Roof Heating and Cooling Loads in Various Climates for the Range of Solar Reflectances and Infrared Emittances Observed for Weathered Coatings

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ABSTRACT

Twenty-four low-slope roof coating systems and four uncoated specimens have been in place since June 1997, exposed to the Knoxville, Tennessee climate. Local weather conditions, temperatures from top to bottom of each 2 ft x 2 ft (0.61 m x 0.61 m) test section and heat flux through the wood fiberboard roof insulation for each test section have been recorded continuously. Periodically, each surface's reflectance over the solar spectrum and emittance in the infrared have been measured in-situ. These data permit direct validation of a computer program for one-dimensional, transient analysis of roof thermal performance.

Nine surfaces covering the range of solar reflectance and infrared emittance were identified from the behavior of fully weathered surfaces in the project. Annual modeling was done for them using Typical Meteorological Year (TMY2) data. Annual cooling load was defined as the sum of hourly heat fluxes through the deck when outdoor temperature was greater than 75˚F (24˚C). For poorly insulated roofs in Knoxville, this cooling load was the lowest for a white-coated roof and the highest for an uncoated surface. Annual heating load was defined as the sum of hourly heat fluxes through the deck when outdoor temperature was less than 60˚F (16˚C). Heating load was the highest for the white-coated surface and an intermediate value for the uncoated surface. A surface covered by a shiny aluminum capsheet, because of its low infrared emittance, displayed the lowest heating load of the nine surfaces. It had an intermediate cooling load.

The heating and cooling loads varied significantly with climate. As insulation level increased, coatings had much less effect on thermal performance. In cooling-dominated climates, the most savings in annual building energy costs were achieved by white-coated roofs. In heating-dominated climates, slightly more savings were achieved by the aluminum capsheet and highest reflectance aluminum coating.

Introduction

Reflective roof coatings can be a critical component of a proactive roof maintenance program and one which results in lower membrane temperatures during sunny periods. Lower membrane temperatures, in turn, reduce the air conditioning load on the building under the roof and lengthen the service life of the roof surface. If cooling loads dominate, peak load reductions and net annual energy savings are also realized after coating a roof. In climates with both significant heating and cooling loads, normal roof heat gain in winter is diminished somewhat by the higher solar reflectance of the coating. Highly reflective roof coatings lead to a heating season penalty, which may be significant relative to the cooling season benefit.

In June 1997, twenty-four different reflective coating systems for low-slope roofs were applied to 2 ft by 2 ft (0.61 m by 0.61 m) test sections on an outdoor test facility at a U.S. national laboratory in East Tennessee. Four sections were left uncoated. Agreements were reached between the U.S. Department of Energy and the trade association representing the manufacturers of cold-applied coatings and cements used for roofing and waterproofing, as well as directly with several of the manufacturers. The parties agreed to a three year project to determine the effect of weathering on the thermal performance of roofs under current coating systems and to model the performance of each system in climates other than East Tennessee's.

Local weather conditions, temperatures from top to bottom of each test section and heat flux through the fiberboard roof insulation for each test section have been recorded continuously since June 1997. Periodically, each surface's reflectance over the solar spectrum (average over wavelengths from 0.2 to 2.5 micrometers) and emittance in the infrared (average over wavelengths from 4 to 40 micrometers) have been measured in-situ. Samples of each coating are also being subjected to weathering on uninstrumented test stands. They will provide participants with specimens for end-of-project tests of the relative mechanical behavior of unprotected membranes and ones protected by coatings.

The twenty-four coating systems include eight white coatings, thirteen aluminum coatings, an aluminized asphalt emulsion and two capsheets. The capsheets have reflective metal surfaces factory-adhered to single-ply membrane material. Pieces were torch-applied to the top of APP-modified bitumen test sections. A total of ten systems were applied to APP-modified bitumen and fourteen were applied to non-flood-coated built-up roofs after the uncoated membranes had aged about four weeks. To achieve consistent application, all liquid coatings were applied by personnel of the national laboratory following instructions of the manufacturers specifically for the small test sections. In order to ensure that the instructions were suitable, representatives of the manufacturers and their trade association applied their respective coatings to locations on the uninstrumented test stands.

This paper is the first publication of results from this project in an open forum. The paper's purpose is to show how much differences in solar reflectances and infrared emittances for current coatings affect the thermal performance of roofs protected by the coatings. A history of solar reflectances for coated and uncoated surfaces is given to justify the fully weathered values that are used to generalize the test results. Infrared emittances are also listed. A model of each test section in Knoxville, validated by measurements, is used with typical meteorological year weather data to generate annual averages for membrane temperatures for comparison to averages of the measurements. Cooling and heating loads are predicted for a variety of roofs and locations. The roofs differ not only in their radiation properties, but also in the amount of insulation installed in them and the thermal mass of their decks. Some results are given from work in progress to devise an Internet calculator for estimating cost savings for whole buildings with coated roofs relative to the same buildings with an uncoated roof.

Weathered Solar Reflectances and Infrared Emittances

The thermal performance of low-slope roofs is directly affected by the thermal radiation properties of the coated or uncoated roof surface. To illustrate the parameters that are involved, Equation (4) in Chapter 28 of the 1997 ASHRAE Handbook of Fundamentals (ASHRAE 1997) gives the following expression for heat flux into a sunlit roof from above:

$$\frac{q}{A} = a\, I_t + h_o\,(t_o - t_s) - e\,\Delta R \qquad (1)$$

where,

$^{q}/_{A}$ = heat flux;
α = (fractional) absorptance of the surface for solar radiation;
I_t = total solar radiation incident on the surface;
h_o = coefficient of heat transfer at the outer surface;
t_o = outdoor air temperature;
t_s = roof surface temperature;
ϵ = (fractional) emittance of the surface; and,
ΔR = difference between sky radiation and radiation emitted by black surface at t_s.

