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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

The DOE Cool Roof Calculator is on the Internet to give up-to-date and unbiased information to assist in selection of an energy-saving surface for low-slope roofs. The current version, intended for small and medium-sized commercial facilities, addresses only the savings based on costs per unit of energy. This paper presents the procedures that were followed to add estimates of savings in demand charges that large facilities often incur for electricity. The program that was used to produce the data for the current version was further validated by comparison of measured and predicted peak heat fluxes over the cooling season in eastern Tennessee for roofs with low R-value. The database used for the current version of the calculator was reworked. Differences in peak deck heat fluxes with solar radiation control and without it were sought over the cooling season as a function of location (as characterized by average level of solar insolation), R-value of the low-slope roof, and solar reflectance and infrared emittance of the roof surface. An example of an electricity rate schedule that includes demand charges shows the impact of the additional savings due to decreased peak demand with solar radiation control. Decreases in peak heat fluxes due to solar radiation control depend strongly on peak solar insolation. Peak solar insolation is relatively constant for the United States. Thus, lower demand charges saved about the same amount of annual operating costs in all U.S. climates with significant cooling requirements. With the inclusion of savings in demand charges, the total savings for a white surface in the severe cooling climate of Miami more than doubled compared to energy cost savings alone. With demand charge savings, the white surface saved more than surfaces with lower solar reflectance and lower infrared emittance in the mixed climate of Knoxville and the heating climate of Minneapolis.

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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 is termed the DOE Cool Roof Calculator. A stand-alone version has since been produced on 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 per unit area of roof surface in annual operating energy costs due to a proposed roof surface rather than 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 energy prices and efficiencies of heating and cooling equipment.

The calculator is part of a solar radiation control fact sheet. The fact sheet, at http://www.ornl.gov/roofs+walls/facts/RadiationControl.htm, presents the range of solar reflectance and infrared emittance for available roof surfaces that resulted from the work with RCMA. Information in the fact sheet guides the user of the calculator to properly select other input values and interpret the output. A research paper (Petrie, et al. 2001) documents the procedures followed to generate the equations that are used in 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. As originally written, it 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 or cooling season. 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, 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 original version of the DOE Cool Roof Calculator can only address the energy cost savings, not the demand charge savings, due to solar radiation control on the large areas of low-slope roofs for large facilities. In concluding the documentation of the original version, Petrie et al. (2001) demonstrate that the database that was used has information about the peak demand. This paper describes the procedures that were followed to bring this information into the form of an addition to the DOE Cool Roof Calculator. Even with this addition, the 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 database for the Cool Roof Calculator, is best done on a case-by-case basis.

PEAK HEAT FLUXES FROM CLIMATIC DATA

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

The series of roofs have R-values that vary from R_{SI}-0.84 to 5.5 m²·K/W (R_{US}-4.75 to 31.5 h·ft²·°F/Btu). 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). 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 30 km (20 miles) 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 0.84 m²·K/W (4.75 h·ft²·°F/Btu) due primarily to two layers of wood fiberboard insulation, one 1.3 cm (0.5 in.) thick on the top of another 2.5 cm (1.0 in. thick). A heat flux transducer was placed between the two layers of insulation in each test section.

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 period. April through September can be considered the cooling season in Knoxville. The two bars for each surface compare the predicted and 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 ±6.3 W/m² [±2.0 Btu/(h·ft²)](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.

