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# Effect of Solar Radiation Control on Electricity Demand Costs – an Addition to the DOE Cool Roof Calculator

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# Effect of Solar Radiation Control on Electricity Demand Costs – an Addition to the DOE Cool Roof Calculator


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## ABSTRACT

*Two versions of the DOE Cool Roof Calculator are on the Internet to assist in selection of an energy-saving surface for low-slope roofs. The CoolCalcEnergy version, for small and medium-sized commercial facilities, gives savings based on costs per unit of energy. This paper documents how the CoolCalcPeak version was added to include estimates of savings in demand charges that large facilities often incur for electricity. The database for the Cool Roof Calculator was reworked. Differences in peak deck heat fluxes with solar radiation control and without it were obtained over the cooling season for varying location (as characterized by average solar insolation), R-value of the low-slope roof, and solar reflectance and infrared emittance of the roof surface. Peak solar insolation is relatively constant over the United States. Thus, lower demand charges save about the same amount of annual operating costs for a particular set of circumstances in all U.S. climates that have significant cooling requirements.*



## TECHNICAL SUBJECT CATEGORIES

Owning and Operating Costs; Building Materials and Building Envelope Performance

## INTRODUCTION

A program of research was conducted from 1997 through 2000 under the auspices of User Agreements between the Buildings Technology Center at the Oak Ridge National Laboratory, the Roof Coating Manufacturers Association (RCMA), and several RCMA member companies. In late 2000, in order to bring the project to a timely completion, we formulated and put an estimating tool on our Internet web site. The interactive tool was dubbed the DOE Cool Roof Calculator. It has since been designated the CoolCalcEnergy version. This version was also produced on a stand-alone compact disk.

The purpose of the calculator is to give up-to-date and unbiased information to assist in the selection of an energy-saving surface for low-slope roofs on commercial buildings. The calculator computes the savings in annual operating costs per unit of roof area due to a proposed roof surface compared to a base roof with low solar reflectance and high infrared emittance. An iterative calculation is also done to estimate the additional R-value of the base roof that would yield the same savings. The results are produced on-line in response to user-selected location and user-input R-value of the roof, solar reflectance and infrared emittance of the roof surface, local prices of utilities purchased for cooling and heating, and efficiencies of cooling and heating equipment.

The calculator is part of a solar radiation control fact sheet. The fact sheet, at http://www.ornl.gov/sci/roofs+walls/facts/SolarRadiationControl.htm, presents the range of solar reflectance and infrared emittance for available roof surfaces that resulted from the work with RCMA. The fact sheet and a specific input help document guide the user of the calculator to properly select other input values and interpret the output. Petrie, et al. (2001) explain the procedures followed to generate the equations that are used in the CoolCalcEnergy version of the calculator. The equations accurately reflect the research-derived effect of solar reflectance and infrared emittance on the thermal performance of low-slope roofs. They permit a flexible, simple-to-use and efficient interactive tool.

The DOE Cool Roof Calculator claims to give a conservative estimate of the roof's portion of the annual cost of operating the heating and cooling systems in the building under the low-slope roof. The CoolCalcEnergy version assumes that the energy to operate the heating and cooling systems is purchased by the building owner or operator at a fixed cost per energy unit during the heating and cooling seasons. Cooling with electricity is assumed. If electricity is also used for heating, separate prices are allowed to reflect seasonal differences.

Charges for electricity often reflect more complications than seasonal differences alone. Time-of-use tariffs establish different charges per kilowatt-hour of electricity for what the utility establishes as on-peak and off-peak times each day. In the limit of real-time pricing (RTP), rates are determined only a day or two in advance of their use (Smith 2002). Since only one set of costs per unit of energy can be input for a particular set of results with the calculator, at least two runs are needed to deal with time-of-use tariffs. The results of a run with on-peak rates and another with off-peak rates can show the effect of the rates. It is then a matter of judgment to estimate how appropriate the results with on-peak rates are. The vagaries of market demand and the weather that affect RTP rates make such judgments very difficult.

Electricity costs for small facilities are generally based only on total electrical energy use, even if complicated by time-of-use provisions. Small facilities are ones for which peak demand is less than about 50 kW during a month. Electricity costs for large facilities, if not determined by real-time pricing, include demand charges that can account for one-third of the monthly bill. They are based on the highest measured monthly electrical power demand. A minimum monthly demand charge, also known as a demand ratchet, may be established as some percentage of the highest peak power metered over the preceding year (BuildingGreen 2001).

The CoolCalcEnergy version of the DOE Cool Roof Calculator addresses only the energy cost savings, not the demand charge savings, due to solar radiation control on the low-slope roofs of large facilities. In concluding documentation of the CoolCalcEnergy version, Petrie et al. (2001) demonstrate that the database that was used has information about the peak demand. The purpose of the present paper is to document the procedures that were followed to bring this information into the form of the CoolCalcPeak version of the DOE Cool Roof Calculator. The equations suitable for an interactive, on-line tool are described. Results with them are compared to those directly from the database. A detailed example follows using demand and energy charges from an actual electricity and natural gas supplier to large commercial customers.

Even with the addition of the CoolCalcPeak version, the DOE Cool Roof Calculator does not give the insight that can be attained from hour-by-hour analysis of building energy use in response to energy-conserving measures such as roof configurations with solar radiation control. For example, only hour-by-hour analysis that is done with appropriate report schedules can segregate energy use into on-peak and off-peak categories. Such detailed analysis, which could be done by further reworking of the calculator's database, is best done on a case-by-case basis with more sophisticated tools than the DOE Cool Roof Calculator.

## PEAK HEAT FLUXES FROM CLIMATIC DATA AND MEASUREMENTS

The database for the DOE Cool Roof Calculator consists of hour-by-hour predictions of the heat fluxes and temperatures throughout low-slope roofs in various locations. Peak demand caused by such roofs is assumed to follow from the peak heat flux that comes through the roofs. Hour-by-hour records of heat flux can be searched for the peaks in any period during the year.

The roofs in the database have R-values that vary from $R_{US}$-5 to 32 h·ft²·°F/Btu ($R_{SI}$-0.9 to 5.6 m²·K/W). Their surface properties include combinations of solar reflectance and infrared emittance that cover the range from the high solar reflectance and high infrared emittance of white roofs to the low solar reflectance and high infrared emittance of black roofs. A metal roof with moderate solar reflectance but low infrared emittance and aluminum-coated roofs with moderate solar reflectance and moderate infrared emittance are also included.

The predictions of hour-by-hour heat fluxes and temperatures were made with the program Simplified Transient Analysis of Roofs (STAR) that was developed and validated at the Oak Ridge National Laboratory (Wilkes 1989). STAR was further validated for the effects of the wide range of surface properties of interest for the DOE Cool Roof Calculator with data from test roofs at the Oak Ridge National Laboratory

(Wilkes, et al. 2000). Actual observed climatic conditions were input to STAR for this validation.

