A Web-based Tool to Estimate the Energy Savings Associated With Solar Radiation Control Applied to Commercial Roofing Systems

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Keywords

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Abstract

Of all building envelope components, low-slope roofs on commercial buildings are directly exposed to the maximum amount of solar radiation. The solar radiation that is absorbed heats the roof surface, and the absorbed solar energy, now characterized by the roof surface temperature, is partially reemitted in the infrared spectrum. Selecting or coating a low-slope roof system so it has a medium to high solar reflectance and low to high infrared emittance can achieve a desired amount of solar radiation control. This paper presents background about an interactive estimating tool and insight into its use to assist commercial building owners and/or operators in selection of a roof system. If a low-slope roof system is given solar radiation control, the estimating tool indicates the maximum possible annual savings in operating costs to condition a building. Alternatively, the tool can give the additional amount of conventional thermal insulation without radiation control that would achieve the same energy savings as the roof with the existing amount of conventional insulation but with solar radiation control. The tool is part of a fact sheet on solar radiation control for low-slope roof systems. The fact sheet is available at our Web site.

Author Biographies

André O. Desjarlais is the Program Leader and Thomas W. Petrie, Ph.D., William A. Miller, Ph.D., and Therese K. Stovall are Senior Research Engineers in the Building Envelopes Group of the Engineering Science and Technology Division at the Oak Ridge National Laboratory.

Introduction

Over the past several years, much attention has been focused on the Urban Heat Island phenomenon occurring in cities across the nation. Professionals, research scientists and public interest groups from a broad spectrum of disciplines have been studying Urban Heat Island impacts, contributing factors and mitigation strategies. Urban Heat Islands are the result of a multitude of factors present in all cityscapes. A key contributor is the dark opaque surface on most roof systems that absorbs solar radiation and heats the roof surface and the environs surrounding the roof.

Solar reflectance and infrared emittance are known to be the principal surface properties that affect the thermal performance of roof surfaces (Akbari and Konopacki 1999, Wilkes et al. 2000). The kind of roof surface and its exposure history can yield a wide range of solar reflectance and infrared emittance values that will impact a roof's contribution to the local Urban Heat Island.

In 1997, the Oak Ridge National Laboratory (ORNL) initiated a research project and a field exposure test site that sought to quantify the potential energy benefits of using solar radiation control. To achieve the generalization of thermal performance that the project required, we developed and published a solar radiation control fact sheet on our Web site. This fact sheet includes a calculator to predict the heating and cooling loads per unit area of a low-slope roof system. The user of the calculator specifies surface radiation properties, insulation level and location for the roof system. The fact sheet presents the range of radiation properties that resulted from the tests as well as other information to guide the user of the tool in applying it to conditions of interest. The user then enters local energy costs and average equipment efficiencies to generate annual operating cost savings due to the proposed surface radiation properties and insulation R-value level. The energy savings calculator can be accessed at the Internet location http://www.ornl.gov/roofs+walls/facts/RadiationControl.htm.

Developing the Calculator

The thermal performance of a low-slope roof system is directly affected by the thermal radiation properties (solar reflectance and infrared emittance) of its roof surface. Both surface properties are dependent on the kind of material that forms the surface and the condition of the surface. Weathering can significantly affect solar reflectance. Surface contamination and alteration (degradation) cause changes in radiation properties. Contamination occurs over time due to atmospheric pollution and biological growth. Alterations occur due to many factors, including ultraviolet radiation; temperature cycling due to sunlight; sudden temperature variations due to rain; moisture penetration; condensation and evaporation of dew; wind; freezing and thawing; and effects of sleet, snow and hail. Rain and deliberate washing may temporarily help to partially restore solar reflectance.

To measure the variation in solar reflectance and infrared emittance due to weathering, a series of field experiments were conducted on two test buildings at ORNL (see Figure 1). In 1997, ORNL began three years of collaborative research with the Roof Coating Manufacturers Association and several member manufacturers. The goals were to measure and model the thermal performance of low-slope roof coatings under weathering conditions imposed by the east Tennessee climate and generalize the test results by determining how much energy could be saved by coatings in various U.S. climates. Similar collaborative projects were started in 1998 on single-ply membranes with the SPRI and its members and in 1999 on metal roofing with the American Iron and Steel Institute, Galvalume Sheet Producers of North America, Metal Building

Manufacturers Association, Metal Construction Association and National Coil Coaters Association.