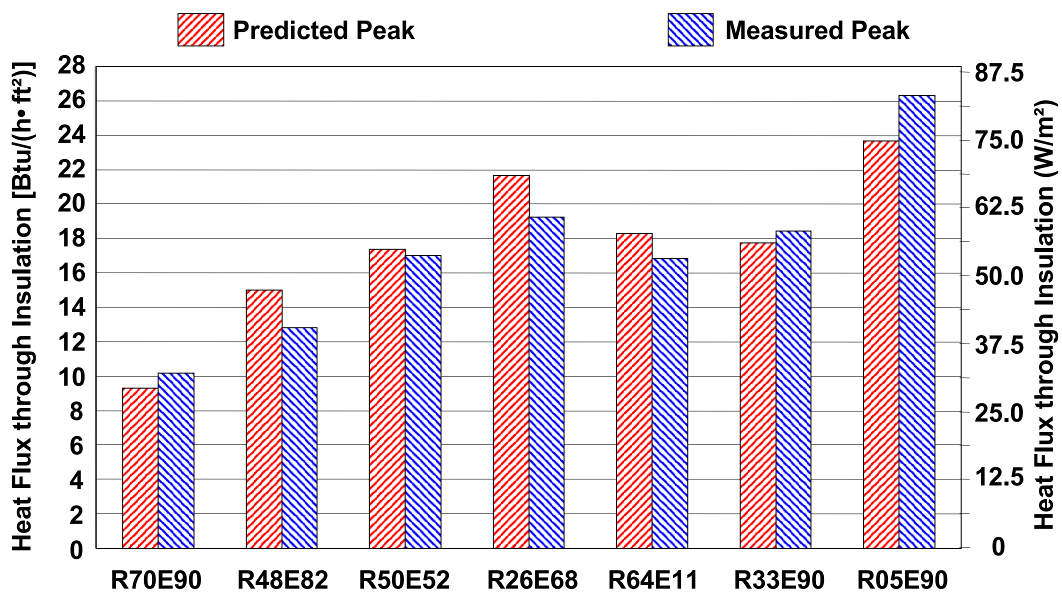


Fig. 1 Comparison of Peak Heat Fluxes Predicted with TMY2 Data for Knoxville and Measured in Oak Ridge

DEVELOPMENT OF AN ESTIMATING TOOL FOR PEAK DEMAND SAVINGS

The database from which the DOE Cool Roof Calculator was developed is a collection of workbooks in spreadsheet files. Each spreadsheet file is for a particular location and roof R-value. The workbooks in each spreadsheet file contain the temperature and heat flux at the outside and inside surfaces of the roof 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 effect of the roof on the peak demand for electricity in a building is assumed to be coincident with the other drivers for peak demand. The heat flux through the roof deck is taken to determine the roof's contribution to demand for electricity. 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 as follows:

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

where,

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

Δ Demand is the difference between maximum deck heat fluxes 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 are not relatively mild.

Development of an estimating tool for peak demand savings requires 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_{SI}-0.8 (R_{US}-5) 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. 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. The calculator would need to multiply the monthly $ Demand Charge from Equation (1) by the number of months for which the

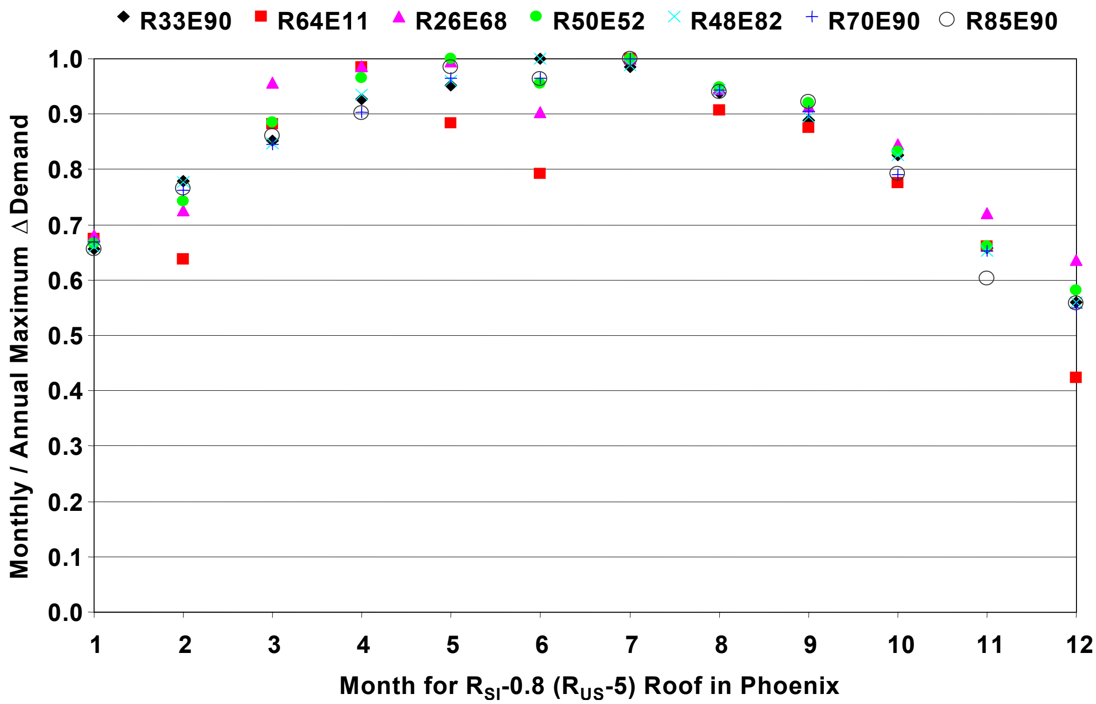


Fig. 2 Monthly Maximum ∆ Demand Compared to Annual Maximum ∆ Demand for a Roof with Various Surfaces in Phoenix