For the opaque surfaces in this project, thermal radiation is either absorbed or reflected so the sum of the fractional solar reflectance, ρ, and fractional solar absorptance, α, is 1.0.

Our experience in prior studies with aluminum-coated and white-coated surfaces showed that the solar reflectance decreases significantly when these surfaces are exposed to the weather (Byerley & Christian 1994; Petrie, Childs & Christian 1998; Smith 1998). To document our experience with the variety of coating systems in this project, we measured the solar reflectance at four locations on each of the 28 test sections monthly during summer 1997 and bimonthly during summer 1998 and summer 1999. A portable solar spectrum reflectometer was used to do the measurements in-situ. Results with this reflectometer compared well to those by the ASTM E-903 method (ASTM 1996). In a collaborative effort, another U.S. national laboratory used a scanning spectrophotometer on five samples of coated and uncoated APP-modified bitumen, obtaining values from 0.08 to 0.82. We measured the solar spectrum reflectance of the same samples with our instrument before and after the E-903 measurements. Agreement on average was within +0.003 with scatter of ±0.02 (Petrie et al. 2000).

Figure 1 is the history of solar spectrum reflectances for the nine surfaces described in the legend of the figure. Best-fit, second-order polynomials through the data for each surface are shown. Individual measurements are given for the R26 surface to display frequency and typical scatter of the measurements. Several aluminum coatings had initial reflectances like that of the R26 surface, which were not consistent with the trend of the rest of their first summer's reflectances. Data for the polynomials did not include these inconsistent initial reflectances associated with curing or "leafing out" of aluminum coatings.

The variety of coating systems in this project broadened our experience with weathering effects. Compared to aluminum-coated surfaces, white-coated surfaces exhibit greater absolute decreases in solar reflectance from higher initial levels. However, their reflectances do not generally fall below those of aluminum-coated surfaces despite weathering. The solar reflectance of the uncoated surfaces has not changed to date. The solar reflectance of the aluminized asphalt emulsion increased slowly as aluminum particles gradually rose to the surface. The legend gives the solar reflectance of each surface at two years and two months into the project. Changes in solar reflectances seem to have stopped and we claim the surfaces are fully weathered.

The coating systems in our project have a wide range of infrared emittance, from 0.11 to 0.90. Because of the potential for a significant effect of these different emittances, we also measured the emittances in-situ with the method of ASTM C-1371 (ASTM 1997). As part of the collaborative effort with another U.S. national laboratory, a scanning emissometer was used on five coated metal coupons, yielding emittances from 0.41 to 0.87 (Berdahl 1997). Results with our portable emissometer agreed on average within -0.018 with scatter of ±0.05. Emittances of the same unweathered coatings on roof membranes were measured by a special technique recommended by the manufacturer of the portable emissometer for such samples. This established the accuracy of the special technique. We measured the emittances at the center of all twenty-eight

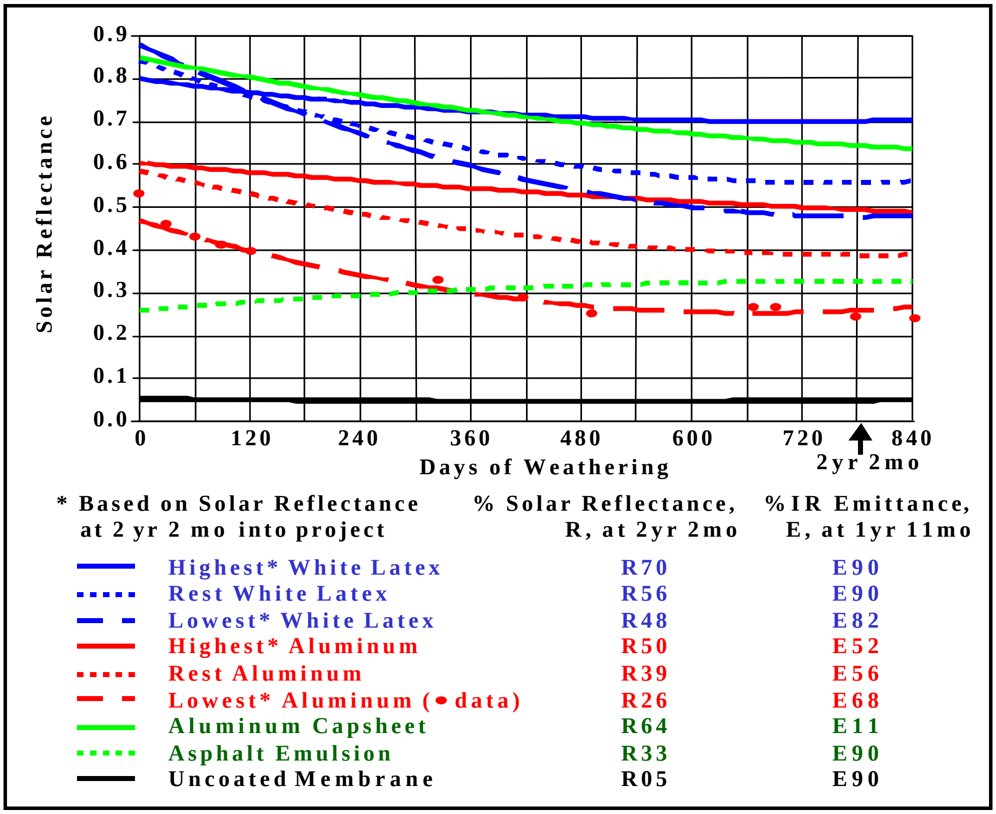

Figure 1. History of Solar Spectrum Reflectances for Various Coated and Uncoated Surfaces Exposed Continuously to the Knoxville, Tennessee Climate since June 1977. Legend Gives RxxEyy Designation of Solar Reflectance and Infrared Emittance for Each Surface

test sections during spring of 1998 and 1999.

