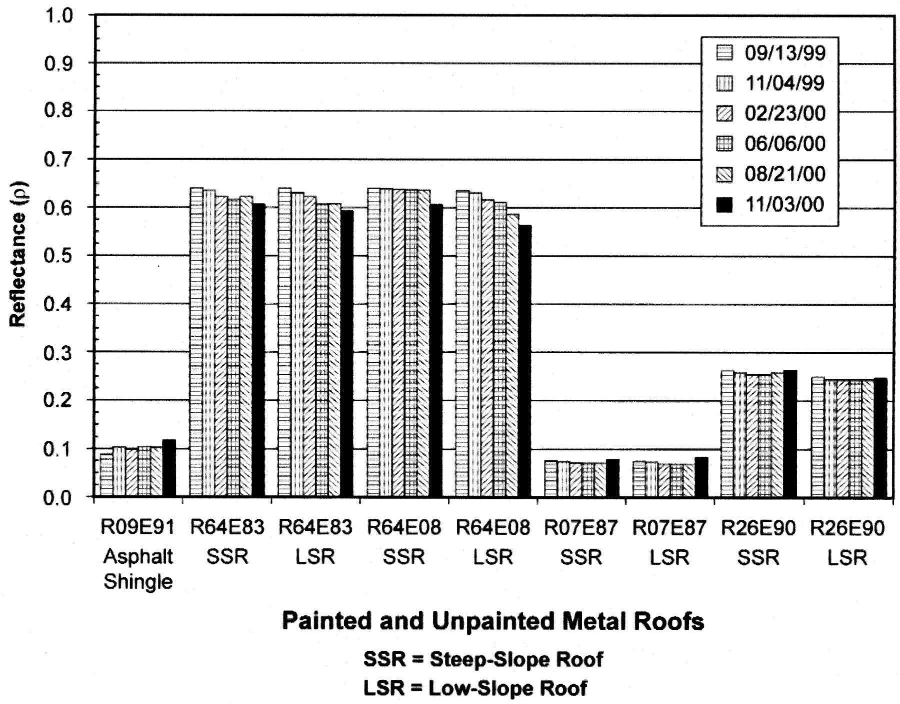

Figure 4 *Reflectance of the painted metal panels tested on the steep-slope and the low-slope metal roof assemblies on the ESRA.*

ing roofs; one of the roofs must be located within a major urban area.

Prior studies conducted with roof coatings revealed that the solar reflectance decreases significantly in the first two years of weathering (Byerley and Christian 1994; Petrie et al. 1998). The results gleaned from the ESRA testing show that the solar reflectance of highly reflective, single-ply membranes drops by about 25% in the first year and then levels out over the next several years. The reduction is caused by surface contamination and weathering of the roof. Contamination occurs over time from atmospheric pollution and biological growth. Ultraviolet radiation, temperature cycling caused by sunlight, sudden temperature swings (e.g., rain), moisture penetration, condensation, wind, hail, and freezing and thawing all contribute to weathering of the roof membrane. However, data describing the impact of weathering are extremely sparse simply because of the time and patience required to collect and interpret the data.

Reflectivity measurements were made every three months on the steep- and low-slope metal roofs; these measurements are shown in Figures 4 and 5. Each metal roof is described generically using an R*xx*E*yy* designation. R*xx* states the solar hemispherical reflectance of a new sample, 1.0 being a perfect reflector. E*yy* defines the infrared hemispherical emittance of the new sample, 1.0 being blackbody radiation. For example, the asphalt-shingle roof is labeled R09E91 in Figure 4. Its fresh-from-the-can surface properties are therefore 0.09 reflectance and 0.91 emittance. Table 1 identifies the R*xx*E*yy* designations for the different painted and unpainted test metals.