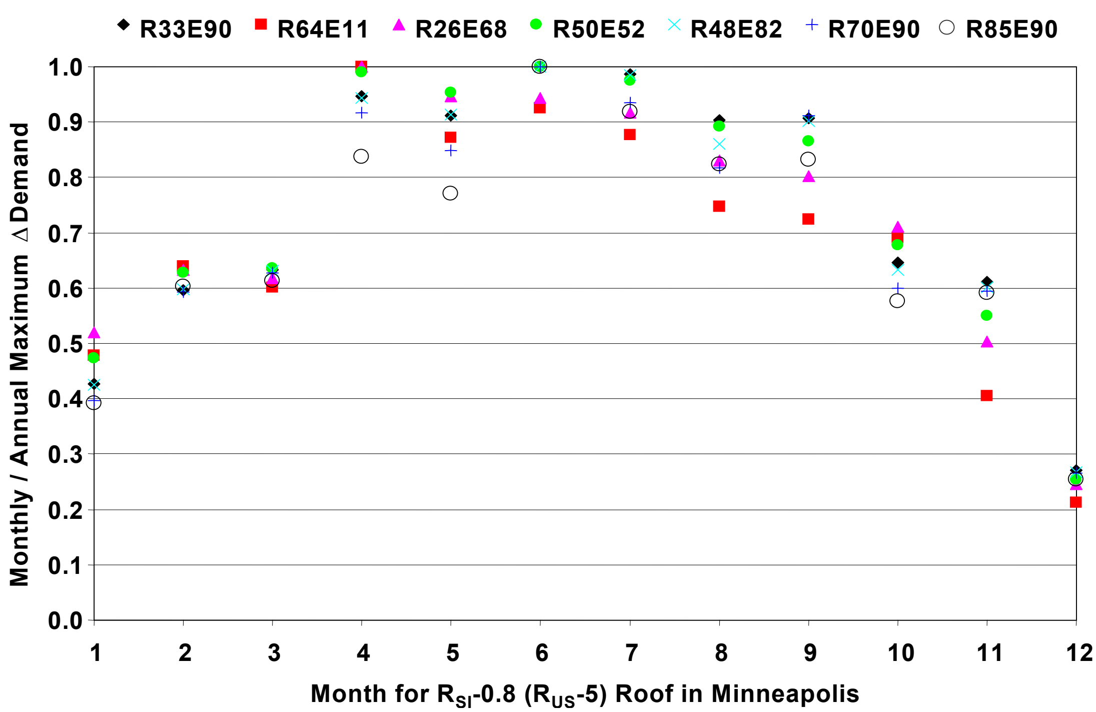


Fig. 3 Monthly Maximum ∆ Demand Compared to Annual Maximum ∆ Demand for a Roof with Various Surfaces in Minneapolis

demand charge is applied. Another value, the annual maximum itself, might be useful to estimate the minimum demand charge or demand ratchet in the other months.

All surfaces in Figures 2 and 3 display a maximum Δ Demand fraction at some time between April and September. However, there appear to be random variations in the fraction that would defy presentation of these variations 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 ensure that the maximum deck heat fluxes for the R05E90 surface and the surfaces with other combinations RxxEyy are occurring at nearly the same time, the database was reworked 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 of RxxEyy.

In the original database that was used for annual heating and cooling loads due to the roof, 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. Instead, 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 add the effect of solar radiation control on electricity demand charges to the DOE Cool Roof Calculator. Since characterization of annual heating loads is not of interest for this addition, parameters used in the original calculator for this purpose 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 (HS) by the cooling degree days in a 65°F base (CDD_{65}) and dividing by 500,000. It was found to work well for characterization of annual cooling loads.

Table 1. Locations used in the addition to the DOE Cool Roof Calculator of the effect of solar radiation control on electricity demand charges

Location	HS [Btu/(h·ft²)][1]	CDD_{65}[2]	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

[1] Annual average hourly solar insolation on a horizontal surface

[2] Annual sum of daily differences between average daily air temperature and 18.3°C (65°F) when average daily air temperature is more than 18.3°C (65°F)

In an effort to be consistent with how the variation of annual cooling load with location was described in the original calculator, Δ Demand in Equation (1) was sought as a function of the cooling index as shown in Table 1. 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.