To generate the database that permitted the development of the DOE Cool Roof Calculator, STAR was exercised with Typical Meteorological Year (TMY2) data (NREL 1995) and fixed inside conditions. To further validate the use of the database to determine peak demand savings, Figure 1 was prepared from predictions and measurements of heat flux through the insulation for seven combinations of solar reflectance and infrared emittance. Predictions used the TMY2 data for Knoxville, Tennessee and measurements were in Oak Ridge, which is 20 miles (32 km) northwest of Knoxville. The percentage solar reflectance is designated Rxx and the percentage infrared emittance is designated Eyy in the description of each test section. The test sections had an R-value of 4.75 h·ft²·°F/Btu (0.84 m²·K/W) due primarily to two layers of wood fiberboard insulation, one layer 0.5 in. (13 mm) thick on the top of another layer 1.0 in. (25 mm) thick. A heat flux transducer, specifically calibrated for the insulation used, was placed between the two layers of insulation in each test section.

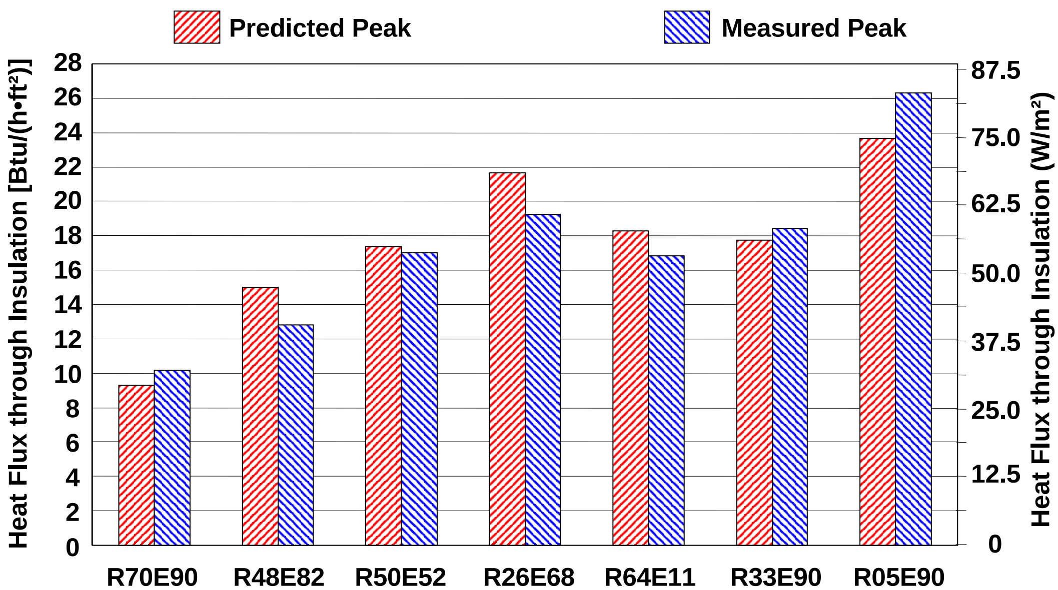



**Fig. 1 Comparison of Peak Heat Fluxes Predicted with TMY2 Data for Knoxville and Measured in Oak Ridge**

Peak heat fluxes were extracted for the seven surfaces from continuous records of measured heat fluxes from April 1999 through September 1999. Predictions with the typical Knoxville meteorological year were analyzed for the same months. April through September is considered the cooling season in Knoxville. The two bars for each surface compare the predicted peak heat fluxes and the measured peak heat fluxes. The average percentage difference between the predictions and measurements is only +2.6%. Peak heat fluxes from TMY2 data for Knoxville agree very well on average with measurements in the same area.

The percentage differences vary from +17% for the R48E82 surface to –10% for the R05E90 surface. The responses of six test surfaces were averaged to yield the measurements for the R05E90 surface. The measurements are judged uncertain to ±2.0

Btu/(h·ft²) (±6.3 W/m²) (Petrie, et al. 2001), that is, ±8% for the R05E90 surface and ±16% for the R48E62 surface. The uncertainty in the measurements appears to be the main reason for differences between predictions and measurements in Figure 1.

## DEVELOPMENT OF AN ESTIMATING TOOL FOR PEAK DEMAND SAVINGS

The database for the DOE Cool Roof Calculator is a collection of workbooks in spreadsheet files. Each spreadsheet is for a particular location and roof R-value. The workbooks in each spreadsheet contain the temperature and heat flux at the outside and inside surfaces of the roof and at boundaries between components for eight combinations RxxEyy of solar reflectance and infrared emittance for all 8760 hours of the typical meteorological year for the location. In addition to the RxxEyy combinations in Figure 1, R85E90 was also included because it corresponds to a new white surface and is expected to show the maximum effect of solar radiation control.

The contribution of the roof to the peak demand for electricity in a building is assumed to coincide with the overall peak demand. The heat flux through the roof deck is assumed to drive the contribution of the roof. As Figure 1 showed, the maximum heat flux through the roof is for the surface R05E90. The difference between the maximum deck heat flux for surface R05E90 and the maximum deck heat flux for the other surfaces RxxEyy yields savings in peak demand by the following equation:

$$\text{\$ Demand Savings} = \frac{\Delta \text{ Demand} \bullet \text{\$ Demand Charge}}{\text{Efficiency for Peak Load}} \qquad (1)$$

where

$ Demand Savings is the savings per unit area of the roof for the period of the demand charge, usually per month,

Δ Demand is the difference between maximum deck heat fluxes [calculated in Btu/(h·ft²)] for surface R05E90 and surfaces with other combinations of solar reflectance and infrared emittance, in units of kW per unit area (kW are obtained by dividing Btu/h by 3412),

$ Demand Charge is the charge per kW of electricity, usually per month, and

Efficiency for Peak Load is the dimensionless efficiency (or coefficient of performance) at which the air conditioner operates to remove the peak heat flux through the deck. Seasonal efficiencies are usually determined at relatively mild conditions. The efficiency for peak load may be significantly lower than the seasonal efficiency because conditions at the time of peak demand are not relatively mild.

Implementation of an interactive estimating tool for peak demand savings is aided by equations that yield Δ Demand as a function of parameters for the roof and climate. To explore the behavior of Δ Demand, monthly values for it were obtained in each workbook. The monthly values were divided by the maximum for the year to form a fraction for each month. Figures 2 and 3 show examples of the result for $R_{US}$-5 ($R_{SI}$-0.9) roofs in Phoenix and Minneapolis, respectively. Phoenix, with a cooling climate, displays a more constant fraction than Minneapolis, with a heating climate. Nonetheless, the fraction drops off at the beginning and end of the year for both climates.

