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MARTIN MARIETTA

Guide for Estimating Differences in Building Heating and Cooling Energy Due to Changes in Solar Reflectance of a Low-Sloped Roof

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Prepared for the
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OPERATED BY
MARTIN MARIETTA ENERGY SYSTEMS, INC.
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ABSTRACT

This work was performed for the National Program on Building Thermal Envelope Systems and Materials. The objective of this work was to develop a method that could be used to evaluate the net energy savings and resultant cost savings associated with changing the solar reflectance of low-sloped roofs. The method that was developed is presented as a guide that provides data and calculation procedures for estimating the change in HVAC energy and resultant cost savings associated with changing the solar reflectance of low-sloped roofs. In most instances, the cooling cost savings associated with a change to a white roof surface (one with higher solar reflectance) exceed the heating cost penalty. If the difference between reduced cooling costs and increased heating costs is significant, it can affect the choice of membrane for a new roof or a re-roofed building. This guidebook helps the user estimate this energy cost difference for his particular roof. It also describes how various factors influence potential energy savings and actual roof surface temperatures for different solar reflectances.

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Part of the
National Program for
Building Thermal Envelope Systems and Materials

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Summary

Guide for Estimating Differences in Building Heating and Cooling Energy Due to Changes in Solar Reflectance of a Low-Sloped Roof

An increase in roof solar reflectance results in a saving of building cooling energy and an increase in building heating energy. This guide provides data and calculation procedures for estimating the change in HVAC energy and resultant cost savings associated with changing the solar reflectance of low-sloped roofs. A brief consideration of exterior surface mass shows that the annual energy and cost savings are small compared to the effect of changing roof solar reflectance.

This guide can be used to perform different types of savings estimates related to changing roof solar reflectance, including: savings for a change to a higher roof solar reflectance, comparison of savings for two different products, and estimating changes in savings due to degradation of reflectance

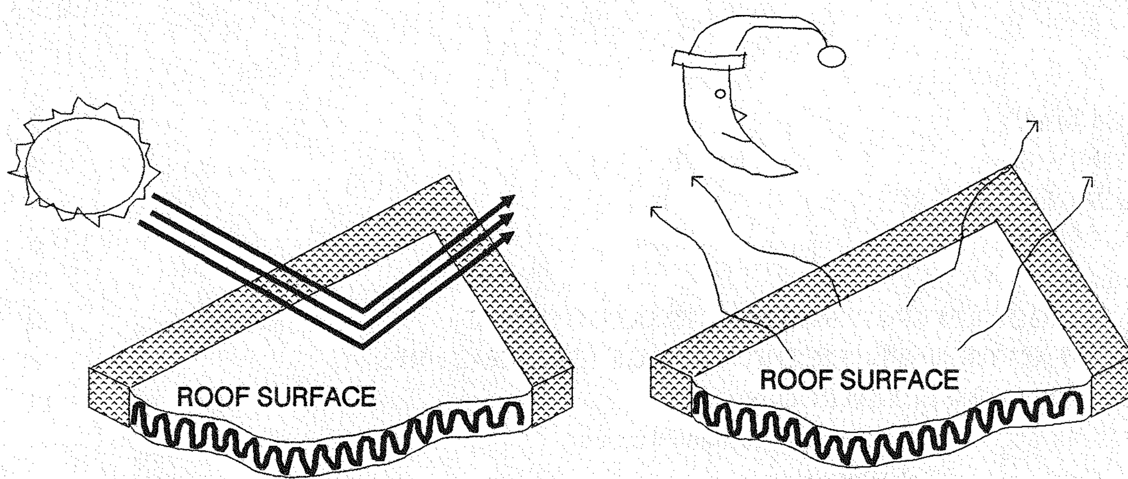
In most instances, the cooling cost savings associated with a change to a white roof surface (one with higher solar reflectance) exceed the heating cost penalty. This should not be construed as a blanket endorsement of high solar reflectance roofs. Many factors beyond the scope of this guide should be considered. Roof maintenance costs, roof life, dirt accumulation, and different material costs are examples.