The spring 1999 infrared emittances of the nine typical surfaces are listed in Figure 1. Comparing the spring 1998 and 1999 measurements, the infrared emittance generally increased more for the thirteen aluminum surfaces (average of 0.07 increase) than for the eight white-coated surfaces (average of 0.02 increase) from the first to the second year. At the end of the second year, the white-coated and uncoated surfaces show infrared emittance near 0.90, which is typical of non-metals. The aluminum-coated surfaces have lower infrared emittance, averaging 0.57 for the thirteen aluminum coatings. The minimum infrared emittance for all systems is 0.11 for the aluminum capsheet. To ensure accurate measurement of its emittance, the emissometer has a reference surface with 0.07 emittance that is used to set the low-end response of the instrument.

Measured and Predicted Membrane Temperatures

The objectives of the project are to document the thermal performance as the coatings weather and to model the performance of each system in climates other than East Tennessee's. The temperatures and insulation heat fluxes measured for the test sections provide evidence about the changing thermal performance. They also allow us to validate a model in the East Tennessee climate for the range of radiation properties. The model is a finite difference representation of the transient heat conduction equation in one space dimension with capability to use the construction features of the test sections and their thermal properties. The thermal conductivity of roof insulation can be allowed to vary linearly with mean insulation temperature (Wilkes 1989).

Direct comparisons of surface temperature and insulation heat flux measurements and predictions were done for several cloudless days throughout the project when the panels were dry but at various stages of weathering. Measured outside air temperature, wind velocity, incident total solar radiation, incident sky radiation and inside surface temperatures were used in the model. The comparisons convinced us that the model is properly sensitive to the wide range of radiation properties. It correctly mirrors effects of changes in solar reflectance and infrared emittance for the three distinct kinds of surfaces in Figure 1: high reflectance, high emittance white coatings; medium reflectance, medium-to-low emittance aluminum coatings; and, low reflectance, high emittance uncoated surfaces.

To model the thermal performance of the coated and uncoated surfaces for different roof insulation levels and different climates, we chose typical meteorological data rather than data from a specific year. The set chosen was the Typical Meteorological Year 2 (TMY2) data (NREL 1995), a widely used compilation of meteorological data from 1961 to 1990 collected at 235 different locations in the U.S. and its territories. Figure 2 was prepared to show how well data generated with TMY2 data for Knoxville agreed with data from measurements. Measured air temperatures and membrane temperatures for the nine surfaces in Figure 1 were averaged all twenty-four hours of each day from July 1998 through June 1999. They were also averaged for the hours in this summer-to-summer period whenever average incident solar radiation exceeded 25 Btu/(h·ft^2) (79 W/m^2). These so-called sunlit average temperatures emphasize the effects of differing radiation properties among the surfaces.

Averages for all twenty-four hours of each day and for sunlit times were also predicted with the model. Boundary conditions for the predictions were inside air temperature of 75°F