Figure 1: *Photo of one of the test buildings at ORNL. Single-ply membranes are located on left side of the building. Various metal roofing systems installed on low-slope and steep-slope configurations are on the right side. Non-instrumented weathering stands with various coatings are in front of the building.*

Among the measurements taken continuously for all the test roofs in these projects were membrane temperature and heat flux through the insulation in the roofs. To measure membrane temperature, a thermocouple was placed against the underside of the membrane after it was adhered to the top layer of insulation. To measure insulation heat flux, a thin 2-inch- (50-mm-) square heat flux transducer was placed within the insulation.

In 1989, ORNL developed and validated a model called Simplified Transient Analysis of Roofs (STAR) to predict heat flows and temperatures within low-slope roof systems. Thermal properties of layers comprising a roof system may vary with temperature. STAR is fully coupled to ambient weather conditions and can accommodate weather files in compilations, such as the Typical Meteorological Year (TMY2) data set available from the National Renewable Energy Laboratory (NREL 1995). Alternately, STAR can use weather data measured along with thermal performance of test roof systems. To validate STAR for a variety of roof surfaces, several cloudless days throughout the project were selected for detailed modeling of thermal performance. Figure 2 depicts the results of one of the heat flux comparisons.

Figure 2 illustrates the ability of STAR to produce predictions that, like the measurements, clearly differentiate among surfaces with different combinations of solar reflectance and infrared emittance. This further substantiates the claim that solar reflectance and infrared emittance are the roof surfaces' principal properties affecting thermal performance. The test roofs only had 1.5 inches (38 mm) of wood fiberboard insulation to maximize the effects of changes in surface properties. Insulation thermal resistance level is, of course, also very important in energy savings.

Annual heating and cooling loads per unit roof surface area for various low-slope roof configurations were generated by STAR using TMY2 typical meteorological year weather data. Simple building operation was assumed. The building interior temperature below the roof deck was held at 73F (21C) year round; no thermostat setup or setback was modeled. Seven different combinations of solar reflectance and infrared emittance, along with four different insulation R-value levels, were used to include the range of roof surface characteristics and thermal insulation levels in typically constructed roofs. Eight geographic locations within the United States were selected to include cooling-dominated climates, heating-dominated climates and mixed climates and cover the range of solar irradiation experienced in the United States.