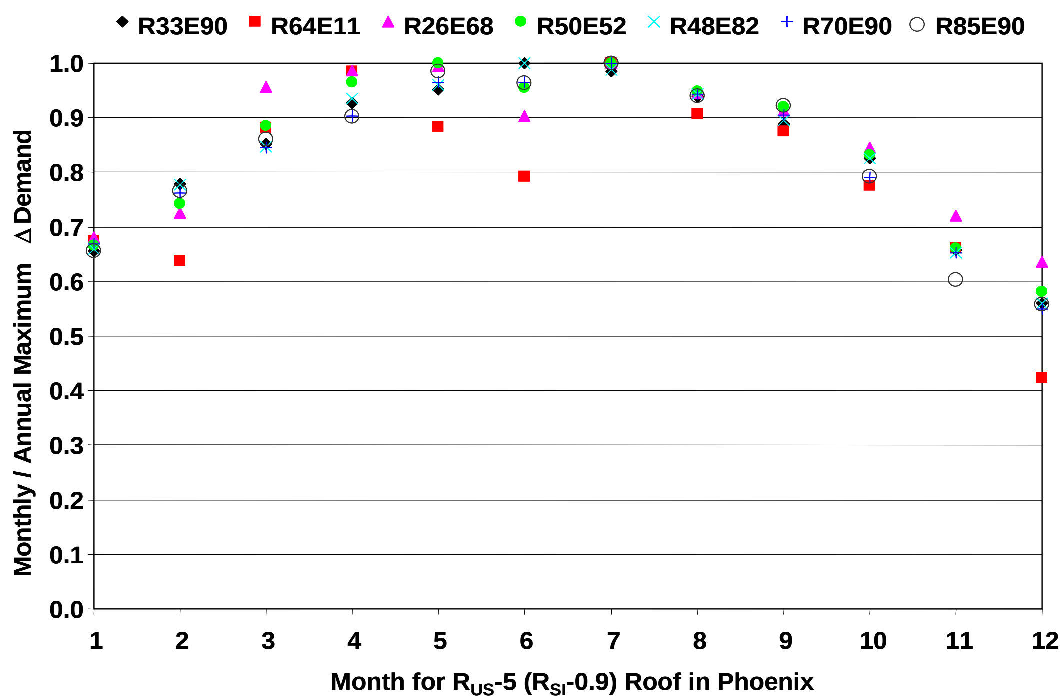



**Fig. 2 Monthly Maximum Δ Demand Compared to Annual Maximum Δ Demand for a Roof with Various Surfaces in Phoenix**

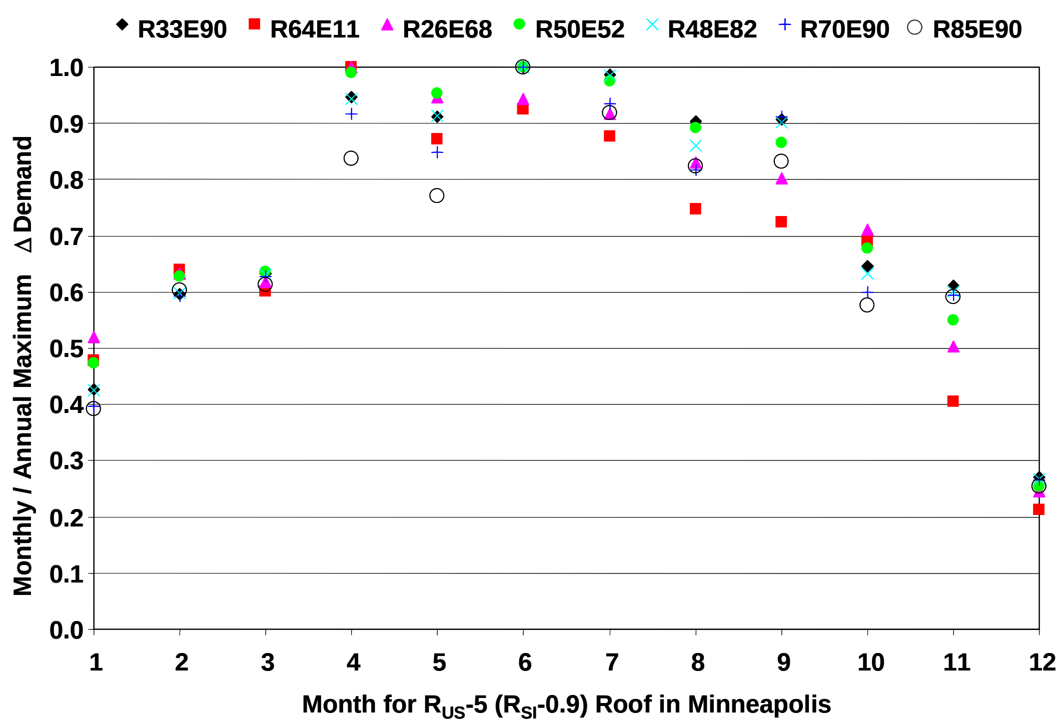



**Fig. 3 Monthly Maximum Δ Demand Compared to Annual Maximum Δ Demand for a Roof with Various Surfaces in Minneapolis**

From April through September, a single value for each surface should adequately characterize the monthly demand reduction with that surface compared to the R05E90 surface during the cooling season. This value, the product of the average fraction from April through September and the annual maximum, can be used to estimate the contribution of demand charges to the annual cost to operate a large building. In the calculator, the monthly $ Demand Savings from Equation (1) is multiplied by the number of months for which the demand charge is applied to estimate cooling season demand savings. Another value, the annual maximum itself, might be useful to estimate the minimum demand charge or demand ratchet in the other months.

At some time between April and September, all surfaces in Figures 2 and 3 exhibit a maximum value of the displayed fraction. However, there appear to be random variations in the fraction that would defy quantification during the year in a form that is simple enough for addition to the DOE Cool Roof Calculator. Thus, no more detailed behavior is sought than an average Δ Demand. To increase the accuracy of the cooling season average, Δ Demand was recalculated week by week instead of month by month. The annual maximum itself and the product of the average fraction and the annual maximum were generated from the weekly data in the period from April through September for each location, R-value and combination RxxEyy.

In the database that was used for the CoolCalcEnergy version of the calculator, the locations selected to cover the range of climates of interest included Anchorage, Alaska. It has very severe heating requirements but negligible cooling requirements. It did not yield peak demand savings for all surfaces. Seattle and Quillayute, Washington were added as locations with minimal but non-negligible cooling requirements. Table 1 summarizes the characteristics of the nine locations used to obtain the effect of solar radiation control on electricity demand charges for the CoolCalcPeak version of the

**TABLE 1**
**Locations Used in the DOE Cool Roof Calculator for the Effect of Solar Radiation Control on Electricity Demand Charges**

| Location | HS [Btu/(h·ft²)]* | $CDD_{65}$† | Cooling Index |
|---|---|---|---|
| Phoenix, Arizona | 76.6 | 3814 | 0.583 |
| Miami, Florida | 64.9 | 4126 | 0.536 |
| Tampa, Florida | 64.8 | 3311 | 0.429 |
| Dallas, Texas | 65.0 | 2414 | 0.314 |
| Knoxville, Tennessee | 55.6 | 1366 | 0.152 |
| Boulder, Colorado | 61.1 | 622 | 0.076 |
| Minneapolis, Minnesota | 52.4 | 634 | 0.066 |
| Seattle, Washington | 44.2 | 127 | 0.011 |
| Quillayute, Washington | 40.3 | 8 | 0.0006 |

* Annual average hourly solar insolation on a horizontal surface

† Cooling degrees days at 65°F, the annual sum of daily differences between average daily air temperature and 65°F (18.3°C) when average daily air temperature is more than 65°F (18.3°C)

calculator. Since characterization of annual heating loads is not of interest for this version, parameters used for heating in the CoolCalcEnergy version are not included in Table 1. The cooling index is a dimensionless and normalized parameter formed by multiplying the annual average hourly solar insolation on a horizontal surface by the cooling degree days in a 65°F (18.3°C) base and dividing by 500,000 (arbitrarily selected to yield cooling indices between 0 and 1). It was found to work well for characterization of annual cooling loads.