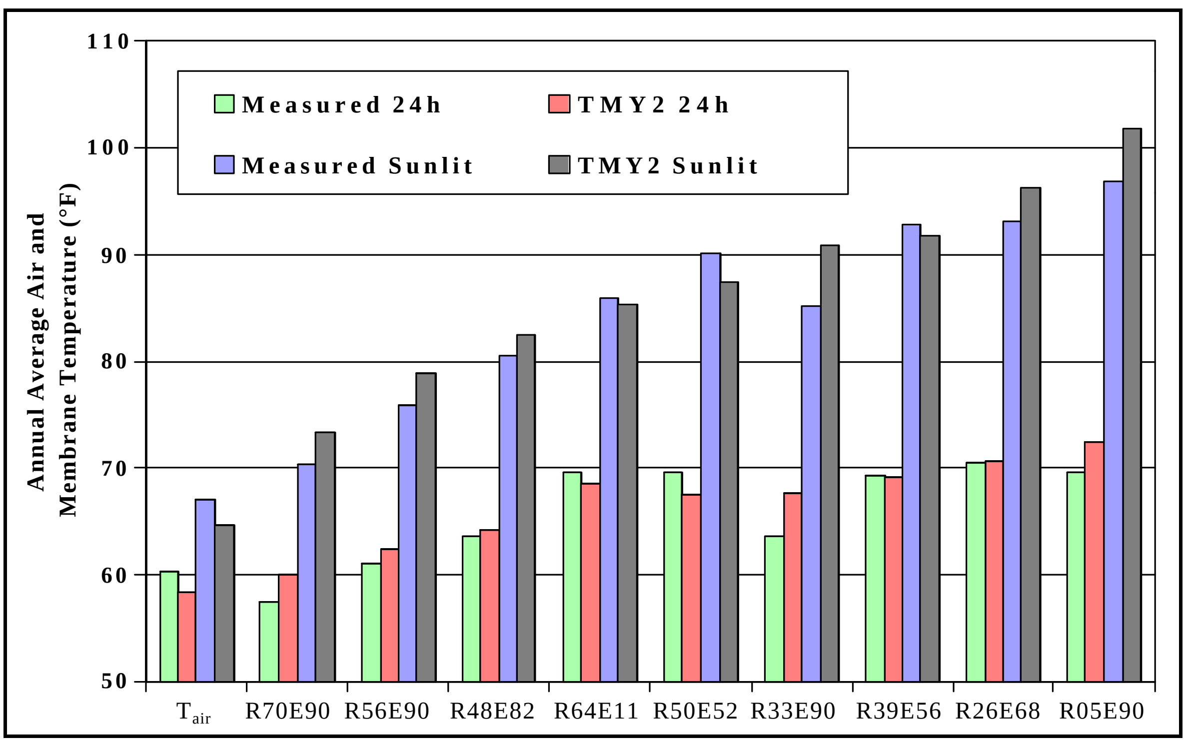

Figure 2. Annual Average Temperatures in Knoxville, Tennessee for Ambient Air and Various Membranes

(24˚C) and TMY2 data for outside air temperature, wind velocity, incident total solar radiation and cloud cover (which the model can use to estimate sky radiation). Test cases with 70˚F (21˚C) inside air temperature showed that sunlit membrane temperatures were at most 0.4˚F (0.2˚C) cooler due to 5˚F (2˚C) cooler inside air temperatures. Membrane temperatures are dominated by outside conditions. The bars for temperatures using Knoxville TMY2 weather are labeled in Figure 2 with the fully weathered solar reflectances from Figure 1. However, the TMY2 temperatures for comparison to the summer-to-summer measurements are the average of separate predictions with solar reflectances for July 1, 1998 and the fully weathered values.

The averages of air temperatures in Figure 2 show that the year of the measurements was slightly warmer than the typical meteorological year. However, average sunlit membrane temperatures with the Knoxville TMY2 data and 75˚F (24˚C) interior temperature are from 3˚F (2˚C) cooler to 6˚F (3˚C) warmer than the measurements. The average for all surfaces is 2˚F (1˚C) warmer. This is attributed to the effects of rain and dew in the measurements, which the TMY2 data cannot duplicate. The aluminum capsheet and all aluminum-coated surfaces except the lowest reflectance one are the surfaces for which the measurements yield higher average sunlit temperatures than the TMY2 data. It is not possible to predict how much rain and dew affect the annual averages. Measurements for the aluminized asphalt emulsion surface, R33E90, indicate that rain and dew lowered average sunlit temperatures at most 6˚F (3˚C).

Figure 2 shows good correspondence between the TMY2 data and the measurements as to how the different radiation properties affect the temperatures. The surfaces are arranged in the order of increasing TMY2 sunlit average membrane temperatures, from lowest for the R70E90 (highest reflectance white) surface to highest for the R05E90 (uncoated) surface. The surfaces would be in the same order using measured sunlit average membrane temperatures except for the R33E90 (aluminized asphalt emulsion) surface. According to the measurements, the R33E90 surface falls between the R48E82 (lowest reflectance white) and R64E11 (aluminum capsheet) surfaces. The uncertain effect of rain and dew again makes it impossible to state exactly how closely the annual averages for the measurements should be to the predictions with TMY2 data.

Annual Cooling Loads

As Figure 2 shows, membrane temperatures are sensitive to the radiation properties of the different coatings. Membrane temperatures are, however, only an indirect measure of the effects of coating systems on thermal performance. Insofar as lower membrane temperatures lead to smaller heat flow into the building during the cooling season, thermal performance is enhanced by coating systems. Insofar as lower membrane temperatures lead to smaller heat flow into the building during the heating season and if internal loads do not dominate the building load, thermal performance may be degraded by coating systems.

The heat flow of direct interest to thermal performance of the roof is that at the bottom of the roof deck. It is available from the roof model by finite difference calculation using temperatures predicted on the deck and just above the deck. Deck heat flow is building load due to the roof if the conditioned space is directly exposed to the roof deck.

The deck heat flow rates per unit area of the roof that the model generated were positive or negative values. Positive values meant flow out of the building (potential heating load). Heating load will be addressed in the section that follows. Negative values meant flow into the building (potential cooling load). They were counted as cooling load if the corresponding outside air temperature was above 75°F (24°C). This assumes that occupants are comfortable without cooling when outside air temperature is below 75°F (24°C). It also assumes that deck heat flows are in phase with outside temperatures. This is true for light weight (LW) plywood or thin metal decks but is less true for medium weight (MW) and heavy weight (HW) concrete decks.

Annual roof cooling loads were obtained by summing the hourly negative heat flow rates per unit roof area when outside air temperature was above 75°F (24°C). Figure 3 presents the magnitude of annual roof cooling loads (multiply Btu/ft² by 11.36 to convert to kJ/m²) in Knoxville for seven different coating systems and five different roof insulation/deck combinations. The six coatings comprising the rest of the white latex coatings, designated R56E90 in Figures 1 and 2, and the nine coatings comprising the rest of the aluminum coatings, designated R39E56 in Figures 1 and 2, are omitted because they are not specific coatings. The roof R-5 LW is a roof with 1.5 in. (3.8 cm) of wood fiberboard insulation on a 0.75-in.(1.9-cm)-thick plywood deck. Total roof R-value is about 5 h·ft²·˚F/Btu (0.9 m²·K/W). Roofs R-13 LW and R-25 LW have thin metal decks with 2 in. (5.1 cm) and 4 in. (10.2 cm) of polyisocyanurate insulation, respectively. Total roof R-values are about 13 h·ft²·˚F/Btu (2.3 m²·K/W) and 25 h·ft²·˚F/Btu (4.4 m²·K/W), respectively. The R-13 HW roof has a 4-in.(10.2-cm)-thick heavy weight concrete deck, which adds thermal mass but no insulation value to the R-13 LW roof. The R-16 MW roof has a 4-in.(10.2-cm)-thick insulating concrete deck, which adds thermal mass and insulation value. Its total R-value is about 16 h·ft²·˚F/Btu (2.8 m²·K/W).