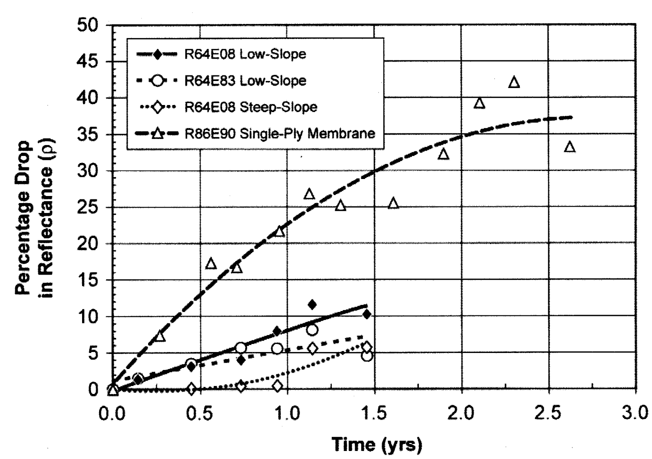

Figure 5 *The painted metal roofs show less reduction in reflectance than do single-ply membranes.*

After one year of exposure, the original values for the low-slope metal roofs R64E83, R64E08, R69E06, and R62E83 have dropped an average of 7%. At the start, the unpainted galvanized metal roof, R66E06, had a mirror-like specular finish. Within 30 days, its surface had a dull appearance and the reflectance had dropped from 0.66 to 0.32; its

TABLE 1
Designations for the Painted and Unpainted Metal Roof Field-Tested on the ESRA

		Reflectance (ρ)	Emittance (ε)	Identifier
Asphalt shingle[a]	Steep-slope	09	91	R09E91
White-painted PVDF	Steep-slope	64	83	R64E83
White-painted PVDF	Low-slope	64	83	R64E83
55% Al-Zn coated steel with acrylic layer	Steep-slope	64	08	R64E08
55% Al-Zn coated steel with acrylic layer	Low-slope	64	08	R64E08
Bronze-painted PVDF	Steep-slope	07	87	R07E87
Bronze-painted PVDF	Low-slope	07	87	R07E87
Black-painted PVDF with Photovoltaic[b]	Steep-slope	26	90	R26E90
Black-painted PVDF with Photovoltaic	Low-slope	26	90	R26E90
Unpainted 55% Al-Zn coated steel	Low-slope	69	06	R69E06
Unpainted Galvanized Steel	Low-slope	66	06	R66E06
Off-white polyester	Low-slope	62	83	R62E83
Built-up roof (BUR)	Low-slope	05	90	R05E90

[a] The asphalt shingles have a red and gray coloring for aesthetic appeal to a homeowner. We made reflectance measurements on shingles having predominantly black, predominantly red, and predominantly gray shading.

[b] Reflectance and emittance measurements are of the photovoltaic strip laminated to the black-painted PVDF.

emittance increased from 0.06 to 0.09. The reflectance of the unpainted galvanized metal reached a minimum after six months of exposure and then again increased with time. Airborne pollution (e.g., dust) actually caused the reflectance of some of the surfaces to increase by lightening the color of the dark surfaces for R07E87 and R26E90. Reflectance of R09E91, the asphalt-shingle roof, also increased with time due to the accumulation of dust (Figure 4).

The painted metal roof panels appear to have excellent corrosion resistance. Their surface opacity limits photochemical degradation caused by ultraviolet light present in sunlight. All painted metal roofs have maintained their fresh-from-the-can appearance. After one year of exposure, acid rains have not etched the metal finish, and there is no evidence of any biological growth on the test roofs. Hence, atmospheric pollution does not appear to stick to the surface because it is washed off by rain. The more reflective roofs on the steep-slope assembly have maintained their reflectance better than their low-slope counterparts (Figure 4). On the other hand, the low reflectance of R07E87 and R26E90 painted metals show little change. The 55% Al-Zn-coated steel roof with a clear acrylic dichromate layer, R64E08, shows a 10% drop in reflectance after one year of weathering. Its steep-slope counterpart has dropped only 3%. The white-painted PVDF roof, R64E83, has similar performance to the 55% Al-Zn-coated steel roof with a clear acrylic dichromate layer.