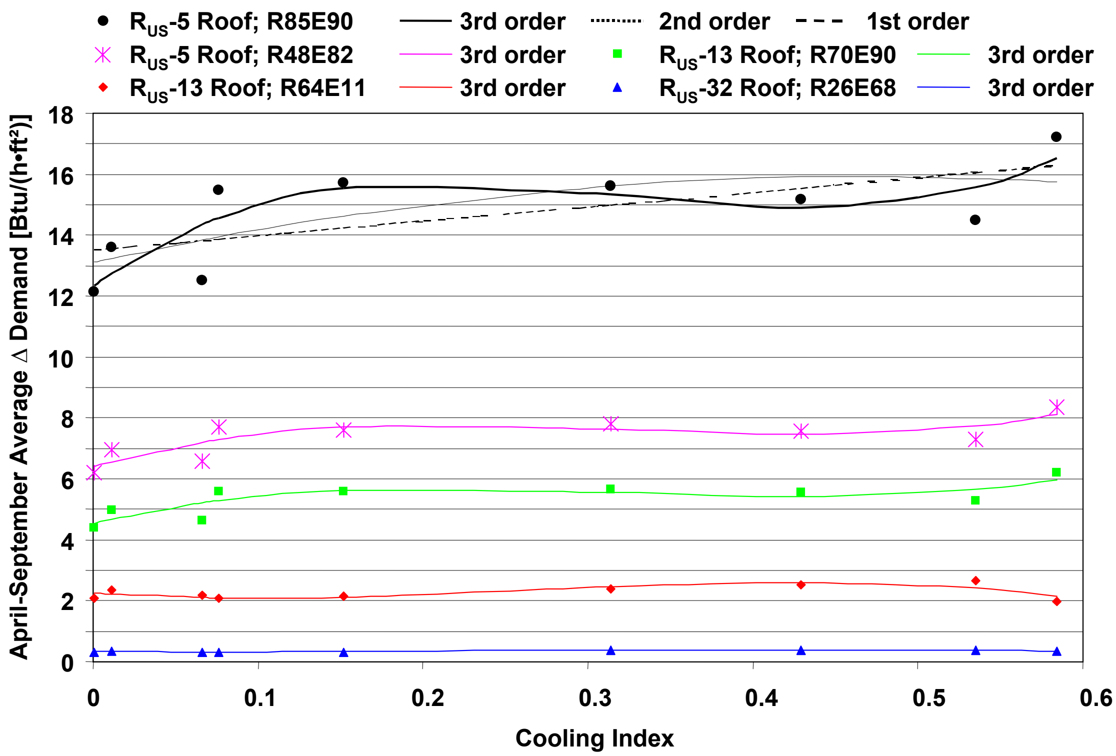


Fig. 4 Average Δ Demand from April through September as a Function of Cooling Index for the Climates in Table 1 and a Variety of Roof R-values and Combinations RxxEyy

Regardless of the order of the fit with cooling index, the correlation coefficient r^2 is about 0.75. The third order fit does capture the variation with cooling index better than the second order and first order fits 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 and there is no difference between the third order, second order or first order fits for the R_{US}-5, R85E90 case. The most

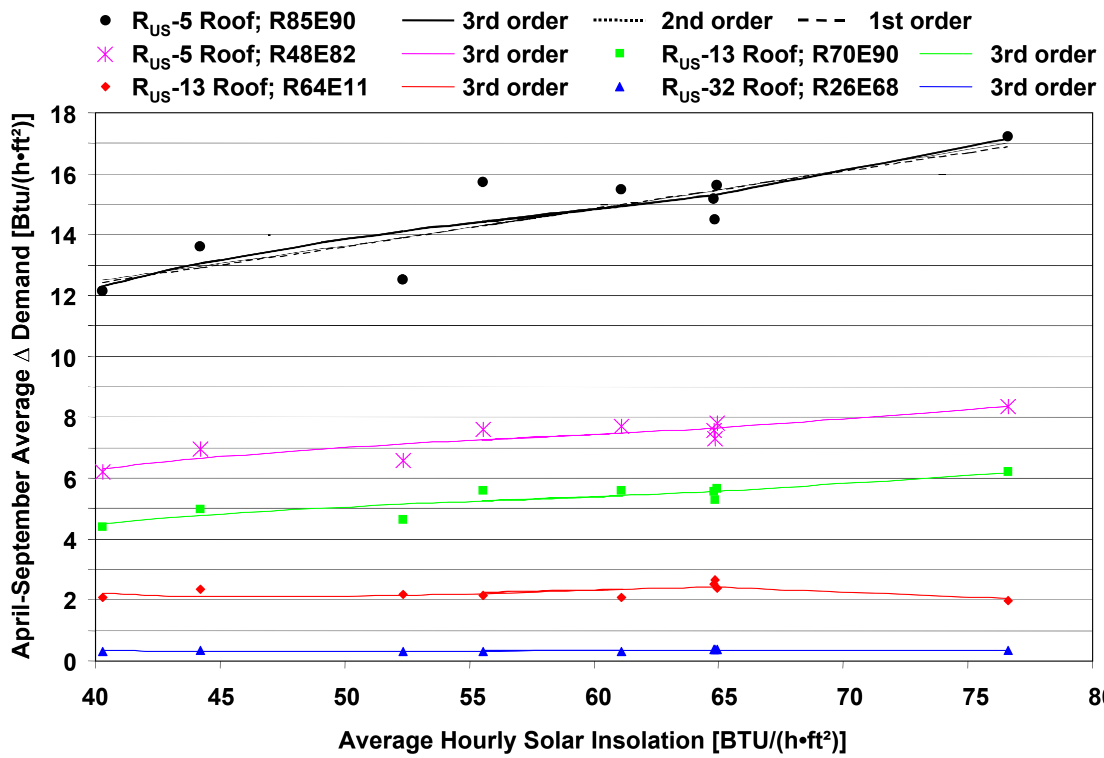


Fig. 5 Average Δ Demand from April through September as a Function of Average Hourly Solar Insolation for the Climates in Table 1 and a Variety of Roof R-values and Combinations RxxEyy

severe deviation of the fit from the data, for Minneapolis and Knoxville at solar insolations 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. Therefore, a fit was done of the form:

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

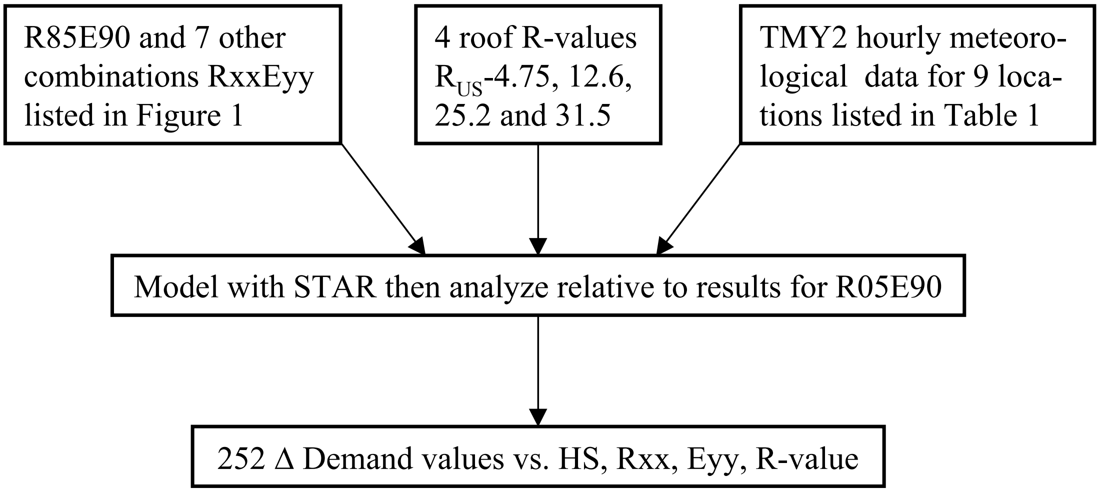
where,

Δ Demand is the difference between maximum deck heat fluxes for surface R05E90 and surfaces 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 is required to yield kW per unit area,

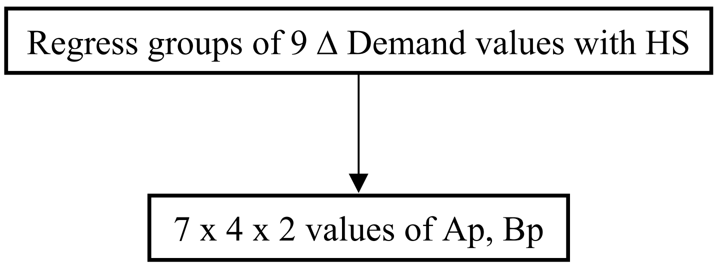
HS is the annual average hourly solar insolation for climates and is available, for example, from summaries of TMY2 data for all locations in the dataset.

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

Regressions and exact fits were done to generate values for the coefficients Ap and Bp in Equation (2). To generate the data to fit, 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 regardless of solar insolation, Δ Demand was essentially constant with random scatter. The regressions predicted a constant Δ Demand at the appropriate level 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 the following dependence on solar reflectance and infrared emittance from our previous experience (Petrie et al. 2001):

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

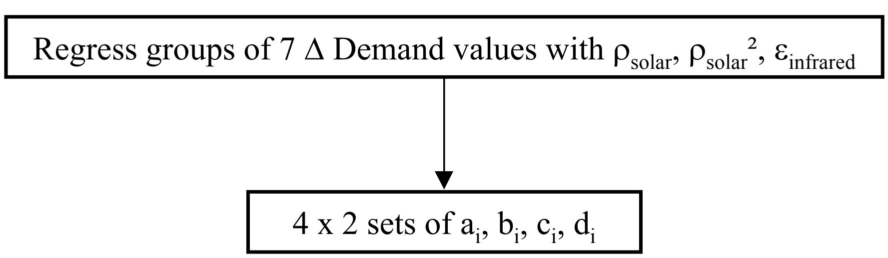
where,

ρ_{solar} is the solar reflectance, which varies from 26% to 85%,

$\epsilon_{infrared}$ 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 thermal resistances of 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 with 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