For Figure 3, inside air temperature was held constant at 72.5˚F (22.5˚C). The resultant annual roof cooling loads for Knoxville increase as the surface radiation properties change from R70E90 to R05E90. Since cooling load is dominated by solar effects, relative changes with different surfaces are the same as in Figure 2 for TMY2 sunlit membrane temperatures. Making ±2.5˚F (±1.4˚C) changes in inside air temperature caused an average 2.3% increase in cooling load per ˚F (4.1% per ˚C) decrease in inside air temperature.

Increasing the amount of roof insulation significantly decreases the cooling loads. For constant interior temperature (no thermostat setup), thermal mass effects are not very significant. The heavy weight concrete deck in the R-13 HW roof behaves the same as the insulating concrete deck in the R-16 MW roof. Its extra thermal mass is equivalent to an increase of about 3 h·ft²·˚F/Btu (0.5 m²·K/W). Thermal mass effects could be more significant with daily thermostat setup during unoccupied hours in the cooling season. Heat flow through the deck that is delayed by the thermal mass so as to occur during hours of setup might not need to be handled by the air-

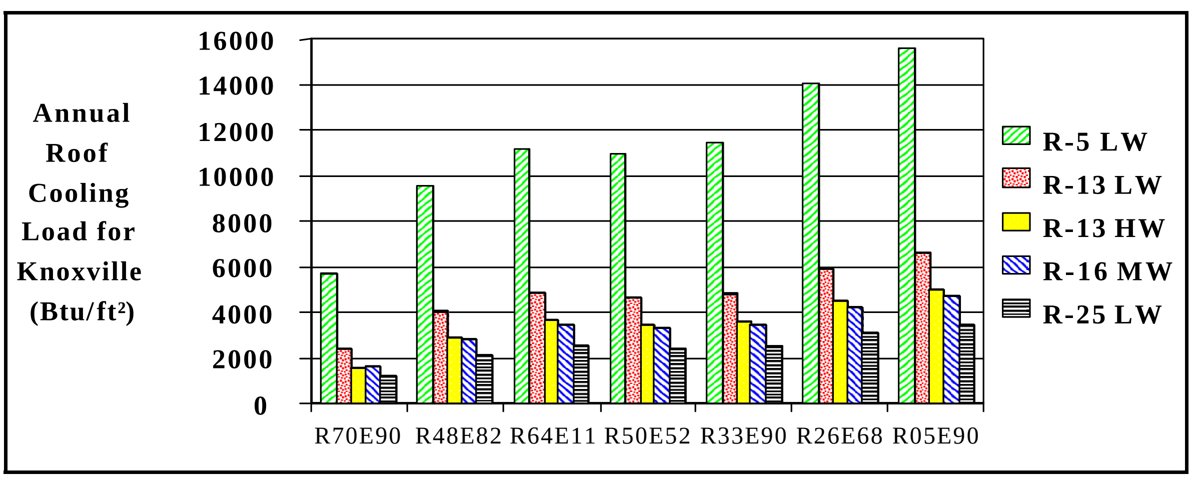

Figure 3. Annual Roof Cooling Load in Knoxville, Tennessee for Various Coatings, Roof Insulation Levels and Decks

conditioning system. It may dissipate to the outside before the air conditioning system returns to operation with the normal occupied set point.

Assuming an R-13 LW roof is the most typical low-slope roof on commercial buildings, Figure 4 shows the effect of location on its cooling load for the same seven combinations of RxxEyy as in Figure 3. In the hot and humid climate of Miami, cooling loads are about twice those in Knoxville for the R-13 LW roof and the respective surfaces. Cooling loads in Figure 4 for the various surfaces on the R-13 LW roof in Minneapolis are very similar to the respective loads on the R-25 LW roof in Knoxville in Figure 3.

Cooling loads are the highest for Phoenix, which has intense solar radiation. From the weather summaries accompanying the TMY2 data sets, average daily solar radiation for Phoenix is 1839 Btu/ft² (20,890 kJ/m²) compared to 1557 Btu/ft² (17,690 kJ/m²) for Miami. This is despite Miami having 4126 cooling degree days (65˚F base) compared to 3814 for Phoenix. Cooling loads in Figure 4 for the various surfaces on an R-13 LW roof in Phoenix are about the same as cooling loads in Figure 3 for the various surfaces on an R-5 LW roof in Knoxville with one exception. The R64E11 surface retains absorbed solar energy because of its low infrared emittance and yields a higher cooling load in Phoenix.