The performance of both painted metal roofs as compared to a highly reflective single-ply membrane is the most dramatic (Figure 5). After one year of exposure on the ESRA, the single-ply membrane, R82E90, has degraded 25% as compared to only about a 10% drop for the painted metals. Both materials were tested side by side on the ESRA and endured the same extremes in weather. Inspection of the membrane revealed a film of dirt, whereas dirt does not appear to attach as easily to the smoother surface finish of the metal roof. Data for the R64E08 steep-slope roof are also shown in Figure 5. Its reflectance has dropped about 5% as compared to about 10% for its low-slope counterpart. The result shows the beneficial effect of washing from precipitation. As slope increases, the benefit increases, helping to limit drops in reflectance.

The emittance of the painted metal roofs did not vary much after one year of weathering. The average change in emittance was less than 2% for all painted metal roofs, which is consistent with the observations of Petrie et al. (2000) for roof coatings. The slope of the roof had no effect. However, the unpainted R64E08 and R66E06 low-slope roofs showed increases in emittance as previously discussed.

THERMAL PERFORMANCE OF PAINTED AND UNPAINTED METAL ROOFING

The thermal performance of the painted and unpainted metal roofs tested on the ESRA is driven by the roofs' exterior temperatures. In the summer, the higher the roof temperature, the greater the potential for heat leakage into the building and the greater the burden on the comfort cooling system. For winter, the lower the temperature, the greater the potential for heat leakage from the building and the greater the energy consumed for comfort heating. The following energy balance

TABLE 2
ESRA Field Data for the Steep-Slope Roof Assembly

Test Roofs	Weathered Reflectance	Weathered Emittance	T_{max} °F (°C)	T_{min} °F (°C)	$\bar{T}_{Sunlit}$ [a] °F (°C)	Q_{deck} [b] Btu/ft^2 (kJ/m^2)
August 2000 (test roofs exposed for one year)						
R64E83	0.610	0.826	123.0 (50.26)	48.5 (9.2)	92.8 (33.8)	17.1 (194.5)
R64E08	0.627	0.176	142.0 (61.1)	57.0 (13.9)	107.3 (41.8)	41.4 (470.5)
R07E87	0.069	0.890	157.3 (69.6)	51.4 (10.8)	113.4 (45.2)	44.6 (506.2)
R09E91	0.106	0.881	164.1 (73.4)	49.4 (9.7)	117.2 (47.3)	45.2 (513.6)
R26E90	0.254	0.907	163.3 (72.9)	48.8 (9.3)	116.0 (46.7)	48.4 (549.2)
R07E87	0.069	0.878	166.5 (74.7)	49.8 (9.9)	118.7 (48.2)	52.8 (599.8)
February 2000 (test roofs exposed for seven months)						
R07E87[c]	0.066	0.874	126.5 (52.5)	12.4 (-10.9)	73.1 (22.8)	-62.9 (-714.0)
R07E87	0.066	0.879	129.6 (54.2)	11.9 (-11.2)	74.2 (23.4)	-67.1 (-762.3)
R26E90	0.250	0.900	124.8 (51.6)	10.5 (-11.9)	70.5 (21.4)	-71.4 (810.4)
R09E91	0.096	0.896	126.3 (52.4)	11.5 (-11.4)	73.0 (22.8)	-72.6 (-824.5)
R64E08	0.644	0.121	103.4 (39.7)	21.7 (-5.7)	65.6 (18.7)	-75.9 (-862.3)
R64E83	0.624	0.828	83.0 (28.3)	9.8 (-12.3)	50.7 (10.4)	-99.4 (-1129.0)

[a] The sunlit temperature is the metal temperature averaged from roughly 6 a.m. to 6 p.m.
[b] Q_{deck} is the average daily heat flow per unit area through the metal decking.
[c] Attic cavity is not vented.

made on the roof surface mathematically describes the exterior temperature of the metal roof (T_m):

$$q_{bldg\ load} = q_{in}$$
$$-k\frac{dT}{dz} = (1-\rho)I_{solar} - \varepsilon\sigma(T_m^4 - T_{sky}^4) - \hbar(T_m - T_{air}) + q_{lat} \quad (1)$$

where

$\hbar$ = convective heat-transfer coefficient
I_{solar} = solar radiation
T_{air} = outside ambient air temperature
T_m = surface temperature of the metal roof
q_{lat} = latent heat flux from either condensing or evaporating water
ε = infrared hemispherical emittance
ρ = solar hemispherical reflectance
σ = Stefan-Boltzmann constant
z = depth into the roof