An increase in solar reflectance will decrease the peak daytime temperatures of a roof. Black surfaces routinely exceed 160°F on summer days. Under similar conditions flat white surfaces reach 135°F and glazed white surfaces seldom go above 120°F.

The important parameters to consider when evaluating the total energy impact of a change in roof solar reflectance are: insulation R-value, climate, solar radiation, building use and type, and the efficiencies of heating and cooling equipment. For example, **the fuel cost savings for a change to a white roof surface decrease sharply with increases in the amount of roof insulation.**

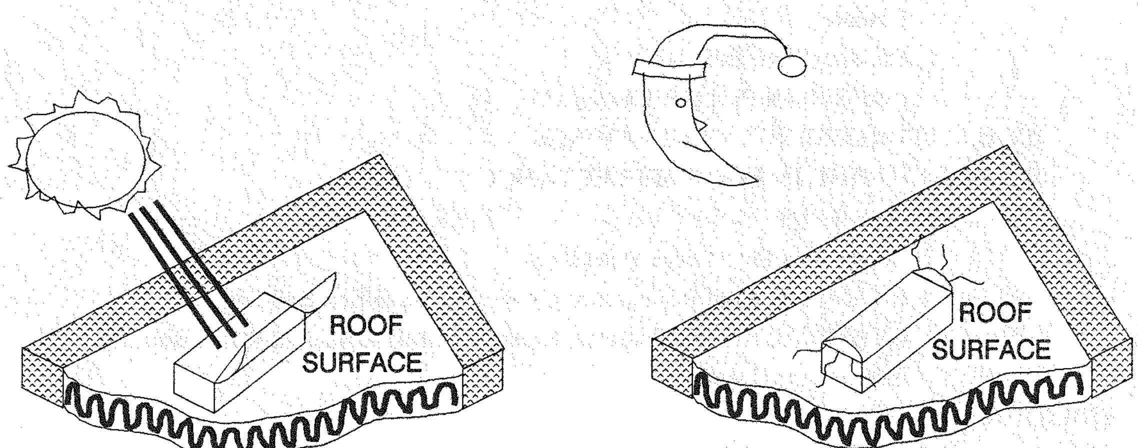
Roof surface aging generally decreases the solar reflectance of a white coating or membrane and increases the solar reflectance of an originally black one. Thus, the decreased effectiveness of an aged white surface compared to a black surface is underestimated if the simultaneous aging of the black surface is not taken into account.

Adding mass – for example, pavers or ballast – to the surface of a roof lowers the peak daytime membrane temperatures 10–20°F compared to a bare black membrane.



(a) (b)

In the summer, high solar reflectance helps keep the heat from the sun away from the building during the day (a), and high infrared emittance helps radiate heat away from the roof both day and night (b).



(a) (b)

In the winter, low solar reflectance helps to trap heat from the sun during the day (a), and low infrared emittance reduces heat radiated from the roof both day and night (b).

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PURPOSE

This guidebook describes a procedure that can be used to estimate changes in heating and cooling costs and the net energy cost difference for a building as a result of changing roof "color," or more technically roof solar reflectance.

The cost of heating and cooling a building is affected by roof color. A higher roof solar reflectance reduces the solar energy absorbed by the roof and therefore usually provides a reduction in the cost of air conditioning, while causing heating costs to increase. If the difference between reduced cooling costs and increased heating costs is significant, it can affect the choice of membrane for a new roof or a re-roofed building. This guidebook helps the user estimate this energy cost difference for his particular roof. It also describes how various factors influence potential energy savings and actual roof surface temperatures for different solar reflectances.

The guidebook is intended to be used by building owners, roofing contractors, or other interested individuals who wish to evaluate the energy cost impacts of different roof solar reflectances.

LIMITATIONS

The principal purpose of this document is to answer the question:

What is the net impact of increasing the solar reflectance of a roof on the energy use of a particular building?