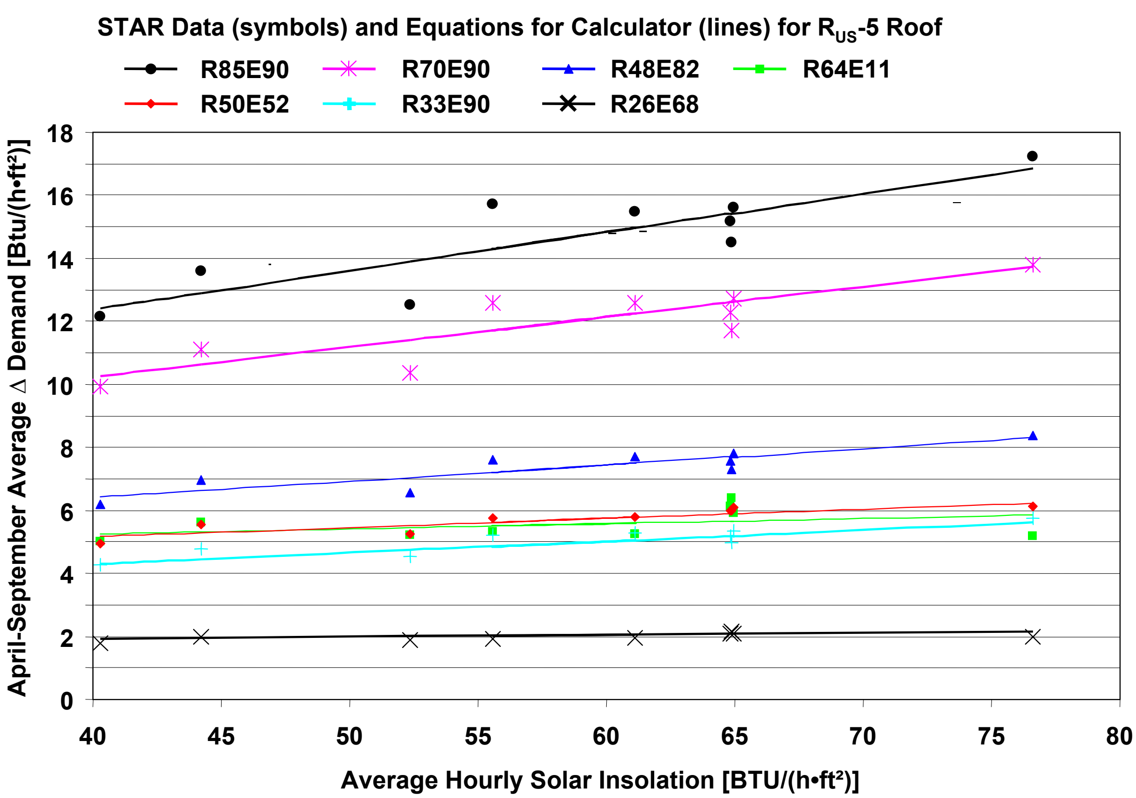


Fig. 6 Average Δ Demand from April through September as a Function of Average Hourly Solar Insolation for the Climates in Table 1, a Roof R-value of R_{SI}-0.8 (R_{US}-5), and Various Combinations RxxEyy

and the lines from Equation (2) with the constants from Equations (4) for an R_{SI}-0.8 (R_{US}-5) roof. The line for the surface R85E90 in Figure 6 is not significantly different from the 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 with 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_{SI}-0.8 (R_{US}-5) 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 also is apparent in Figure 7. The cold climate of Minneapolis in Figure 4 has a shorter cooling season than the hot climate of Phoenix in Figure 3. Thus, annual maximum Δ Demand for the cold climates (with