The roof temperature is strongly dependent on the roof's surface properties of solar reflectance (ρ) and infrared emittance (ε). Convection ($\hbar$) is also important. In the early morning, evaporation and, in the twilight, condensation, will also affect roof temperature. Increasing the reflectance or emittance will reduce the exterior temperature, which in turn results in reduced building load ($q_{bldg\ load}$). Reflectance effects occur during the sunlight hours, while the effects of emittance occur continuously as long as there is a temperature difference between the metal and the radiant sky.[11]

Table 2 lists values of the emittance and reflectance after about a year of field exposure for the steep-slope test roofs. The metal temperature and integrated heat flux are also provided to view the interaction of reflectance and emittance on heat flow into the conditioned space. These data are used in the following discussion on the thermal performance of the steep-slope test roofs. Similar data for the low-slope assembly are listed in the Appendix, Table A-1.

Temperature data for a week of summer and winter weather with clear skies are shown in Figure 6. These data are for metal roof surfaces on the steep-slope assembly. Note that each label on the abscissa in Figure 6 is for midnight. The maximum daily ambient air temperature ranged from about 85°F to 95°F (29.4°C to 35.6°C) over the week in August. In February, the daily maximum air temperature ranged from 40°F to 60°F (4.4°C to 15.6°C). Peak air temperature usually occurs at about 4 p.m., with the peak roof temperature occurring slightly earlier at about 2 p.m.

The summer roof temperature for the R07E87, R26E90, and R09E91 (asphalt-shingle) sections all exceeded 160°F (71.1°C) and on some days reached a peak temperature of 165°F (73.9°C). The more reflective R64E83 and R64E08 test

11. Measures of the global infrared irradiance made by the BTC's field pyrgeometer are used to calculate the radiant sky temperature from the equation for blackbody radiation: $q_{IR} = \sigma T_{sky}^4$.