In an effort to be consistent with how the variation of annual cooling load with location was described in the CoolCalcEnergy version of the calculator, Δ Demand in Equation (1) was sought as a function of the cooling index. Figure 4 shows the result for a variety of roofs. The roof R-values and combinations of solar reflectance and infrared emittance that are selected for display are sufficient to show the range of variation in Δ Demand. Data directly from the program STAR are shown as symbols. Best fits were attempted by the method of least squares to functions of the form Δ Demand = A + B·CI + C·CI² + D·CI³ for 3rd order fits, Δ Demand = A + B·CI + C·CI² for 2nd order fits and Δ Demand = A + B·CI for 1st order fits. The fits are shown by curves through the data.

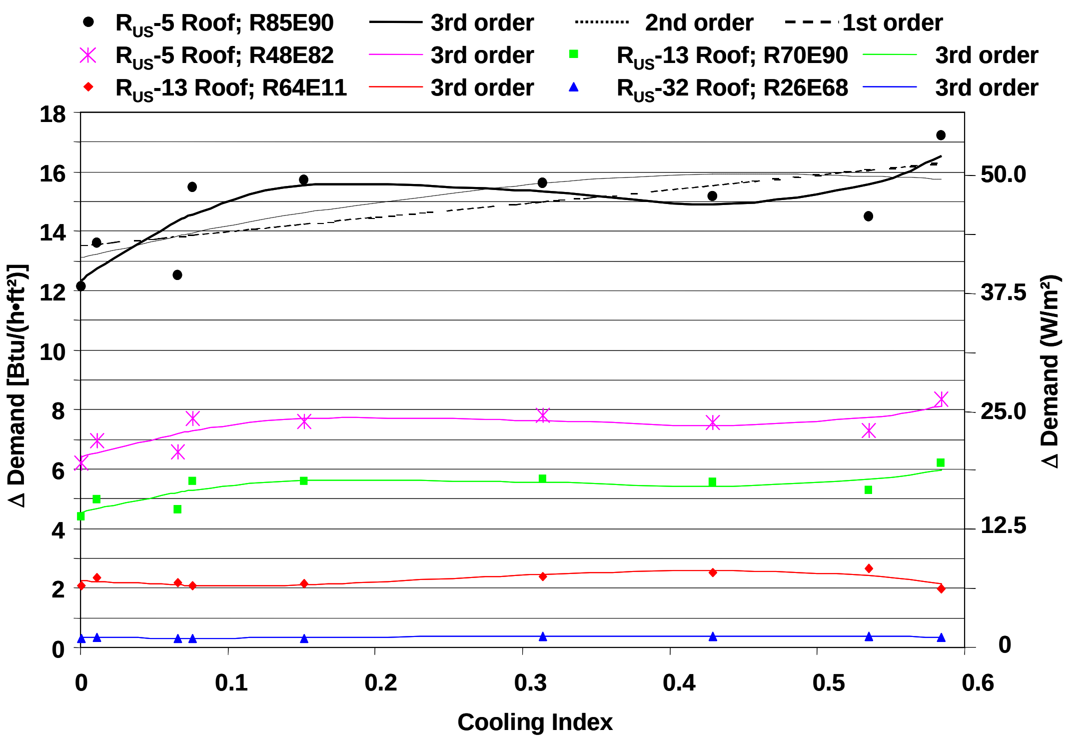



**Fig. 4 Average Δ Demand from April through September as a Function of Cooling Index for the Climates in Table 1 and a Variety of Roof R-values and Combinations RxxEyy**

Regardless of the order of the fit with cooling index, the correlation coefficient r² is about 0.75. The third order fit does capture the variation with cooling index better than the second order fit and first order fit for the $R_{US}$-5, R85E90 case, but the relative minimum at a cooling index of 0.43 is not satisfactory. Peak heat flux should monotonically increase with whatever parameters are selected to capture the effect of increasingly severe cooling climates. Cooling index does not appear to be a satisfactory parameter.

Figure 5 shows the same data as Figure 4, except that the fits are attempted as a function of the annual average hourly solar insolation at the various locations. The resulting correlation coefficients remain around 0.75. There is no significant difference among the third order, second order and first order fits for the $R_{US}$-5, R85E90 case. Therefore, the simplest, first order fits were chosen. The most severe deviation of the first order fits from the data, for Minneapolis and Knoxville, at solar insolation of 52 and 56 Btu/(h·ft²), respectively, is about ±10%. In light of the behavior of Δ Demand in Figures 2 and 3, this is judged acceptable. The form of the fit is

$$\Delta \text{ Demand} = Ap + Bp \bullet HS \quad (2)$$

where

Δ Demand is the difference between maximum deck heat flux for surface R05E90 and a surface with other combinations of solar reflectance and infrared emittance, in units of Btu/h per unit area. For use in Equation (1), division by 3412 was done to yield kW per unit area,

HS is the annual average hourly solar insolation for climates and is available, for example, from summaries of TMY2 data for all locations in the dataset.

Ap and Bp are coefficients to fit the values for Δ Demand.