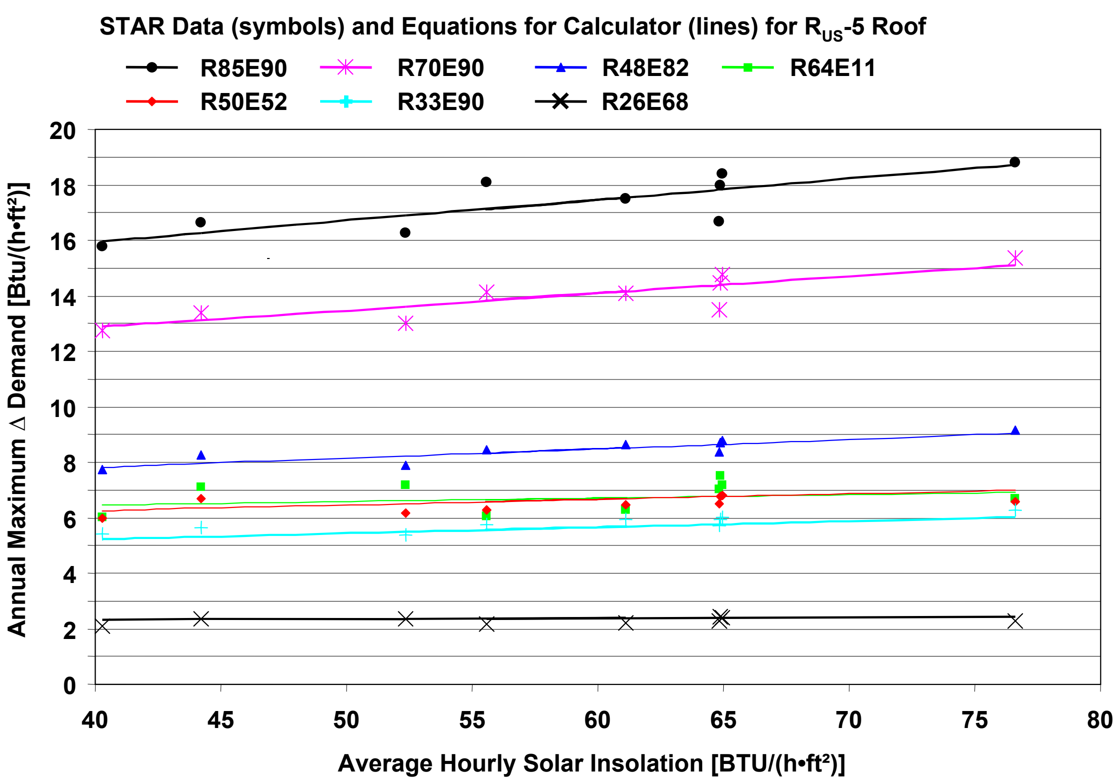


Fig. 7 Annual Maximum Δ Demand as a Function of Average Hourly Solar Insolation for the Climates in Table 1, a Roof R-value of R_{SI}-0.8 (R_{US}-5), and Various Combinations RxxEyy

low average hourly insolation) is of the order of 20% more than the average from April through September while it is only 10% more for the hot climates (with high average hourly insolation). Thus, the slope with average hourly solar insolation for a particular surface is shallower for maximum Δ Demand in Figure 7 compared to the average from April through September in Figure 6.

ANNUAL SAVINGS IN DEMAND CHARGES DUE TO RADIATION CONTROL

An example of a pricing schedule for electricity was sought on the Internet in order to illustrate potential annual savings due to radiation control. The example needed to include demand charges. A pricing schedule with demand charges was found from the General Service Large Schedule of BGE, an electricity and natural gas supplier in central Maryland (http://www.bge.com). For a customer with a monthly 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

It is assumed that the average of the summer peak and the summer intermediate energy charges in Table 2 apply to electricity energy savings due to solar radiation control. The summer demand charges are assumed to apply to peak electricity demand savings due to solar radiation control. 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 in this example. Thus, to estimate savings with solar radiation control for cooling, energy charges are taken as $0.0628/kWh for the cooling season and demand charges are taken as $14.31/kW for, say, six months.

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 yields a conservative value for demand savings.

Any heating is 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/). For Table 3, $0.670 per Therm was used for the total annual energy savings. Then, for Table 4, to ignore any energy savings or penalty during heating and focus only on electricity for cooling, natural gas cost was set to $0.000 per Therm.

Table 3. Example annual energy savings for heating and cooling

Surface vs. R05E90:	R70E90	R50E52	R64E11
Miami Energy Savings for Heating and Cooling: $/ft^2 per year			
R_{US}-5 Roof	0.139	0.065	0.063
R_{US}-13 Roof	0.059	0.027	0.025
R_{US}-25 Roof	0.032	0.015	0.013
R_{US}-32 Roof	0.025	0.011	0.010
Knoxville Energy Savings for Heating and Cooling: $/ft^2 per year			
R_{US}-5 Roof	0.046	0.042	0.064
R_{US}-13 Roof	0.020	0.017	0.024
R_{US}-25 Roof	0.011	0.009	0.013
R_{US}-32 Roof	0.008	0.007	0.010
Minneapolis Energy Savings for Heating and Cooling: $/ft^2 per year			
R_{US}-5 Roof	-0.004	0.019	0.040
R_{US}-13 Roof	-0.001	0.007	0.014
R_{US}-25 Roof	-0.001	0.003	0.007
R_{US}-32 Roof	-0.001	0.002	0.005