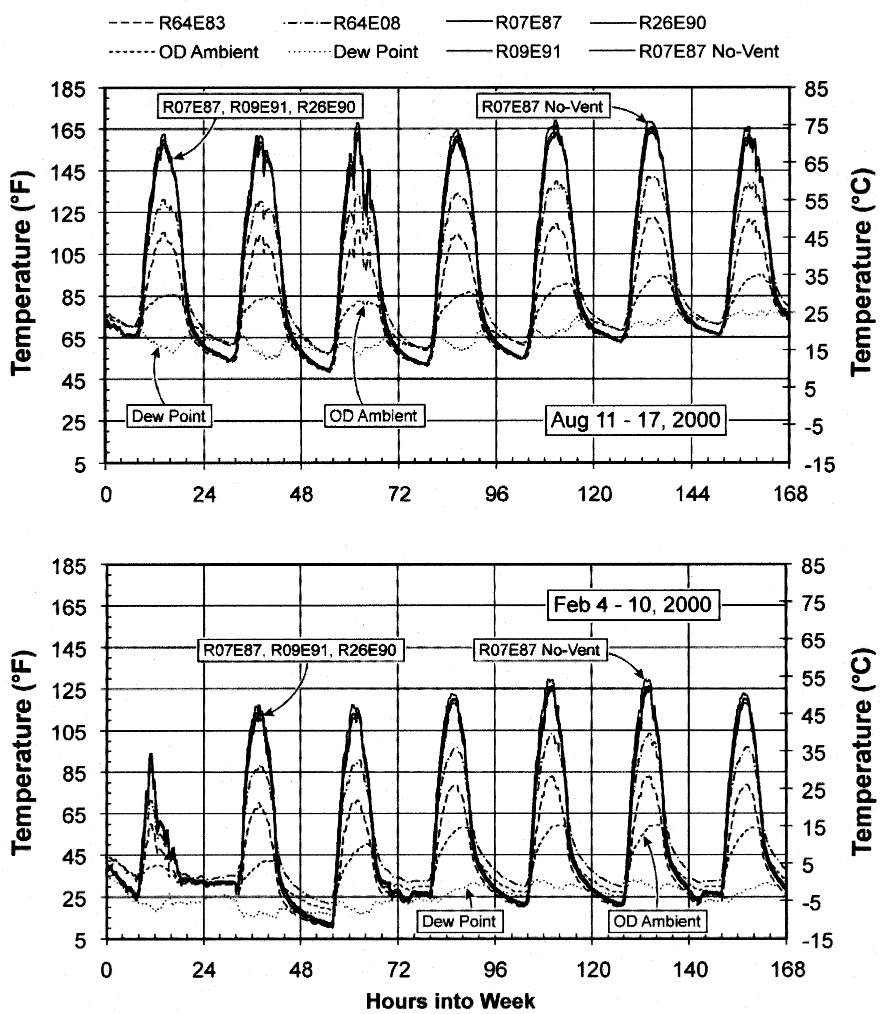

Figure 6 *Field data collected for the steep-slope metal roof assembly for one week of summer and one week of winter data.*

sections had peak temperatures of about 115°F and 135°F (46°C to 57.2°C), respectively. The lower temperatures, in turn, imply less heat transmission into the building. On August 11, 2000, however, the R64E83 roof emittance was 0.826 as compared to 0.176 for the R64E08 test roof. Therefore, the 20°F (11.1°C) difference in roof temperature is driven predominantly by the effect of emittance. The effect is even better depicted for the February data (Figure 6). During the evening hours, the lower emittance test roof (R64E08) maintains a temperature that exceeds the dew point temperature of the ambient air. Therefore, during the evening hours, less heat leaks to the outdoor ambient from the less emissive of the two metal roofs.

The Figure 6 data for the painted and unpainted metal steep-slope roofs were cast in terms of the exterior roof temperature averaged over the hours between 6 a.m. and 6 p.m. The averaged data were then fit using the reflectance and emittance as the independent variables; these data are shown in Figure 7. For the month of February, decreasing the reflectance caused less than a 5°F (2.8°C) increase in the average roof temperature—its effect is relatively flat in the winter. However, decreasing the emittance from 0.6 to 0.3 caused the average roof temperature to increase about 15°F (8.3°C). For August, the effects of reflectance and emittance are more equally weighted (Figure 7). If the reflectance is increased from 0.3 to 0.6, the average roof temperature in August decreased about 15°F (8.3°C) for emittance fixed at 0.60. Conversely, about a 20°F (11.1°C) decrease in roof temperature occurs if the emittance is reduced 0.3 units for reflectance fixed at the moderate value of 0.6.

The results show that a moderate reflectance with low emittance would be thermally efficient in a predominantly heating-load climate. Therefore, the design of a metal roof for predominantly heating-load applications should focus on the surface emittance because greater performance gains are