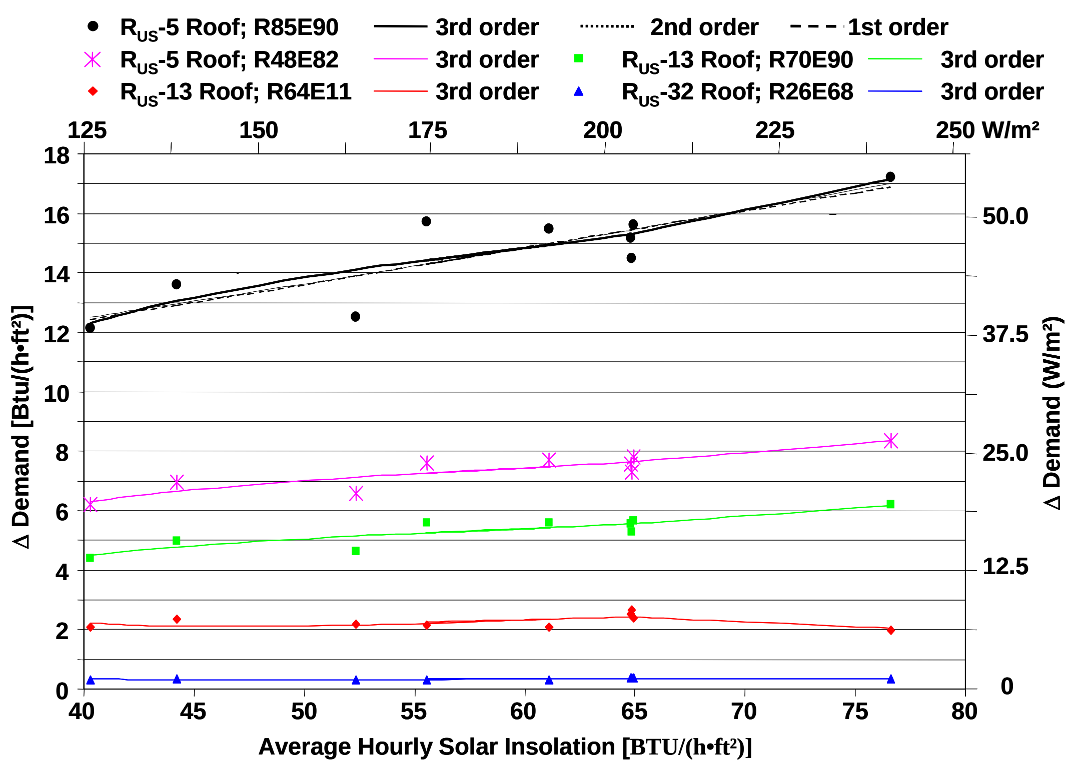
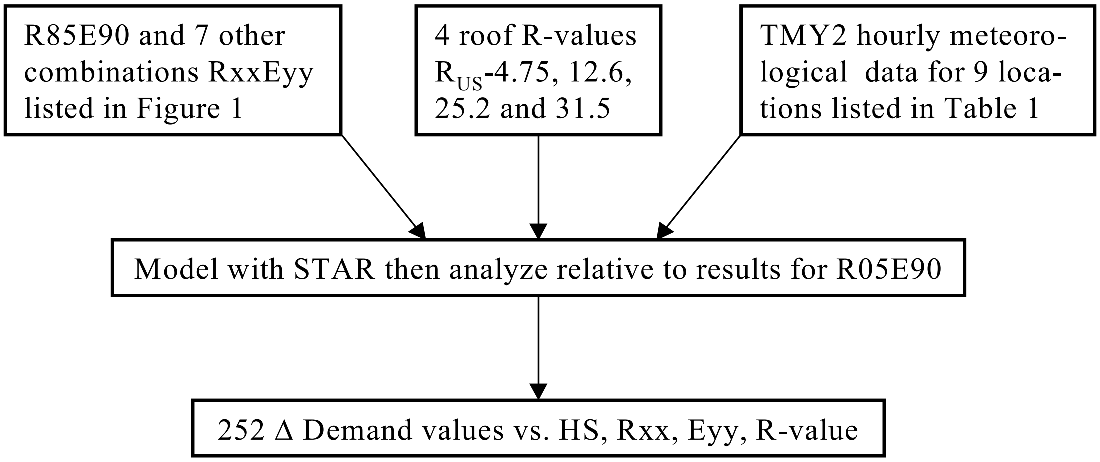
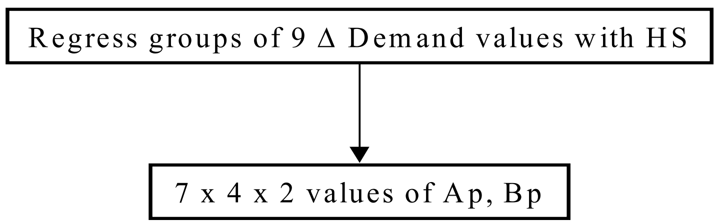



**Fig. 5 Average Δ Demand from April through September as a Function of Average Hourly Solar Insolation for the Climates in Table 1 and a Variety of Roof R-values and Combinations RxxEyy**

Regressions and exact fits were done to generate values for the coefficients Ap and Bp in Equation (2) as functions of the parameters. These steps were taken:




Then, for each of seven RxxEyy combinations compared to R05E90 and each of the four roof R-values,




The regression coefficients, $r^2$, for Ap and Bp varied from 0.732 to 0.823 except for the combinations R64E11 and R26E68. For these two surfaces, Δ Demand was essentially constant with random scatter regardless of solar insolation. The regressions predicted the appropriate level of Δ Demand but reported low regression coefficients.

To capture the dependence on solar reflectance and infrared emittance, the sets of Ap and Bp for each R-value were assumed to have a known dependence on solar reflectance and infrared emittance. Our previous experience (Petrie et al. 2001) suggested the following form:

$$Ap_i, Bp_i = a_i + b_i \bullet \rho_{solar} + c_i \bullet \rho_{solar}^2 + d_i \bullet \varepsilon_{infrared} \quad (3)$$

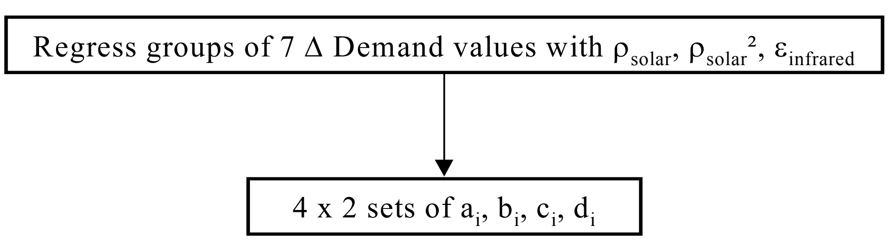
where,

$\rho_{solar}$ is the solar reflectance, which varies from 26% to 85%,

$\varepsilon_{infrared}$ is the infrared emittance, which varies from 11% to 90%, and

$a_i$, $b_i$, $c_i$ and $d_i$ are constants corresponding to each $Ap_i$ or $Bp_i$.

Then, for each $Ap_i$ or $Bp_i$,



Consistent with our previous experience with the form of Equation (3), the correlation coefficients for the eight sets of $a_i$, $b_i$, $c_i$ and $d_i$ all exceeded 0.995. Finally, the four values of $a_i$, $b_i$, $c_i$ or $d_i$ for each of the thermal resistances $R_{US}$-4.75, $R_{US}$-12.6, $R_{US}$-25.2 and $R_{US}$-31.5 were fit exactly to equations of the form:

$$a_i = a1_i + a2_i \bullet R + a3_i \bullet R^2 + a4_i \bullet R^3 \quad (4a)$$
$$b_i = b1_i + b2_i \bullet R + b3_i \bullet R^2 + b4_i \bullet R^3 \quad (4b)$$
$$c_i = c1_i + c2_i \bullet R + c3_i \bullet R^2 + c4_i \bullet R^3 \quad (4c)$$
$$d_i = d1_i + d2_i \bullet R + d3_i \bullet R^2 + d4_i \bullet R^3 \quad (4d)$$

where,

$a_i$, $b_i$, $c_i$ or $d_i$ are the coefficients to display dependence on solar reflectance and infrared emittance by Equation (3),

R is the thermal resistance of the roof,

$a1_i$, $a2_i$, $a3_i$ and $a4_i$ are the coefficients required to fit each $a_i$ exactly with R,

$b1_i$, $b2_i$, $b3_i$ and $b4_i$ are the coefficients required to fit each $b_i$ exactly with R,

$c1_i$, $c2_i$, $c3_i$ and $c4_i$ are the coefficients required to fit each $c_i$ exactly with R, and

$d1_i$, $d2_i$, $d3_i$ and $d4_i$ are the coefficients required to fit each $d_i$ exactly with R.