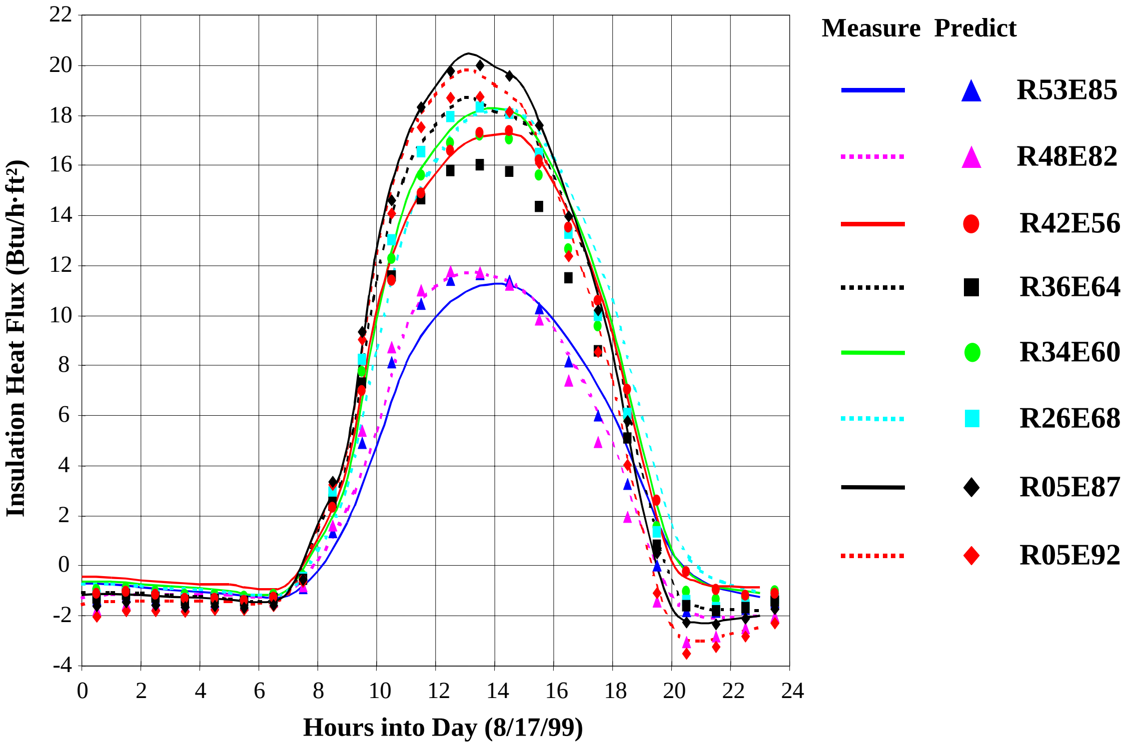
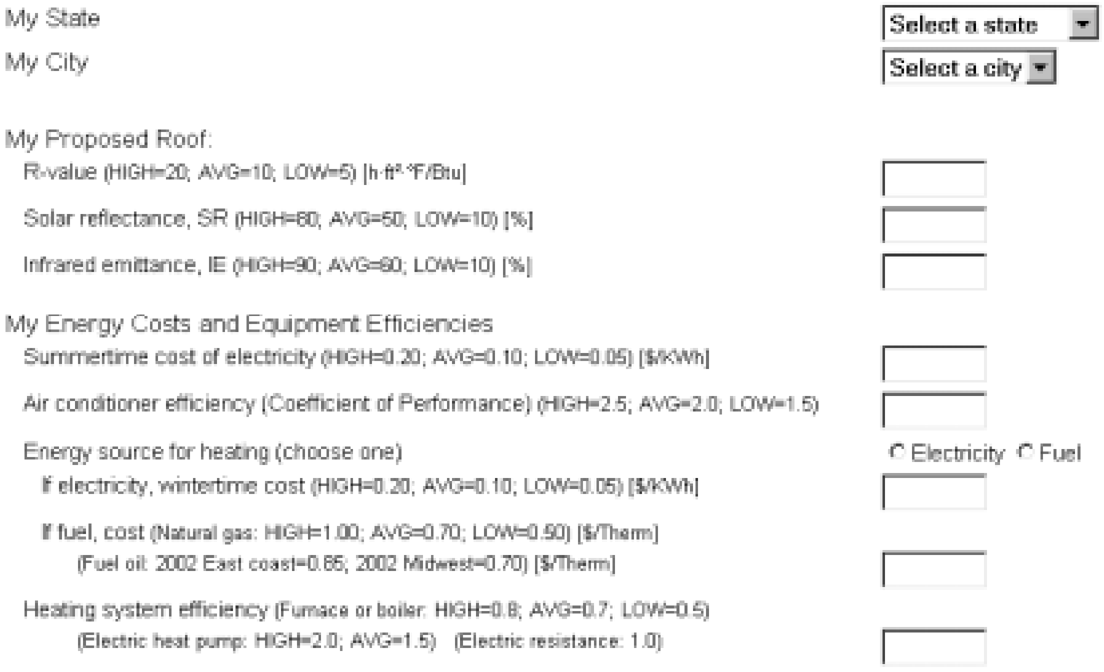


Figure 2: *A comparison between the measured and predicted heat fluxes for a test roof with eight different surfaces. The code RxxEyy is used to differentiate surface characteristics with "xx" being the aged solar reflectance and "yy" representing the aged infrared emittance.*

The estimating tool (calculator) needed to be comprehensive and flexible without being overly complicated to use and difficult to implement on our Web site. Therefore, equations in the form of polynomials were selected as the means to predict annual cooling and heating loads as a function of location, surface radiation properties (solar reflectance and infrared emittance) and roof insulation level (R-value). Petrie et al. (2001) presented a detailed description of the development of these polynomials. The following ranges are considered valid for the calculator: 5 h ft² °F/Btu < R-value < 40 h ft² °F/Btu; 5 percent < ρ_{solar} < 85 percent; and, 5 percent < $\varepsilon_{infrared}$ < 95 percent for all locations in the TMY2 data set.

Using the Calculator

The energy savings calculator can be accessed on the Internet at http://www.ornl.gov/roofs+walls/facts/RadiationControl.htm. The data entry screen is depicted in Figure 3 with ranges of possible input values given for each input. More detailed help is also available on line for selection of input values.