It is intended to shed quantitative insight and aid in decision making; it is not intended to provide answers with scientific precision. The heating and cooling factors provided in this document are based on computer simulations of annual building energy use with typical meterological year weather data as input. These simulations kept some values as constants which would normally vary throughout the year as the weather changes. Also, some factors that would affect energy use were not included so that the procedure presented here could be kept simple. Accordingly, the following limitations are noted:

1. The roof's reflectance of solar energy throughout the year is characterized by a single value of solar reflectance and the reflection of sunlight is the same from all parts of the roof for all seasons.

2. The roof is dry. Any effect due to the presence of accumulated water as a liquid, frost, or snow is not treated.

3. The roof is totally exposed to the sky. No external shading such as trees or other structures was considered.

4. The infrared emittance is assumed to be the same for all surfaces.

5. Reference to a roof in this document indicates a near-flat roof. The construction consists of a metal deck, insulation, and an exterior waterproof covering. Pitched roofs and roofs over attic spaces are not covered. Cases presented do include that of a suspended ceiling below the roof assembly.

6. Changing roof reflectance can affect the energy use of a building and can also affect the size of heating or cooling equipment needed. A change in energy use or a change in equipment size can possibly lead to cost savings. Cost savings from a change in energy use could benefit both existing buildings and new building designs, while a cost savings from a change in equipment size would typically benefit new building designs. The savings evaluated here pertain only to the savings from changes in heating and cooling energy use, and potential equipment cost benefits would have to be evaluated separately.

A multitude of interrelated factors affect building energy use. Definition of periods of heating and cooling are determined by coupling of these factors. Correlations of computed results for selected conditions, such as those presented, are useful to show trends and help quantify effects; however, they cannot and should not be interpreted as exactly matching every unique setting.

This document is intended to provide a straightforward aid to users in estimating the energy conservation potential offered by use of reflective roofs. The data provided are based on computations using a widely accepted simulation code (DOE-2.1B) which has been corroborated by some experimental measurements. However, many considerations emerge when applying the technology of higher reflectance roof surfaces, and the procedure presented in this document is not intended to imply that analysis of changes in energy use from application of this technology is simple.

Section 1

ROOF REFLECTANCE AND ITS SIGNIFICANCE

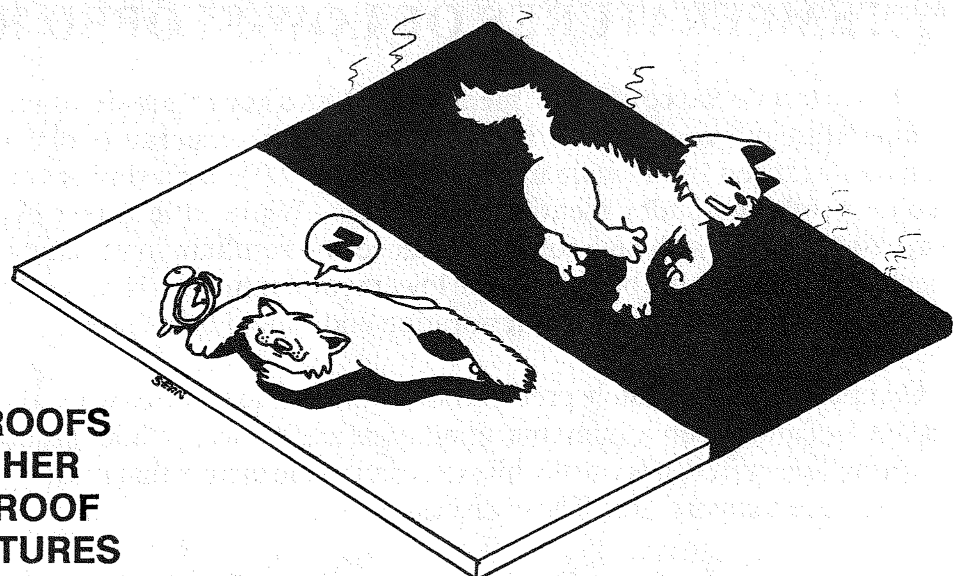
It is common experience that some sunlit objects become hotter than others. This is true for roofs. It is possible that one could comfortably touch one roof yet find the touch of another most uncomfortable under otherwise identical climatic conditions. Just how hot a roof gets depends on many factors and a major one is the roof surface solar reflectance.