Arrays resulted that comprised 4 x 4 constants for the intercept Ap and 4 x 4 constants for the slope Bp in Equation (2). They allow very efficient prediction of Δ Demand for allowable R-value of the roof, solar reflectance and infrared emittance of the roof surface, and average hourly solar insolation for the location. Figure 6 shows the data from STAR and the lines from Equation (2) formed by using the constants from Equations (4) for an $R_{US}$-5 ($R_{SI}$-0.9) roof. The line for the surface R85E90 in Figure 6 is

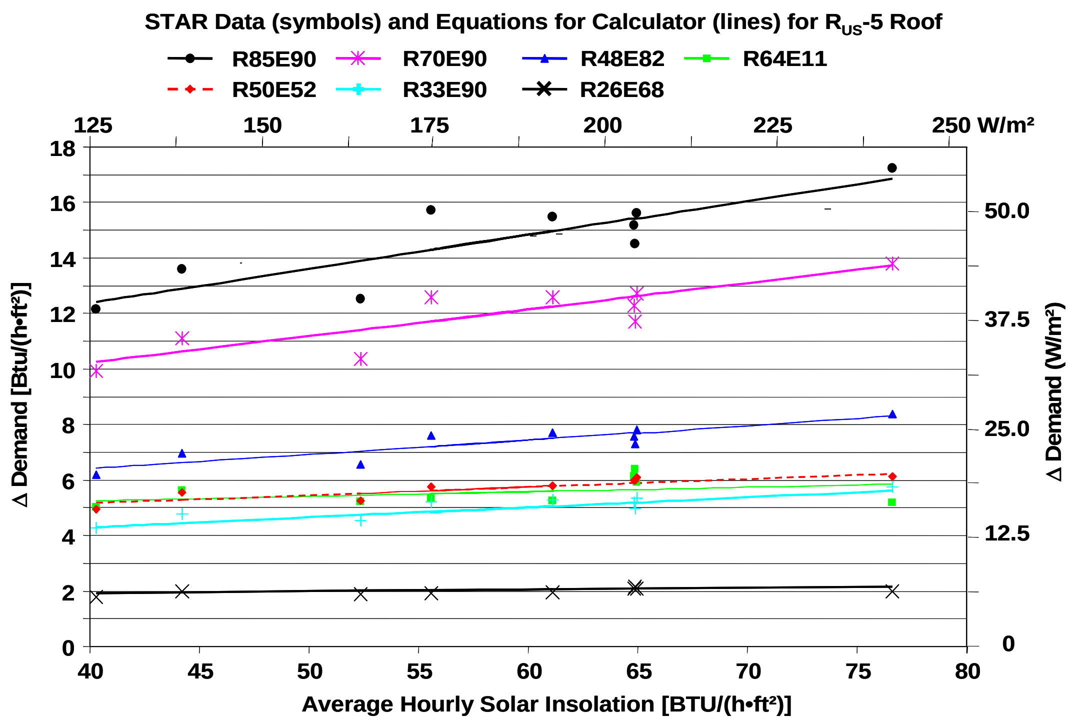



**Fig. 6 Average Δ Demand from April through September as a Function of Average Hourly Solar Insolation for the Climates in Table 1, a Roof R-value of $R_{US}$-5 ($R_{SI}$-0.9), and Various Combinations RxxEyy**

the same as the straight (long-dashed) line in Figure 5 for an $R_{US}$-5 roof with the R85E90 surface. Figure 5 shows results from the first step in the procedure, before the fits to solar reflectance, infrared emittance and R-value. Because of the high correlation coefficients for the fits to solar reflectance and infrared emittance and the exact fit to R-value, this agreement is expected.

Another two arrays, each comprising 4x4 constants, were generated to estimate the annual maximum Δ Demand as a function of R-value of the roof, solar reflectance and infrared emittance of the roof surface, and average hourly solar insolation for the location. The annual maximum Δ Demand may be of interest for minimum demand charges in months when cooling season demand charges are not in effect. It also shows how much the average Δ Demand differs from the maximum. Figure 7 shows the behavior of the annual maximum Δ Demand for an $R_{US}$-5 ($R_{SI}$-0.9) roof. Generally, the maximum Δ Demand differs from the average Δ Demand from April through September by 10% to 20%. The behavior shown in Figures 2 and 3 is apparent in Figure 7. The hot climate of Phoenix in Figure 3 has a longer cooling season than the cold climate of Minneapolis in Figure 4. Thus, annual maximum Δ Demand for the hot climates (with high average hourly insolation) is of the order of only 10% more than the average from April through September. It is 20% more for the cold climates (with low average hourly insolation). Thus, the slope with hourly solar insolation for a particular surface is steeper for the average Δ Demand in Figure 6 than it is for the maximum Δ Demand in Figure 7.

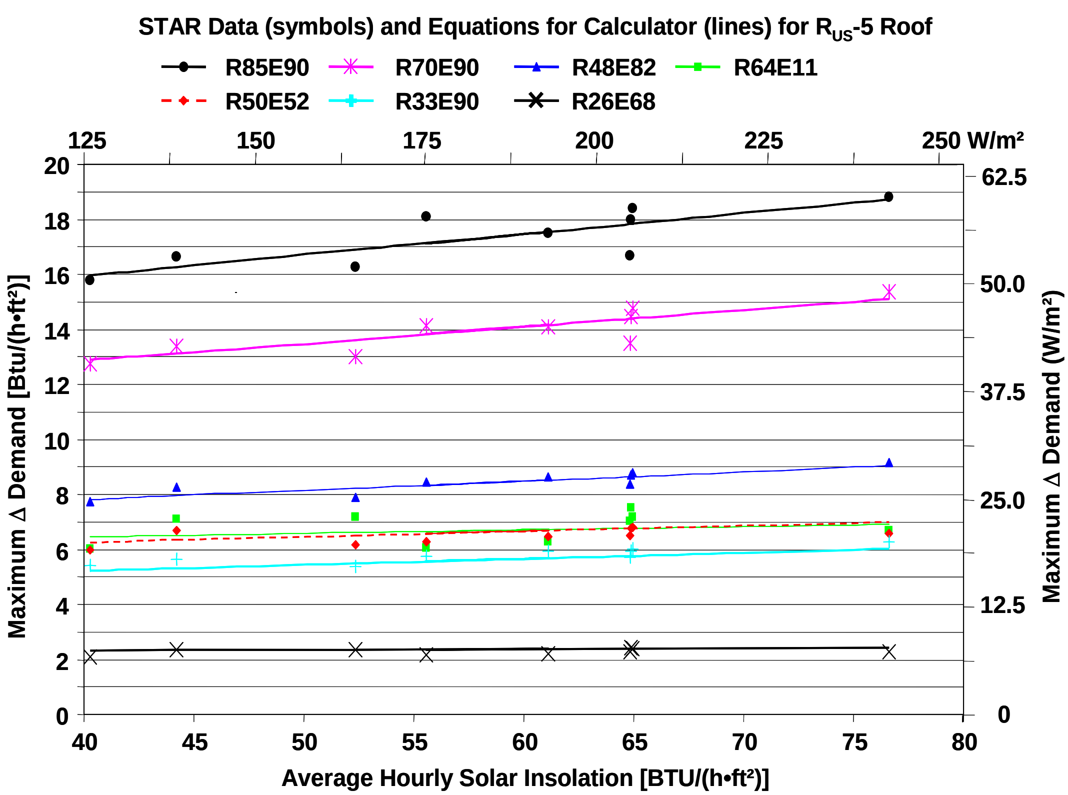



**Fig. 7 Annual Maximum Δ Demand as a Function of Average Hourly Solar Insolation for the Climates in Table 1, a Roof R-value of $R_{US}$-5 ($R_{SI}$-0.9), and Various Combinations RxxEyy**

## ANNUAL SAVINGS IN DEMAND CHARGES DUE TO RADIATION CONTROL

An example of an actual pricing schedule for electricity was sought in order to illustrate how the DOE Cool Roof Calculator estimates potential annual savings due to solar radiation control. The example needed to include demand charges. A pricing schedule with demand charges was found on the Internet from the General Service Large Schedule of BGE, an electricity and natural gas supplier in central Maryland (http://www.bge.com). For a monthly peak demand of 60 kW or more, monthly net rates effective from July 2002 through June 2003 include the charges in Table 2.