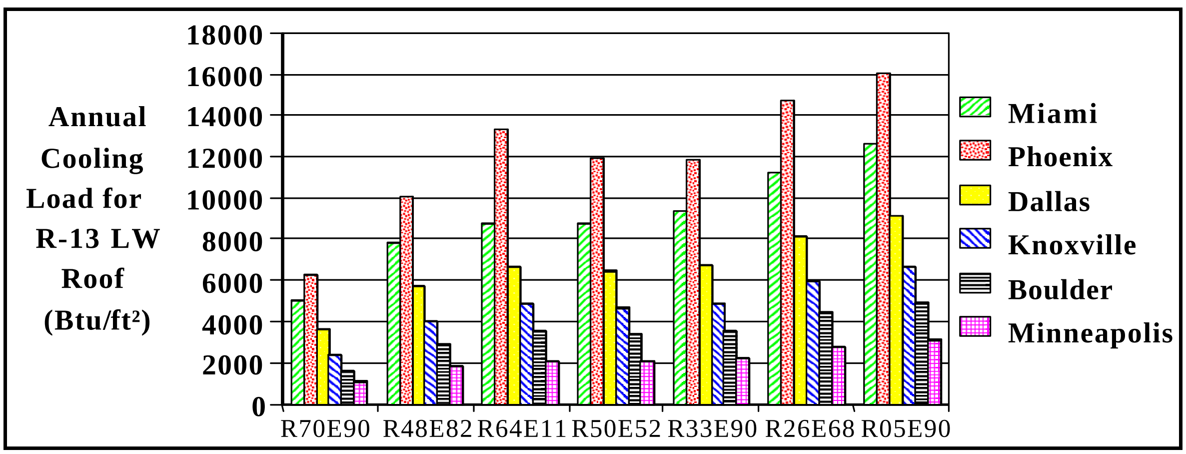

Figure 4. Annual Roof Cooling Load for an R-13 Light Weight Roof for Various Coatings and Locations

Annual Heating Loads

Positive deck heat flow rates per unit of roof area calculated by the model were used to estimate the annual heating loads for the same combination of roofs, surfaces and locations as in Figures 3 and 4. A positive value was counted in the heating load if its corresponding outside air dry bulb temperature was below 16°C (60°F). This assumes that internal building loads fulfill the need for heating until outside temperature is below 16°C (60°F). Annual roof heating loads were obtained by summing the hourly positive heat flow rates meeting this criterion.

Figure 5 presents annual roof heating loads (multiply Btu/ft² by 11.36 to convert to kJ/m²) in Knoxville for seven different coating systems and five different roof insulation/deck combinations. The inside air temperature was held constant at 72.5˚F (22.5˚C). Making ±2.5˚F (±1.4˚C) changes in inside air temperature caused an average 3.3% increase in heating load per ˚F (5.9% per ˚C) increase in inside air temperature.

The annual roof heating loads for Knoxville generally decrease as the surface radiation properties change from R70E90 to R05E90. For all the roofs, the lowest heating load in Knoxville

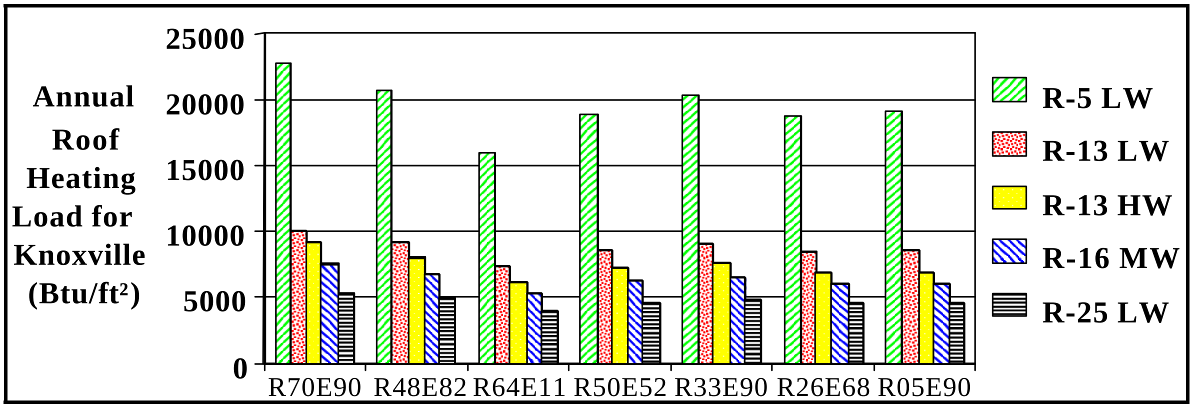

Figure 5. Annual Roof Heating Load in Knoxville, Tennessee for Various Coatings, Roof Insulation Levels and Decks

is for the R64E11 surface. The low infrared emittance of this surface causes it to retain absorbed solar energy better than any other surface, a desirable effect for heating. For the R-5 LW roof, there is not as much difference in Figure 5 between maximum and minimum heating loads as there is in Figure 3 between maximum and minimum cooling loads. There is more heating load difference in Figure 5 between the R-5 LW and R-13 LW roofs for all surfaces than between the R70E90 and R64E11 surfaces for the R-5 LW roof. Insulation level has more effect on heating loads than do surface radiation properties.

For constant interior temperature (no thermostat setback), thermal mass effects do not seem as significant for heating as for cooling. The heavy weight concrete-decked R-13 HW roof outperforms the thin metal-decked R-13 LW roof. However, the insulating concrete-decked R-16 MW roof has lower heating load than the heavy weight concrete-decked R13 HW roof.