Some roofs reflect the sun's rays better than others and hence do not get as hot. Highly reflective surfaces are often thought of as being "white." Dark-colored roofs, which generally have low reflectances, are typically much hotter than white roofs during daytime hours and can easily reach temperatures of 165°F during clear, sunny conditions.

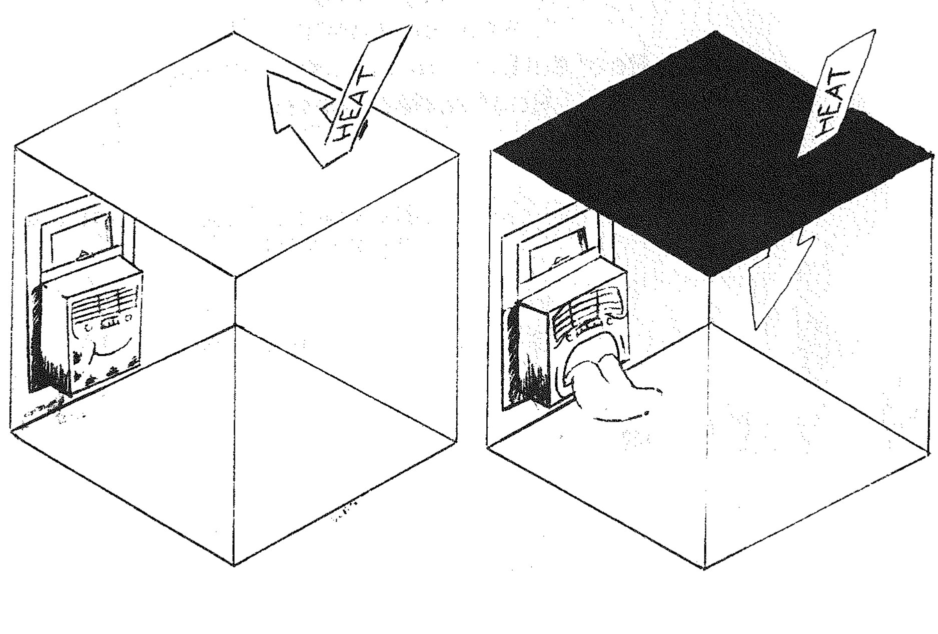
Roof solar reflectance affects daytime roof surface temperature and hence impacts building heating and cooling costs. The biggest temperature effect occurs during the day, when the sun heats the roof and increases the heat flow into the building. Heat flow into a building is an asset when building heating is needed and a liability when building cooling is needed. Hence, roof reflectance can effect energy savings by impacting heating and cooling energy requirements. In terms of energy needs, a white (highly-reflective) roof is preferred during sunlit hours when building cooling is needed and a black one is preferred during sunlit hours when building heating is needed. Thus, there is a counteracting influence of roof solar reflectance (color) on a building's heating and cooling energy requirements in many parts of the country.

The prevalence of asphaltic materials in built-up roofs means that many existing low-sloped roofs are black and have a low solar reflectance. Aggregate surfacing can increase the roof's reflectance. Roofs are also constructed using painted and unpainted metal roofs. Single-ply membranes are becoming more commonplace as a roof covering. With both painted roofs and membranes, a range of colors is available. Since low-sloped roofs constitute a significant portion of the overall thermal envelope of low-rise buildings and with the many available options for roof color, changing roof reflectance is now a viable option for reducing the energy costs of many buildings.

The most notable examples of reduced energy costs come from replacing black roofs by white roofs on buildings with high air conditioning loads. The prospects of reduced energy costs, along with the lower surface temperatures of white membranes, have been instrumental in creating a strong demand for high reflectance, white membranes. In general, white systems are more expensive. The cost differential is unique for a given situation and must be known by the decision maker. Thus, it is necessary to also provide a decision maker with a good estimate of the cost savings that will result for different reflectance options.