My State
My City

My Proposed Roof:
R-value (HIGH=20; AVG=10; LOW=5) [h·ft²·°F/Btu]
Solar reflectance, SR (HIGH=80; AVG=50; LOW=10) [%]
Infrared emittance, IE (HIGH=90; AVG=80; LOW=10) [%]

My Energy Costs and Equipment Efficiencies
Summertime cost of electricity (HIGH=0.20; AVG=0.10; LOW=0.05) [$/KWh]
Air conditioner efficiency (Coefficient of Performance) (HIGH=2.5; AVG=2.0; LOW=1.5)
Energy source for heating (choose one) ○ Electricity ○ Fuel
If electricity, wintertime cost (HIGH=0.20; AVG=0.10; LOW=0.05) [$/KWh]
If fuel, cost (Natural gas: HIGH=1.00; AVG=0.70; LOW=0.50) [$/Therm]
(Fuel oil: 2002 East coast=0.66; 2002 Midwest=0.70) [$/Therm]
Heating system efficiency (Furnace or boiler: HIGH=0.8; AVG=0.7; LOW=0.5)
(Electric heat pump: HIGH=2.0; AVG=1.5) (Electric resistance: 1.0)

Figure 3: *This is the data entry screen for the radiation control calculator. Roof location, R-value, proposed solar radiation control along with energy costs and equipment efficiencies are needed to estimate potential energy savings*

There are 235 different locations built into the pull-down lists in the calculator. If an exact location that is desired is unlisted, use one with similar weather. This location may not necessarily be in the same state.

After a roof location has been selected, a low-slope roof system and solar radiation control that is being considered must be described. Solar radiation control entails either coating an existing black roof surface or replacing a black surface with a nonblack one. The first roof descriptor is the R-value of the roof assembly in U.S. units (hr ft^2 F/Btu). The R-value gives the total thermal resistance of the roof assembly. Most of the R-value in a low-slope roof assembly is due to conventional insulation. A metal deck and a waterproofing membrane, even if its outside surface exhibits solar radiation control, do not add any significant amount of R-value. Underneath many low-slope roof assemblies are simple plenum spaces and dropped ceilings. This plenum space and dropped ceiling add a small amount of thermal resistance. If the building under study has such an arrangement, increase the roof assembly R-value by about 3 hr ft^2 F/Btu.

Simple plenum spaces can include well-insulated supply and return air ducts for the building conditioning system. More complicated situations are not allowed because of interactions between the duct system and plenum air. The basic assumption of the calculator is that the heat flow through the roof deck directly affects the load on the building conditioning system.

After the roof's R-value is inputted, the proposed radiation control system must be described. Table 1 provides the 10 example surface descriptions and combinations of solar reflectance and infrared emittance that were obtained after two years of weathering in research conducted to support this calculator. These data should help decide appropriate solar reflectances and infrared emittances for the type of radiation control being considered. Coatings on existing black roofs and replacement membranes for solar radiation control have the same range of solar reflectances and infrared emittances. Replacement membranes tend not to weather as rapidly as coatings.

Once the location of the roof and its description are provided, economic factors are needed. The calculator needs the price of electricity for cooling (in U.S. dollars per kilowatt hour), annual average coefficient of performance (COP) of the air conditioning system, and how the building is heated, whether by electricity or by burning a fuel (choose one or the other). If heat with electricity is selected, the price of electricity for heating (in U.S. dollars per kilowatt hour) is required. If a fuel is selected, input the price of that fuel (in U.S. dollars per therm). A therm is 100,000 Btu of heating value. Natural gas prices typically are given in dollars/therm or in dollars/MCF. If local gas prices are in dollars/MCF (dollars per 1000 cubic feet), divide by 10 to get the dollars/therm. For example, natural gas with a price of $6.50 per MCF costs $0.65 per therm. Heating oil prices are usually given in dollars/gallon. Multiply this number by 0.71 to get dollars/therm. For example, heating oil at $1.20/gallon would be $0.85/therm. The seasonal average efficiency of the heating equipment also must be inputted.