**TABLE 2**
**Example Monthly Net Rates for Large Electricity Customers**

| | Summer | Non-Summer |
|---|---|---|
| Demand Charges | $14.31/kW | $8.69/kW |
| Peak Energy Charges | $0.06874/kWh | $0.05195/kWh |
| Intermediate Energy Charges | $0.05683/kWh | $0.04852/kWh |
| Off-Peak Energy Charges | $0.04232/kWh | $0.04258/kWh |

The summer demand charges in Table 2 are assumed to apply to peak electricity demand savings due to solar radiation control. It is assumed that the average of the summer peak energy charges and the summer intermediate energy charges applies to electricity energy savings. Off-peak energy charges are ignored. Since there are non-summer charges based on measured monthly demand, a constant monthly ratchet charge based on maximum annual electricity demand is assumed not to apply. Thus, to estimate savings with solar radiation control for cooling in this example, monthly demand charges are taken as $14.31/kW for six months and energy charges are taken as $0.0628/kWh for the cooling season.

The cooling season average air conditioner COP is assumed for this example to be 2.5. Air conditioner COP at peak conditions is taken to be the COP at average conditions. Air conditioner COP is lower at peak conditions than it is at average conditions because peak conditions are more severe than average conditions. Average COP is generally available from manufacturer's data for air conditioners while COP at peak conditions would need to be estimated. Using average COP in Equation (1) yields a conservative value for demand savings. The CoolCalcPeak version of the calculator uses the same user-input value of COP for both energy and demand savings. The detailed output of the calculator gives the demand savings and the energy savings for cooling only.

Any heating for this example is assumed to be done with natural gas at a furnace efficiency of 0.80. Average natural gas cost to U.S. commercial customers in 2002 was $0.670 per Therm, down from $0.845 per Therm in 2001 (http://www.eia.doe.gov/). The detailed output of the calculator gives the energy savings for heating only. If it is negative, the proposed surface to do solar radiation control has an energy penalty relative to a black surface. The CoolCalcPeak calculator also sums the annual demand savings and the energy savings during heating and cooling for an estimate of total annual savings.

Results from the calculator for the example in this section are shown in Figures 8, 9 and 10 for Miami, Knoxville and Minneapolis, respectively, for three roof surfaces and the range of roof R-values for which the calculator was developed. The lower blue cross-hatched bars represent the annual energy savings for cooling and heating. The upper red cross-hatched bars represent the annual demand savings. The total height of the cross-hatched bar for each surface and R-value represents total annual savings due to solar radiation control.

Total annual savings due to solar radiation control decrease significantly as R-value increases for all surfaces and locations. This is an expected result. Specifying the proper amount of solar radiation control and the proper amount of conventional insulation for a given situation is difficult. It involves economic comparisons between annual savings over the life of the roof and present costs to install more or less of both options.

The narrow solid bar inside the cross-hatched bar for each surface and R-value gives the annual energy savings for cooling only. This may be of interest in buildings where internal loads cause a cooling situation year round. All solar radiation control surfaces save energy during cooling. The R70E90 surface (a white surface) saves the most of the three surfaces that are shown.

The savings for cooling only can be compared directly to the savings during cooling and heating. If the savings for cooling only are larger than the savings for cooling plus heating, there is a heating penalty associated with the surface. For the R70E90 surface, the heating penalty is slight in Miami but significant in Knoxville and Minneapolis. For Minneapolis, in fact, there are no energy savings for cooling plus heating with this surface. For the R50E52 surface (an aluminum-coated surface), the heating penalty is negligible. In Knoxville, this surface saves energy during both the cooling and heating seasons. The R64E11 surface (an aluminum capsheet), with its low infrared emittance that retains roof energy, especially at night, has no heating penalty. In Knoxville and Minneapolis, it gives greater annual energy savings than the R70E90 surface. In Miami, however, total annual energy savings with it are not as great as with the R70E90 surface.

The annual demand savings significantly improve the annual savings for all surfaces in Figures 8, 9 and 10. The relatively shallow slope in Figure 6 of $\Delta$ Demand with increasing solar insolation for U.S. locations means that peak demand reduction due to solar radiation control does not vary much over the United States. Thus, the demand savings for electricity during cooling for this example are about the same in Miami, Knoxville and Minneapolis for particular R-value and surface. For this example in Miami, annual demand savings nearly equal annual energy savings, effectively doubling the annual savings with solar radiation control. In Knoxville and Minneapolis, they make the R70E90 surface more attractive than either the R50E52 or the R64E11 surface. Clearly, for a facility that has electricity demand charges, the cost to install solar radiation control on low-slope roofs can be further justified because of savings in demand charges.

## CONCLUSIONS

This paper has presented the procedures followed to generate the equations that are used to add estimates to the DOE Cool Roof Calculator of savings from lower peak demand for electricity due to solar radiation control. Hour-by-hour heat fluxes through