Table 4. Example annual energy savings for cooling only

Surface vs. R05E90:	R70E90	R50E52	R64E11
Miami Energy Savings for Cooling Only: $/ft^2 per year			
R_{US}-5 Roof	0.141	0.064	0.060
R_{US}-13 Roof	0.060	0.027	0.024
R_{US}-25 Roof	0.033	0.015	0.013
R_{US}-32 Roof	0.025	0.011	0.010
Knoxville Energy Savings for Cooling Only: $/ft^2 per year			
R_{US}-5 Roof	0.074	0.034	0.033
R_{US}-13 Roof	0.031	0.014	0.013
R_{US}-25 Roof	0.017	0.008	0.007
R_{US}-32 Roof	0.013	0.006	0.005
Minneapolis Energy Savings for Cooling Only: $/ft^2 per year			
R_{US}-5 Roof	0.041	0.018	0.016
R_{US}-13 Roof	0.017	0.007	0.006
R_{US}-25 Roof	0.009	0.004	0.003
R_{US}-32 Roof	0.007	0.003	0.003

The differences between the entries in Table 3 and Table 4 for the same location, R-value and surface properties show the effect of radiation control during the heating season. For the R70E90 surface (a white surface), there is a heating penalty. It is slight in Miami but significant in Knoxville and Minneapolis. Without it, Table 4 shows that theR70E90 surface saves the most for cooling in all locations. For the R50E52 surface (an aluminum-coated surface), the heating penalty is negligible. In Knoxville, this coating helps to save 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 in Table 5 complete the example. As Figure 6 showed, the effect of location on savings due to solar radiation control is not great. 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 RxxEyy. In Miami, annual demand savings for low-slope roofs equal or exceed annual energy savings. In Knoxville and Minneapolis, they also make the R70E90 surface more attractive than the R64E11 surface. Table 6 sums the entries in Tables 3 and 5 to emphasize this feature. Clearly, for a facility that has electricity demand charges, solar radiation control on its low-slope roof can be further justified because of savings in demand charges.

Table 5. Example annual demand savings for electricity during cooling only

Surface vs. R05E90:	R70E90	R50E52	R64E11
Miami Demand Savings for Electricity during Cooling: $\$/ft^2$ per year			
R_{US}-5 Roof	0.124	0.058	0.055
R_{US}-13 Roof	0.055	0.025	0.022
R_{US}-25 Roof	0.029	0.013	0.012
R_{US}-32 Roof	0.022	0.010	0.009
Knoxville Demand Savings for Electricity during Cooling: $\$/ft^2$ per year			
R_{US}-5 Roof	0.115	0.055	0.054
R_{US}-13 Roof	0.051	0.023	0.022
R_{US}-25 Roof	0.027	0.012	0.011
R_{US}-32 Roof	0.021	0.009	0.009
Minneapolis Demand Savings for Electricity during Cooling: $\$/ft^2$ per year			
R_{US}-5 Roof	0.112	0.054	0.053
R_{US}-13 Roof	0.050	0.023	0.022
R_{US}-25 Roof	0.026	0.012	0.011
R_{US}-32 Roof	0.020	0.009	0.009

Table 6. Example total annual savings with solar radiation control

Surface vs. R05E90:	R70E90	R50E52	R64E11
Miami Demand Savings for Electricity during Cooling: $/ft^2 per year			
R_{US}-5 Roof	0.263	0.123	0.118
R_{US}-13 Roof	0.114	0.052	0.047
R_{US}-25 Roof	0.062	0.028	0.025
R_{US}-32 Roof	0.047	0.021	0.019
Knoxville Demand Savings for Electricity during Cooling: $/ft^2 per year			
R_{US}-5 Roof	0.161	0.097	0.118
R_{US}-13 Roof	0.070	0.040	0.046
R_{US}-25 Roof	0.038	0.021	0.024
R_{US}-32 Roof	0.029	0.016	0.018
Minneapolis Demand Savings for Electricity during Cooling: $/ft^2 per year			
R_{US}-5 Roof	0.108	0.073	0.093
R_{US}-13 Roof	0.048	0.030	0.036
R_{US}-25 Roof	0.026	0.016	0.019
R_{US}-32 Roof	0.019	0.011	0.013

CONCLUSIONS

Hour-by-hour heat fluxes through 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 with solar radiation control and without 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 eastern Tennessee.

The cooling season average and the maximum Δ Demand were fit as a function of location (as characterized by 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 revised DOE Cool Roof Calculator was exercised in Miami, Knoxville and Minnesota to estimate the effect of solar radiation control on annual energy costs, cooling operating energy costs (by setting natural gas prices to $0.000 per Therm) and demand costs.

The energy costs show the expected heating penalty for a white (R70E90) surface in all climates. It is especially severe in Minneapolis. An aluminum coating (R50E52) showed little heating penalty. An aluminum capsheet (R64E11) saved in all climates during heating and cooling but not as much as the white roof in Miami. For the assumed electricity rate schedule and other parameters, lower demand charges with solar radiation control saved about the same amount of annual operating costs in all climates for a given surface and roof R-value. Including the demand charge savings for the R70E90 surface nearly doubled its total savings in Miami. With the demand charge savings, the R70E90 surface saved more in all climates relative to the R50E52 and R64E11 surfaces.

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