Figure 6 shows the effect of location on heating load for the seven different RxxEyy combinations on the R-13 LW roof, which is chosen as the most typical low-slope roof on commercial buildings. Heating loads are the highest for Minneapolis, about twice those in Knoxville for the same surfaces. In the hot and humid climate of Miami, heating loads are insignificant for this R-13 LW roof regardless of surface. Heating load is roughly proportional to the heating degree-days (65˚F base) from the TMY2 weather summaries: 8002 for Minneapolis vs. 3662 for Knoxville vs. 141 for Miami. For all surfaces, the respective R-13 LW roofs in

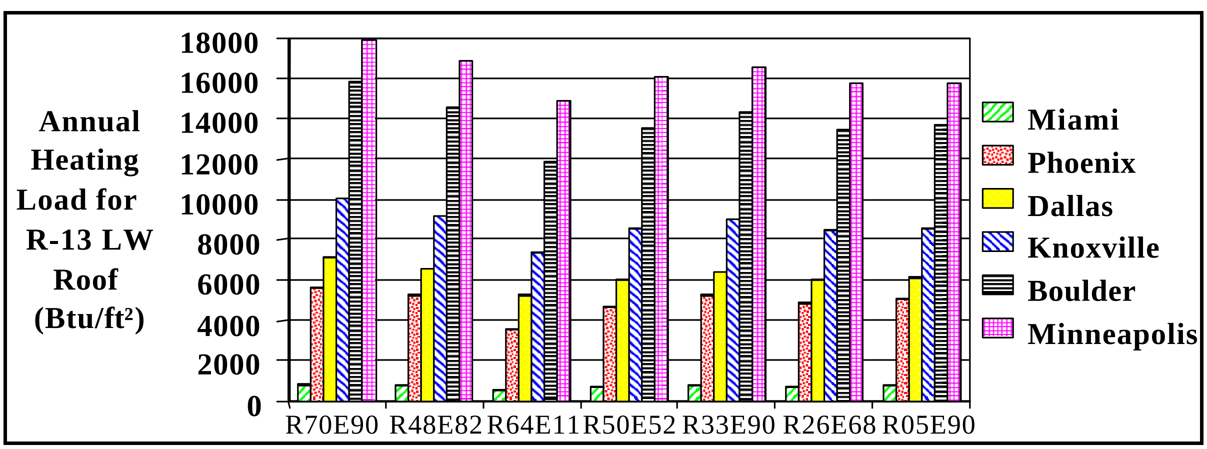

Figure 6. Annual Roof Heating Load for an R-13 Light Weight Roof for Various Coatings and Locations

Minneapolis have lower heating loads than the R-5 LW roofs in Knoxville. This reinforces the comment above about the importance of insulation level on heating loads.

Application of the Results

The cooling and heating loads presented above allow comparisons of the thermal performance of candidate roof coating systems from cooling-dominated to heating-dominated climates and over the range of low-slope roof insulation levels and decks. The application that is likely of most interest for such comparisons is to determine the savings, if any, in utility costs for conditioning a building after installing a candidate coating on its roof. Work is in progress toward presentation of a radiation control coatings fact sheet on our website. This fact sheet will contain a calculator to estimate annual cost savings based on the user's input.

An estimate of cost savings is obtained by using the annual cooling and heating loads that generated Figures 3, 4, 5 and 6. Assuming cooling is done with electricity costing $0.0723 per kilowatt-hour (1999 U.S. average for commercial uses) (EIA 2000) and at an average coefficient of performance of 2.5, annual cooling costs result for each case. Assuming heating is done with natural gas costing $5.48 per 1000 cubic feet (1998 U.S. average delivered price to commercial customers) (EIA 2000) and at an average furnace efficiency of 0.85, annual heating costs result for each case. Table 1 show the total costs (cooling+heating) for the coated roofs less the total costs for the uncoated roof with the same configuration and at the same location. Units are U.S. $/ft² of roof surface. Multiply $/ft² by 10.76 to convert to $/m².

The estimates in Table 1 show that all coatings save energy costs in all locations. Relative to an installed cost in excess of $0.50/ft² ($5.38/m²) (Petrie and Childs 1998), only the installation of surface R70E90 and possibly R48E82 on the poorly insulated roof R-5 LW in Miami could be justified solely on energy cost savings. The criterion used is a simple payback time (ratio of installed cost to annual savings) of 6 years or less. Note the emergence of R64E11 and R50E52

Table 1. Annual Utility Cost Savings ($/ft²) for Coated Roofs Relative to Uncoated Roofs in Three Locations. (See text for assumptions made to generate estimated savings)

	R70E90	R48E82	R64E11	R50E52	R33E90	R26E68
Miami						
R-5 LW	0.149	0.094	0.083	0.078	0.064	0.029
R-13 LW	0.064	0.040	0.034	0.033	0.028	0.012
R-25 LW	0.034	0.021	0.018	0.017	0.014	0.006
Knoxville						
R-5 LW	0.061	0.042	0.059	0.042	0.028	0.016
R-13 LW	0.026	0.018	0.023	0.017	0.012	0.006
R-25 LW	0.014	0.009	0.011	0.008	0.006	0.003
Minneapolis						
R-5 LW	0.008	0.009	0.039	0.019	0.005	0.009
R-13 LW	0.004	0.004	0.015	0.007	0.002	0.004
R-25 LW	0.002	0.002	0.007	0.004	0.001	0.002

as the surfaces that save the most energy costs in the heating-dominated climate of Minneapolis and the equality of R70E90 and R48E82 with R64E11 and R50E52 in the mixed climate of Knoxville.