DARKER ROOFS MEAN HIGHER SUMMER ROOF TEMPERATURES



IN SUMMER, A DARKER ROOF CAN IMPOSE A HIGHER COOLING LOAD ON BUILDING COOLING SYSTEMS

Section 2

FACTORS INFLUENCING SURFACE TEMPERATURES OF LOW-SLOPED ROOFS

The solar reflectance of a roof membrane plays a key role in determining the daytime temperature of a roof. On a bright summer day the temperature of a black membrane can easily exceed 160°F while it can be as low as 100°F for a similar roof with a smooth white membrane under identical conditions. While little direct evidence exists to suggest that roofs with high solar reflectance and resultant lower daytime temperature peaks have a longer life because of the lower temperatures, it is generally felt that higher temperatures will accelerate deterioration and should be avoided.

Computers can accurately predict roof surface temperatures when the characteristics of the roof and the environmental conditions are known. While this degree of detail is not usually required, it is worthwhile to describe the factors that most significantly affect roof surface temperature. Those discussed are:

Roof surface color and texture
Solar intensity
Sky conditions
Roof insulation
Roof surface infrared emittance
Roof surface mass

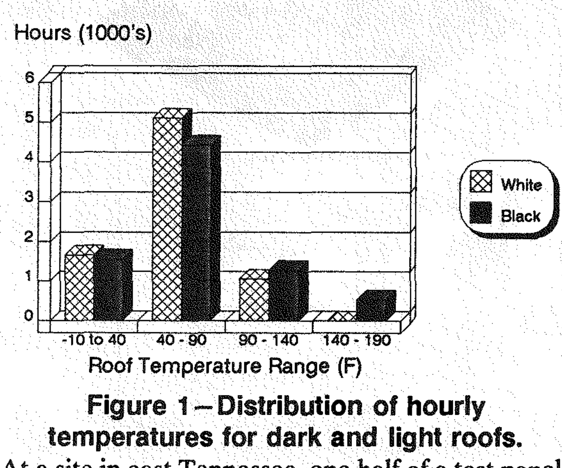


Figure 1 – Distribution of hourly temperatures for dark and light roofs.
At a site in east Tennessee, one half of a test panel was covered with a black EPDM membrane and the other half with a white EPDM membrane. The panel was insulated to R–7.5. The figure shows that, for 7824 hourly measurements within the period of March 1986 to March 1987, the white membrane had more hours at moderate temperatures and no hours at 140–190°F.

ROOF SURFACE COLOR AND TEXTURE

It is well known that a dark colored membrane absorbs more solar energy than a light colored one. One property that characterizes this effect is the "solar reflectance." If incident solar energy is totally absorbed the surface has a reflectance of zero and if it is totally reflected it has a reflectance of one. All materials have values somewhere between zero and one. The solar reflectance of several common materials is given in Appendix B. Color is a fairly good indicator of solar reflectance. Dark surfaces have low solar reflectance and light surfaces high solar reflectance. Texture also is significant in determining the solar reflectance of a surface. Generally, light reflecting from a rough surface has a better chance of striking the surface a second time – and therefore being absorbed – than light from a smooth surface. Thus, other things being equal, a rough surface will have a lower solar reflectance and therefore will be warmer in sunlight than a smooth surface. Aging, either from chemical changes in a membrane or from dirt or contaminants in the air, usually tends to drive roof surfaces toward the color gray. Thus, initially white roofs with high solar reflectance tend toward lower reflectances and higher temperatures while initially black roofs with low solar reflectance tend toward a higher reflectance and lower temperatures.