Surface	Solar Reflectance, %	Infrared Emittance, %
Acrylic Latex Coating	70	90
Aluminum Coating	50	50
Aluminized Asphalt Emulsion	35	90
Aluminum Metal Capsheet	65	10
Asphalt Surface	5	90
White Single-ply Membrane	70	90
Gray Single-ply Membrane	50	90
White PVDF Painted Metal	60	90
Bronze PVDF Painted Metal	5	90
Acrylic-coated Galvalume	60	15

Table 1: *Weathered solar reflectance and infrared emittance for typical roof surfaces.*

For detailed information on state-by-state costs, see the Energy Information Administration (EIA) websites. Local energy prices may be significantly different from statewide averages so the best source of information is local rates. If necessary, consult the EIA websites before using the calculator to make a decision about appropriate energy prices for your specific location. For electricity the specific locator is
http://www.eia.doe.gov/cneaf/electricity/epm/epmt53.txt;
for heating oil the locator is
http://www.eia.doe.gov/pub/oil_gas/petroleum/data_publications/winter_fuels_report/current/pdf/tablec3.pdf; and
for natural gas the locator is
http://www.eia.doe.gov/pub/oil_gas/natural_gas/data_publications/natural_gas_annual/current/pdf/table_023.pdf.

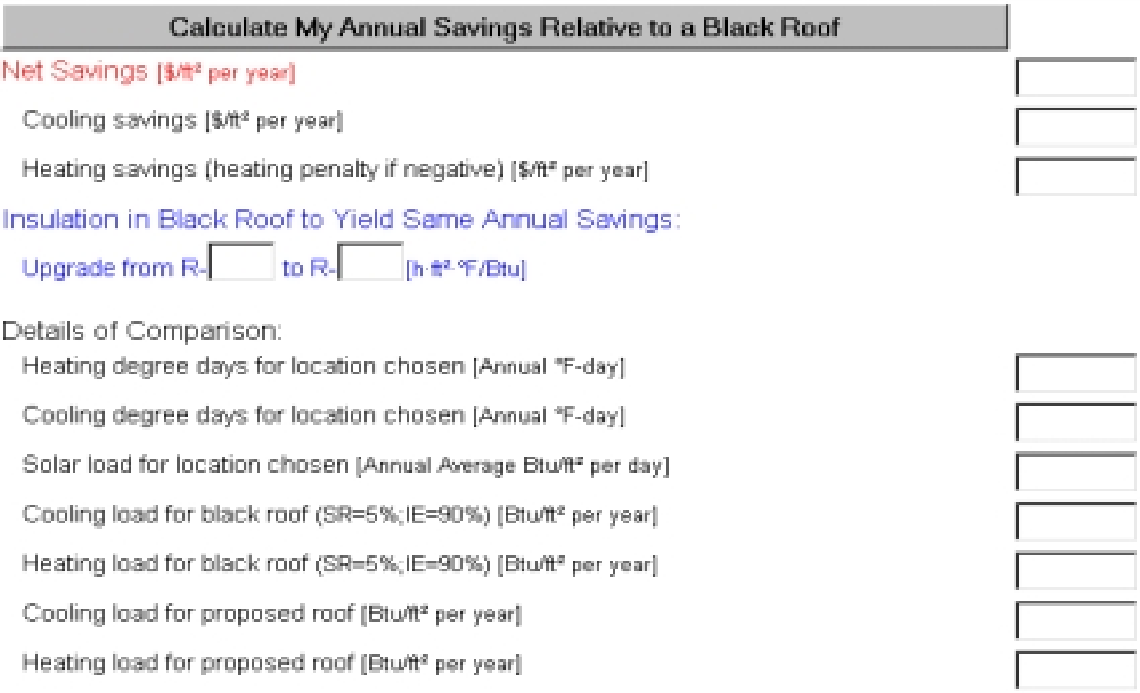
Average seasonal efficiency of cooling equipment and heating equipment depends upon the kind of equipment and its condition. Electric air conditioning often is rated by a seasonal energy efficiency ratio (SEER). Typical values for old equipment are 7 to 10 Btu/Watt-hour. New, very efficient equipment may have SEER values as high as 16 Btu/Watt-hour. COP is used in the calculator and is a fraction without units formed by dividing SEER by 3.4. Thus, old equipment has COPs from 2 to 3 while new, very efficient equipment may have a COP as high as 4.7. These COPs do not account for ducting losses; an additional deduct ranging from 10 to 50 percent should be considered to account for this additional energy loss.