For the energy costs assumed, the estimates in Table 1 appear to give the maximum benefit of coatings on annual energy costs. We have done trials using DOE2.1E (LBNL 1993) with the energy costs and the same deck heat fluxes used for Table 1. A one-story warehouse building with severe cooling thermostat setup in unoccupied hours and severe heating thermostat setback in unoccupied hours showed savings that are about 50% of the savings in Table 1 for Miami. For Knoxville, energy costs for this building decreased with application of coatings but the amount is not significant for any coating system (less than $0.005/ft²). In Minneapolis, energy costs generally increased with coatings, but, like in Knoxville, the amount is not significant (less than $0.01/ft²). Results for the same variations in roofs and climates were obtained for a two-story, all-electric office building with high internal loads. Savings were slightly smaller, in general, than the savings in Table 1 for the respective cases.

Potential energy cost savings are not the only reason to install coating systems. The waterproofing and ultraviolet degradation protection offered by coatings, if they extend the service life of a roof by more than five years, could easily justify their cost. Once a roof leaks, the alternative is usually tear off and installation of a new roof. Table 1 shows that energy cost savings may be an additional justification for the decision to install a coating system, one that becomes more significant in cooling-dominated climates with poorly insulated roofs.

Conclusions

In a three-year study of currently available coating systems for low-slope roofs, results to date have yielded the following conclusions:

- Solar reflectances of white-coated and aluminum-coated surfaces decrease due to weathering but achieve fully weathered values after about two years. On a scale from 0 to 1, the fully weathered values vary from 0.05 for the uncoated surfaces to 0.70 for the white coating with the highest reflectance.
- Infrared emittance of the surfaces does not change much from year to year. On a scale from 0 to 1, the increase was 0.07 on average for the aluminum coatings and 0.02 on average for the white coatings from year one to year two of exposure.
- Predictions, with a computer program for roofs only and with typical meteorological year climatic data, compared to measurements indicate that rain and dew lower annual average sunlit membrane temperatures for Knoxville no more than 6˚F (3˚C).
- Annual cooling and heating loads predicted with the program and U.S. average prices for energy yield positive savings in annual building energy costs for all coatings and all locations and all roof insulation levels relative to uncoated roofs. DOE2.1E trials indicate that the savings from the roof-only program are the maximum savings one can expect.
- White-coated surfaces show the most energy savings relative to uncoated surfaces in cooling-dominated climates. An aluminum capsheet, with very low infrared emittance, shows the most savings in the mixed and heating-dominated climates. Savings are significant only in cooling-dominated climates with poorly insulated roofs.

References

ASHRAE. 1997. *1997 ASHRAE Handbook: Fundamentals*. Atlanta, Ga.: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

ASTM. 1996. *Designation E 903-96: Standard Test Method for Solar Absorptance, Reflectance, and Transmittance of Materials Using Integrating Spheres.* West Conshohocken, Pa.: American Society for Testing and Materials.

ASTM. 1997. *Designation C 1371-97: Standard Test Method for Determination of Emittance of Materials Near Room Temperature Using Portable Emissometers.* West Conshohocken, Pa.: American Society for Testing and Materials.

Berdahl, P.H. 1997. Lawrence Berkeley National Laboratory Fax Transmittal to T. Petrie and A. Desjarlais at Oak Ridge National Laboratory: Spectral Emittance Measurements on ORNL Roof Coating Samples. November 4.

Byerley, A.R. and J.E. Christian. 1994. "The Long Term Thermal Performance of Radiation Control Coatings," 5.59-5.71, *ACEEE 1994 Summer Study on Energy Efficiency in Buildings*. Washington, D.C.: American Council for an Energy Efficient Economy.

EIA. 2000. Energy Information Administration Form EIA-826, "Monthly Electric Utility Sales," and Energy Information Administration Form EIA-176, "Annual Report of Natural and Supplemental Gas Supply and Disposition." Accessed 3/8/00 at EIA Internet sites.

LBNL. 1993. "DOE-2 Supplement, Version 2.1E." LBL-34947. Berkeley, Calif.: Lawrence Berkeley National Laboratory.

NREL. 1995. "TMY2s," Data CD, June 1995. Golden, Colo.: National Renewable Energy Laboratory.

Petrie, T.W. and P.W. Childs. 1998. "Radiation Control Coatings Installed on Federal Buildings at Tyndall Air Force Base. Volume 2. Long-Term Monitoring and Modeling." ORNL/CON-439/V2. Oak Ridge, Tenn.: Oak Ridge National Laboratory.

Petrie, T.W., P.W. Childs and J.E. Christian. 1998. "Radiation Control Coatings on Rough-Surfaced Roofs at a Federal Facility: Two Summers of Monitoring plus Roof and Whole Building Modeling," 353-371, *Proceedings, Thermal Performance of the Exterior Envelope of Buildings VII*. Atlanta, Ga.: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

Petrie, T.W., A.O. Desjarlais, R.H. Robertson and D.S. Parker. 2000. "Comparison of Techniques for In-Situ, Non-Damaging Measurement of Solar Reflectances of Low-Slope Roof Membranes." Presented at 14th Symposium on Thermophysical Properties, June 25-30, 2000. To be published in *J. Chemical and Engineering Data*.

Smith, T.L. 1998. "Field Performance of APP-Mod Bit Membranes and Coatings," *Professional Roofing 28* (11): 16-20.

Wilkes, K.E. 1989. "Model for Roof Thermal Performance." ORNL/CON-274. Oak Ridge, Tenn.: Oak Ridge National Laboratory.