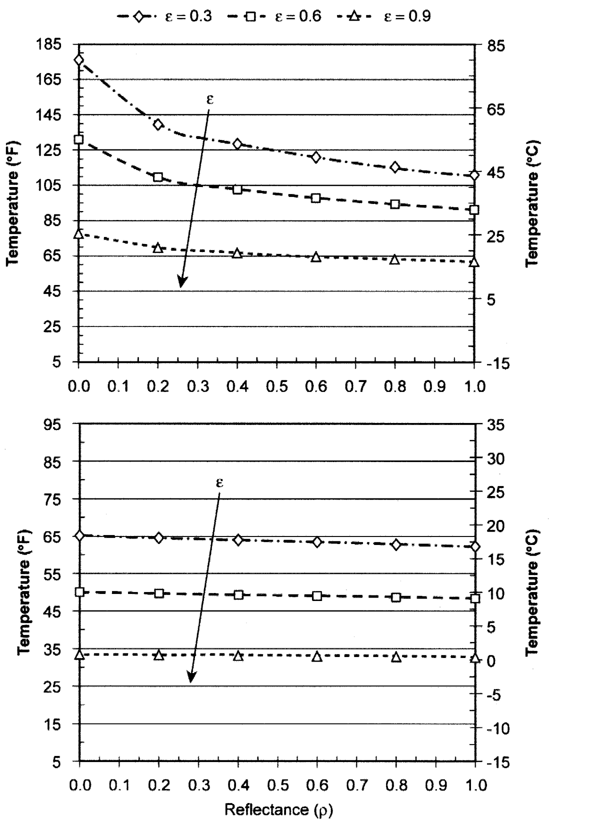

Figure 7 *The effect of emittance and refelctance for field exposure data collected for summer (top) and winter (bottom) plots.*

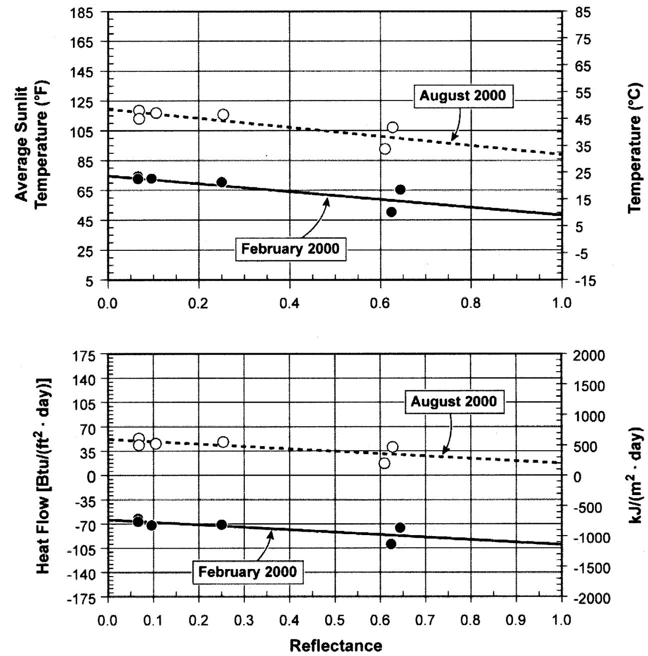

Figure 8 *The data for the steep-slope metal roof assembly in Figure 6 are cast into the average sunlit (about 6 a.m. to 6 p.m.) roof temperature and the daily (24-hour) averaged heat flow through the deck, Table 2.*

achievable with decreases in emittance. In predominantly cooling-load climates, painted metal roofs with high reflectance and high emittance both equally enhance thermal performance of the roof. Here, design should focus on increasing both the emittance and reflectance to decrease the exterior roof temperature, which in turn decreases the heat leakage into the building.

The daily average heat flow into the building (q_{deck}) was calculated for a full week of data by integrating the HFT measurements, which are monitored at 15-second intervals and recorded every 15 minutes. We fit the data using regression analysis to extrapolate the potential benefits of reflective roofing (Figure 8). Results for a week in August show that increasing the reflectance drops the average sunlit roof temperature and therefore reduces the amount of heat transmission through the roof. The steep-slope metal roofs, with reflectance of about 0.6, have an average sunlit temperature of about 100°F (37.8°C) as shown in Figure 8. If the metal roofs were perfect reflectors ($\rho = 1$), then their average temperature would drop to about 90°F (32.2°C). The heat leakage into the building would then drop an additional 43% for a steep-slope roof. This translates into about 15 Btu/(ft^2·day) (170 kJ/[m^2·day]) less heat flux into the building during the summer. The analogy therefore provides insight into the limits of what can be achieved with improved surface reflectance.

Conversely, decreasing the reflectance in the winter causes heat leakage from the building to decrease. The reflectance, if decreased from 0.6 to 0.25, increases the average roof temperature by about 10°F (5.6°C). If the roof surface were a perfect absorber ($\rho = 0$), the temperature would increase only an additional 5°F (2.8°C). Therefore, about a 15% decrease in heat leakage from the building occurs if metal with a reflectance of 0.25 is used instead of metal with a 0.6 reflectance. The results show the trade-offs between winter and summer, which cannot be fairly judged except through seasonal simulations.