Heating equipment seasonal efficiency is entered as a fraction in the calculator. For fuel-burning equipment the fraction always is less than 1.0, ranging from 0.5 to 0.6 for old, inefficient equipment to 0.8 to 0.9 for typical new equipment. Condensing, natural gas furnaces may have seasonal heating efficiencies as high as 0.95. Electric resistance heating converts electricity directly into heat with an efficiency of 1.0. A better use of electricity for heating is to run an electric heat pump. Electric heat pumps often are rated by a seasonal heating performance factor (SHPF). It has the same units as SEER. COP is used in the calculator and is a fraction without units. For air-to-air heat pumps, a typical value is 1.5 with a value as high as 2.0 in mild climates.

A user of the calculator does not input the indoor temperature of the building. The calculator was developed for 73F (21C) indoor temperature. Test cases showed that it can be used for buildings between 67 and 78F (19 and 26C). Thermostats at different set points in the summer and winter also are allowed as long as the thermostat settings are the same with and without solar radiation control. Heating and cooling loads are affected by indoor temperature, but the calculator always compares a proposed roof system to a black-surfaced roof system by taking differences.

Figure 4 depicts the data output screen for the calculator. Once input data are entered, clicking on the “Calculate My Savings” bar generates values. The net operating savings is given in dollars per square foot of roof area per year. If you want dollars per square meter, multiply the given output by 10.76. This calculator shows you two ways to improve the roof to save the same amount of annual operating energy and cost. The first way is to install the solar radiation control proposed by the input data. That answer is shown in red on the calculator. The second way is to add more insulation to the roof system. The blue line of output shows how much insulation must be added to save the same amount of annual operating energy and cost as would be saved by the installation of solar radiation control.

The rest of the output from the calculator is listed under “Details of Comparison”. The heating and cooling degree days and average solar irradiation are listed for the location that was chosen. The calculator was developed from hour-by-hour annual weather data for each location. The heating and cooling loads calculated from these data are then listed for a black-surfaced roof system and the proposed roof system. These loads are annual sums of the heat flow per square foot through the deck of the roofs. They only are for the roof assembly and are for very simple heating and cooling conditions. Depending on how the building is operated, how its walls and windows are configured and how much internal load it has due to equipment and occupants, the actual heating and cooling loads will be different from the simple roof assembly loads that are listed.



Calculate My Annual Savings Relative to a Black Roof

Net Savings [$\$/\text{ft}^2$ per year]

Cooling savings [$\$/\text{ft}^2$ per year]

Heating savings (heating penalty if negative) [$\$/\text{ft}^2$ per year]

Insulation in Black Roof to Yield Same Annual Savings:

Upgrade from R- to R- [$\text{h}\cdot\text{ft}^2\cdot{}^\circ\text{F/Btu}$]

Details of Comparison:

Heating degree days for location chosen [Annual °F-day]

Cooling degree days for location chosen [Annual °F-day]

Solar load for location chosen [Annual Average Btu/ft^2 per day]

Cooling load for black roof (SR=5%;IE=90%) [Btu/ft^2 per year]

Heating load for black roof (SR=5%;IE=90%) [Btu/ft^2 per year]

Cooling load for proposed roof [Btu/ft^2 per year]

Heating load for proposed roof [Btu/ft^2 per year]

Figure 4: *The data output screen for the radiation control calculator. Energy savings per unit area of roof are given for solar radiation control. The same savings can be achieved by adding conventional insulation. Details of the simple calculations are given for additional insight.*

An Example

Figure 5 depicts the type of analyses that can be quickly performed by using the calculator. The energy savings associated with replacing a flood-coated BUR (R05E90) with a roofing system having three different surface treatments (R70E90, R64E11, and R50E52), two levels of insulation R-value (R-5 and R-15) in three cities (Knoxville, Tenn.; Phoenix; and Chicago) are shown. The three alternate surface treatments have respective surface properties similar to an acrylic latex, aluminum foil-laminated capsheet, and aluminum coating that have been weathered for three years.