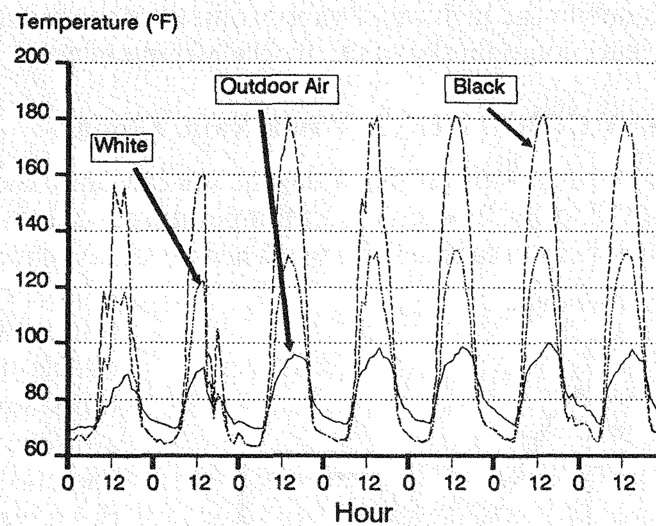


Figure 2 – Comparison of surface temperatures for white and black roof membranes, July 15–21, 1986.
The difference between the peak temperatures of white and black membranes during typical hot summer conditions is pronounced, as shown above. These temperature measurements are from the data summarized in Fig. 1.

SOLAR INTENSITY

The sun is the primary energy source for a roof surface that is heated above the ambient air temperature. The amount of useful sunlight varies with time of year, and with location and local weather peculiarities. In general, southern sites and mountainous regions have more useful sun and therefore higher roof temperatures. In many instances, however, local high cloud cover or high humidity absorb solar radiation and significantly reduce the amount of useful sunlight. For example, February useful sunlight in New Orleans, LA, on the Gulf coast is about the same as in Laramie, WY, and in the summer it is actually about 30 percent less. This

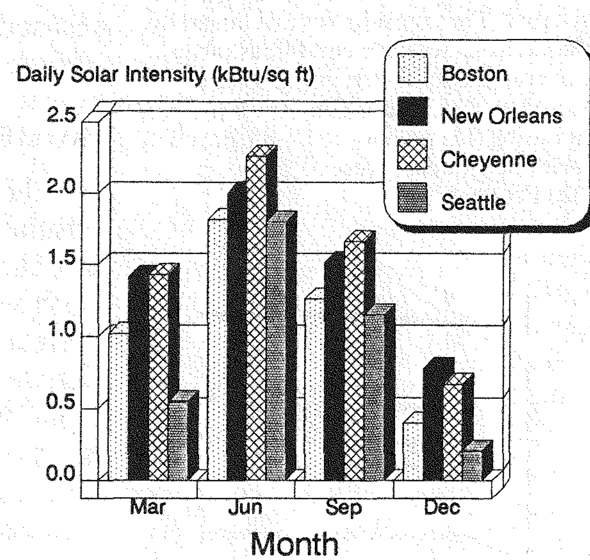


Figure 3 – Comparison of solar intensity.
The data on average solar energy for each month for the 4 cities show that differences during the summer are not as different as might be expected for climates that are noticeably different. Lower winter solar energy in some climates means that increases in heating energy use for buildings with white membranes would be smaller.

is due to the high water vapor content of the air along the Gulf Coast compared to the clear mountain sky of the Rocky Mountain area.

SKY CONDITIONS (Wind, Rain, Clouds)

During a warm summer day the sun can cause the temperature on a dark roof to reach 160°F to 180°F when the air temperature is only 80°F to 90°F. Since the roof is not very massive and cannot store much heat, events such as a quick shower, a cool wind, or even a large cloud can lead to reductions in roof temperatures. Exact calculation of the effects of these rapid changes on particular roofs are difficult to carry out because they are such irregular phenomena. The chart to the left shows the approximate effect of wind. For a black built-up roof the maximum peak temperature during a week of hot summer weather can be 5–10°F lower when the wind increases from 0 to 10 mph, and 25–30°F lower in a 20 mph wind. Note that for a high-solar-reflectance white roof, the initial difference between surface temperature and air temperature is reduced. Therefore, the magnitude of rapid temperature changes caused by sky conditions will be much less severe for a white roof than for a black roof.