CONCLUSIONS

The painted metal roofs have maintained their fresh-from-the-can appearance—the steep-slope roofs more so than the low-slope roofs. They appear to have an excellent corrosion-resistant surface whose opacity limits photochemical degradation caused by ultraviolet light present in sunlight. After a year of exposure, acid rain has not etched the metal finish, and there is no evidence of any biological growth on the test roofs. Drops in reflectance are due more to airborne pollution than to any effect of the sun. Therefore, as roof slope increases, the washing action of precipitation increases, which helps to refresh the reflectance.

Exposure data for the more reflective painted metal roofs show promise that the roofs will qualify for the Energy Star® label for steep-slope roofing. Drops in reflectance are about 10% after one year of exposure; however, three years of weathering are required for certification. In low-slope applications, the initial reflectance appears too low, and further data are required to determine whether the painted metal can maintain reflectance above 0.5 for three years of exposure.

The design of a metal roof for predominantly heating-load application should focus more on the level of roof insulation than on the surface reflectance or emittance. A moderate reflectance with a low emittance showed the least heat leakage from the test roofs. In predominantly cooling-load climates, the high reflectance and high emittance of white-painted metal roofs both equally impact the thermal performance of the roof. Here, design should focus on increasing both the emittance and reflectance to decrease the exterior roof temperature, which in turn decreases the heat leakage into the building.

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APPENDIX A

TABLE A-1
ESRA Field Data for the Low-Slope Test Assembly

Test Roofs	Weathered Reflectance	Weathered Emittance	T_{max} ºF (ºC)	T_{min} ºF (ºC)	$\overline{T}_{Sunlit}$ [a] ºF (ºC)	Q_{deck} [b] Btu/ft (kJ/m^{2})
			August 2000 (test roofs exposed for one year)			
R64E83	0.599	0.826	123.3 (50.7)	49.1 (9.5)	93.6 (34.2)	13.8 (156.4)
R62E83	0.586	0.808	126.9 (52.7)	47.9 (8.8)	95.9 (35.5)	18.0 (204.1)
R64E08	0.586	0.166	142.8 (61.6)	53.9 (12.2)	108.7 (42.6)	59.1 (671.2)
R69E06	0.580	0.113	147.8 (64.3)	52.6 (11.4)	111.6 (44.2)	68.5 (778.1)
R66E06	0.228	0.346	156.0 (68.9)	50.3 (10.2)	117.3 (47.4)	69.2 (785.7)
R26E90	0.241	0.885	158.1 (70.1)	48.1 (8.9)	115.4 (46.3)	NA
R05E90	0.040	0.900	159.0 (70.6)	35.3 (1.8)	109.3 (42.9)	45.3 (514.1)
			February 2000 (test roofs exposed for 7 months			
R66E06	0.286	0.180	121.1 (49.5)	22.7 (-5.2)	74.6 (23.7)	-57.4 (-652.4)
R64E08	0.622	0.117	101.6 (38.7)	27.9 (-2.3)	67.1 (19.5)	-60.9 (-691.5)
R69E06	0.647	0.081	101.2 (38.4)	26.8 (-2.9)	66.3 (19.1)	-69.4 (-787.7)
R05E90	0.036	0.900	113.8 (42.9)	8.7 (-12.9)	64.2 (17.9	-84.8 (-963.2)
R26E90	0.240	0.891	109.2 (42.9)	12.0 (-11.1)	63.9 (17.7)	-95.1 (-1080.3)
R62E83	0.600	0.821	82.7 (28.2)	12.3 (-10.9)	51.7 (10.9)	-113.3 (-1264.1)
R64E83	0.620	0.828	79.9 (26.6)	13.0 (-10.6)	50.7 (10.4)	-117.7 (-1336.9)

[a] The sunlit temperature is the metal temperature averaged from roughly 6 a.m. to 6 p.m.
[b] Q_{deck} is the average daily heat flow per unit area through the metal decking.