Cooling energy savings are calculated for a roof with a proposed solar radiation control relative to one without solar radiation control. Multiplying the cooling energy savings by an appropriate average price for electricity and dividing by the average efficiency for the air-conditioning equipment converts energy savings to cooling equipment operating cost savings. Similarly, the heating energy penalty can be calculated for a proposed roof with solar radiation control relative to one without solar radiation control. Multiplying heating energy penalty by an appropriate average price for heating energy and dividing by the average efficiency for the heating equipment converts heating energy penalty to heating equipment operating cost penalty. Net annual operating cost savings are the cooling cost savings less the heating cost penalty. For the purpose of this example, average 1999 national prices for electricity and natural gas were used ($0.0723/KWh and $0.548/therm, respectively). The air conditioner COP was assumed to be 2.0, and the heating equipment efficiency was 85 percent. For the cooling-dominated climate of Phoenix and the mixed climate of Knoxville, the white acrylic latex solar control strategy yields the maximum energy savings. With a roof insulation level of R-5, energy savings are $\$0.24/\text{ft}^2$ per year and $\$0.09/\text{ft}^2$ per year for Phoenix and Knoxville, respectively. When the R-value level is increased to R-15, energy savings are reduced to $\$0.08/\text{ft}^2$ per year and $\$0.03/\text{ft}^2$ per year. For the heating-dominated climate of Chicago with an insulation level of R-5, the aluminum capsheet offers the highest level of energy efficiency among the solar control strategies ($\$0.05/\text{ft}^2$ per year). When a level of insulation equal to R-15 is present in the roof, the energy savings for solar radiation control are reduced to $\$0.015/\text{ft}^2$ per year.

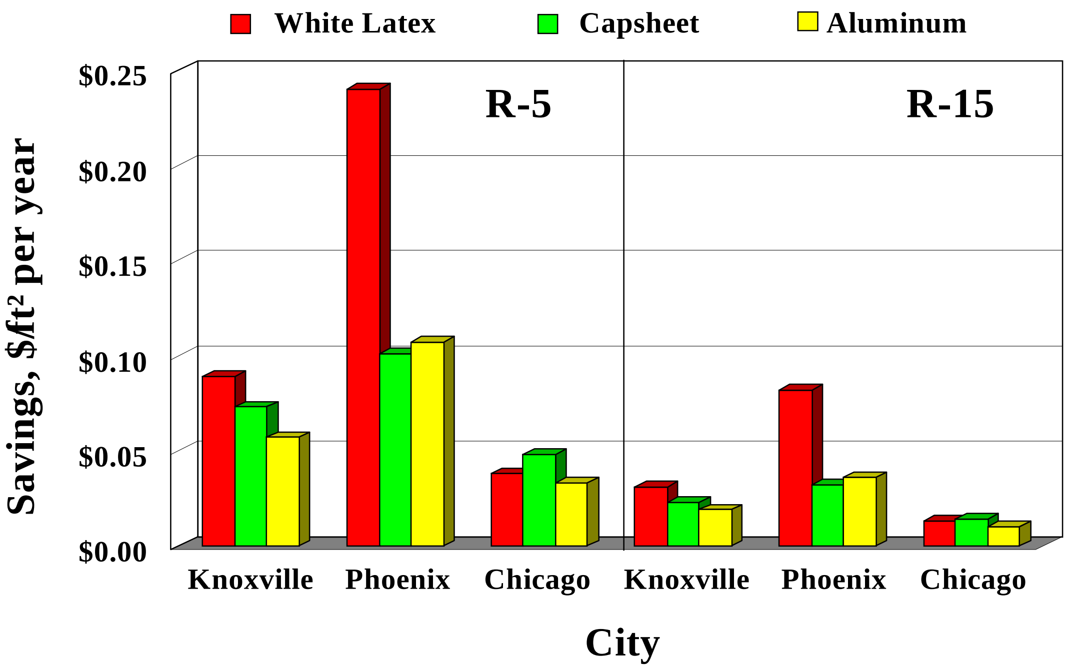


Figure 5: *The energy savings associated with the use of radiation control in lieu of an R05E90 roof surface.*

Summary

A radiation control fact sheet has been developed for low-slope roof assemblies. It features an interactive "calculator" to estimate annual operating cost savings with solar radiation control. Alternately, it yields the amount of conventional insulation without solar radiation control that would save as much annual operating energy and cost as the roof with solar radiation control and the existing amount of conventional insulation.

The "calculator" estimates a change in building energy load due solely to changes in the low-slope roofing system. It only addresses energy consumption and does not deal with energy demand charges that typically are included in the energy bill for large users. Additional savings may be obtained through the reduction of peak energy demand. Annual savings in energy and other benefits of solar radiation control need to be weighed against the cost to install a particular strategy in a particular situation.

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