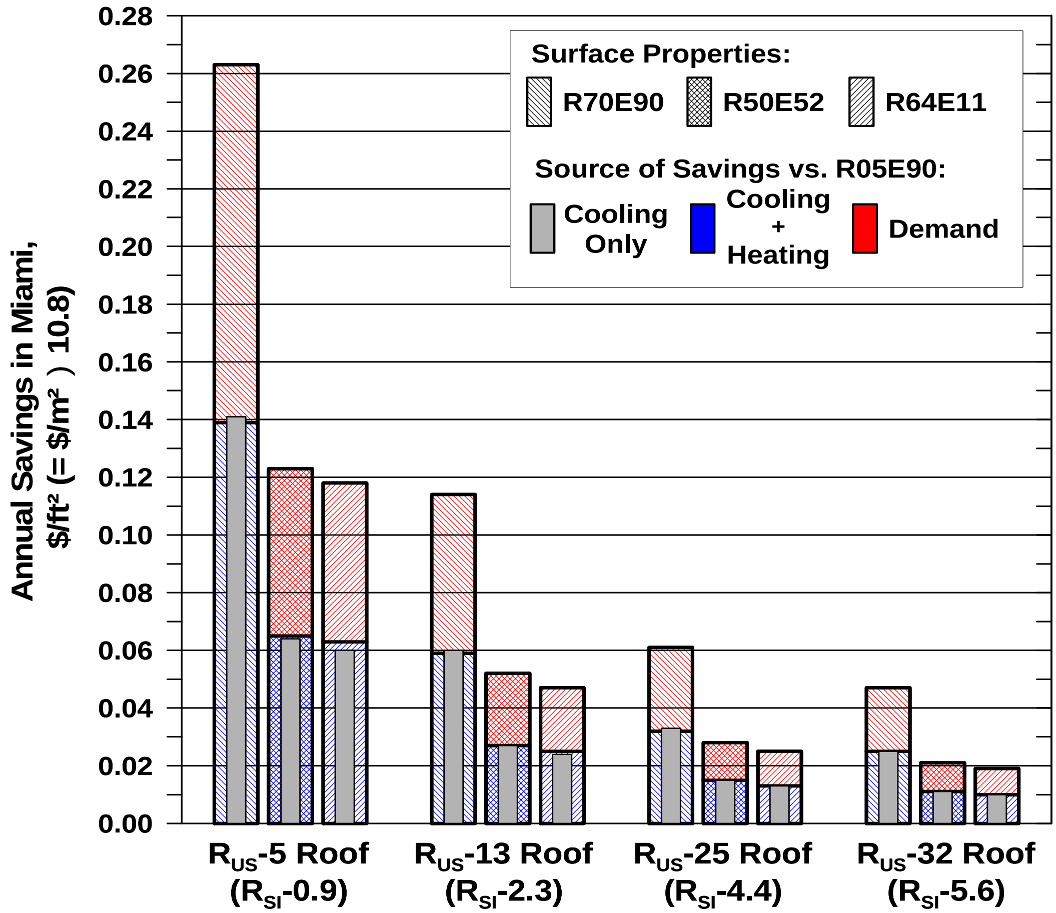



**Fig. 8 Example Annual Energy and Demand Savings as a Function of Roof R-Value and Surface Properties vs. a Black Roof in Miami**

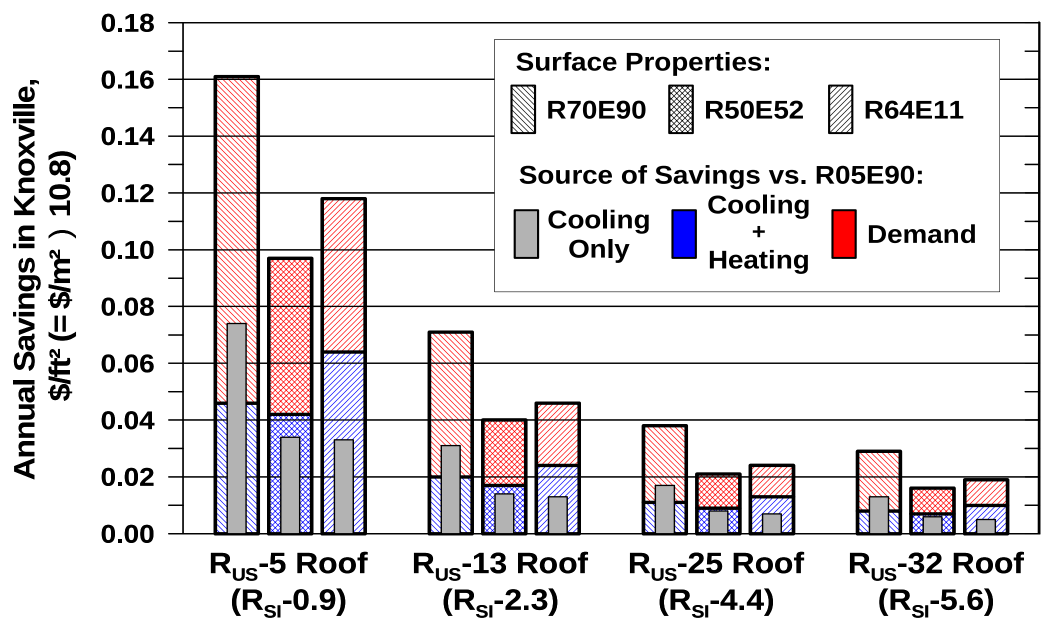



**Fig. 9 Example Annual Energy and Demand Savings as a Function of Roof R-Value and Surface Properties vs. a Black Roof in Knoxville**

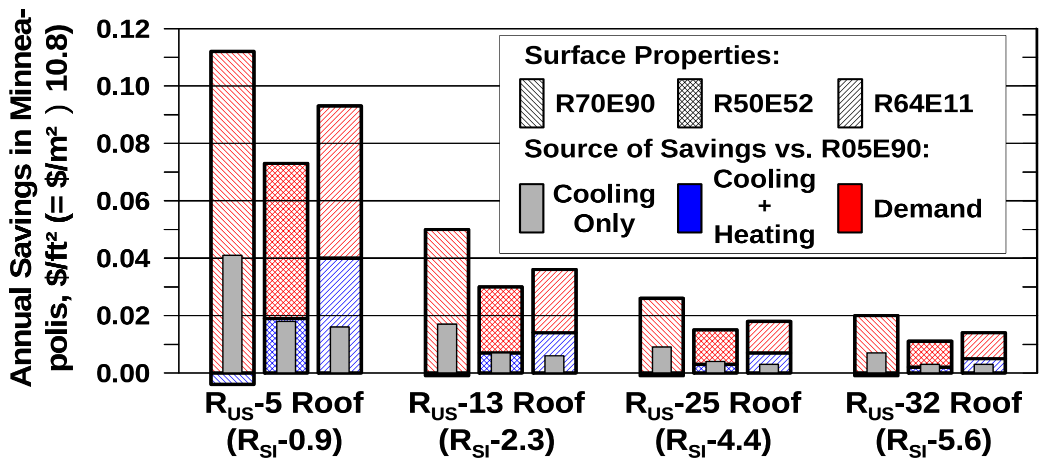



**Fig. 10 Example Annual Energy and Demand Savings as a Function of Roof R-Value and Surface Properties vs. a Black Roof in Minneapolis**

the deck were examined for various low-slope roofs in the range of U.S. climates with non-negligible cooling needs. The differences in peak deck heat fluxes without solar radiation control and with it were sought over the cooling season, defined as April through September in all climates. Values for the differences, defined as Δ Demand, were generated with a model of low-slope roof thermal performance. The model was validated by direct comparison of predicted and measured peak heat fluxes through the insulation of a roof configuration with low R-value in the climate of East Tennessee. The predicted and measured heat fluxes showed average agreement within 3%.

The cooling season average Δ Demand and the maximum Δ Demand were fit as a function of location (as characterized by average horizontal solar insolation), R-value of the roof, and solar reflectance and infrared emittance of the roof surface. Simple linear functions of solar insolation were chosen. The coefficients of these functions were, in turn, fit to solar reflectance, infrared emittance and R-value to yield excellent reproduction of the values that were predicted directly by the validated program.

An example of an electricity rate schedule was located on the Internet that included charges of $14.31 per kW of peak summer monthly demand and $0.0628 per kWh of summer peak and intermediate use. Year 2002 average cost of $0.670 per Therm of natural gas to U.S. commercial customers was used for heating. Typical equipment efficiencies were also specified. The CoolCalcPeak version of the DOE Cool Roof Calculator was exercised with Miami, Knoxville and Minneapolis climatic data to estimate the effect of solar radiation control on annual energy costs for cooling only, annual energy costs for cooling and heating and annual demand costs for various roof surfaces and insulation R-values.

The energy costs show the expected heating penalty for a white (R70E90) surface in all climates. It makes this surface show no energy cost savings for heating and cooling in Minneapolis. An aluminum coating (R50E52) showed little heating penalty. An aluminum capsheet (R64E11) had positive savings in all climates during heating and cooling. For the assumed electricity rate schedule and other parameters, lower demand with solar radiation control saved about the same amount of annual operating costs in all climates for a particular surface and roof R-value. Including the demand charge savings for the R70E90 surface nearly doubled its total savings in Miami and allowed it to save more in all climates than the R50E52 and R64E11 surfaces.

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