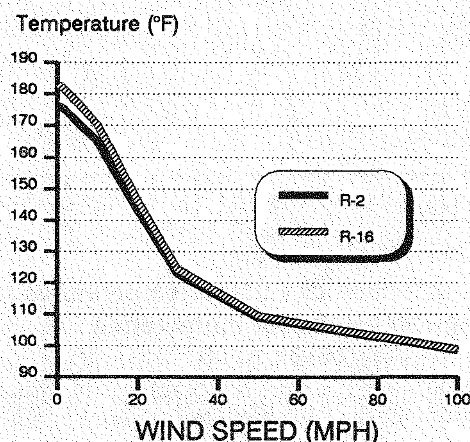


Figure 4 – Effect of wind.
The effect of wind speed on maximum membrane temperature is shown in this figure for a black roof. These results were obtained by simulation using weather conditions taken from the same data shown in Fig. 1 for a week in May 1986. The maximum air temperatures during this week were 80–85°F, and the solar energy peaks were 300–320 Btu/hr-ft^2.

ROOF INSULATION

Other things being equal a roof with more insulation will have less heat carried from the roof into a building on a sunny day than a roof with less insulation and this should cause it to have a higher surface temperature. The magnitude of the surface temperature depends upon the amount of insulation. As can be seen in Fig. 5, after even a small amount of insulation has been added to a roof, further increases have little effect on the temperature. The reason is that the surface temperature depends upon the net exchange of energy between the roof surface and the outdoor and indoor environments. As the amount of roof insulation is increased, the surface becomes more shielded from energy exchange with the indoor environment (conditioned space), and the surface temperature is controlled by

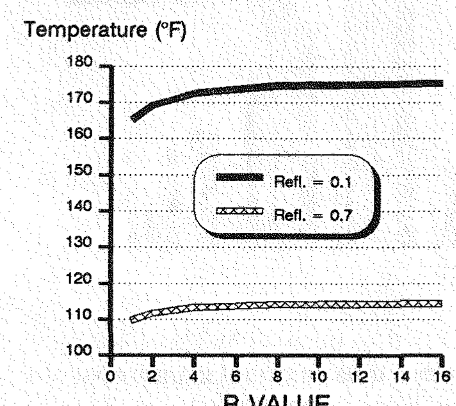


Figure 5 – Effect of R-value.
Using the same data as shown in Fig. 4, the effect of changes in R-value on maximum membrane temperature for a black membrane were modeled and are shown for two values of reflectance.

external influences such as solar energy, wind, rain, and outdoor air temperature. Note, however, that insulation increases still have an impact on fuel bills. That is, if the insulation is doubled, the peak daytime surface temperature may only decrease a few degrees, but the heat loss or gain (and costs for resulting heating or cooling energy) will still be approximately halved.

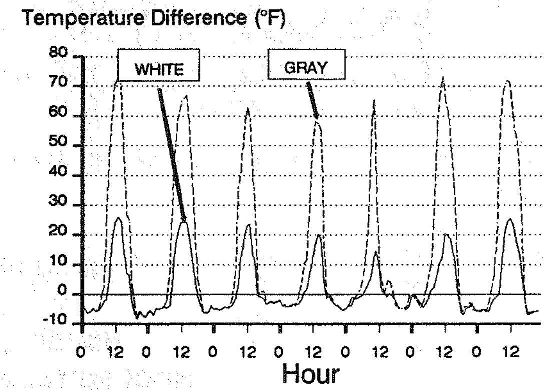


Figure 6—Effect of infrared emittance. The effect of infrared emittance at night can be seen in this figure. Solar energy heats the roof to significant temperature differences between the roof surface and ambient air during the day, but the temperature difference is often negative at night—indicating that the roof is cooled below the air temperature. The night cooling effect is shown to be nearly identical for white and gray roofs. The data are for the week of August 2, 1988.

ROOF SURFACE INFRARED EMITTANCE

A roof surface radiates infrared energy to the sky and the surroundings. During the day incident solar energy more than makes up for this infrared radiation, and a roof can be heated well above the ambient air temperature. During the evening, however, with no solar radiation, the loss of radiant energy to the sky can cool a roof below the ambient air temperature. Evening surface temperatures 20°F below air temperatures on clear, low humidity nights are common for well insulated roofs. While radiant cooling of a roof will increase the nighttime heat loss, the effect is not included in the calculations of this manual because most roofing materials have about the same infrared radiation properties even though their solar radiation properties can be quite different.

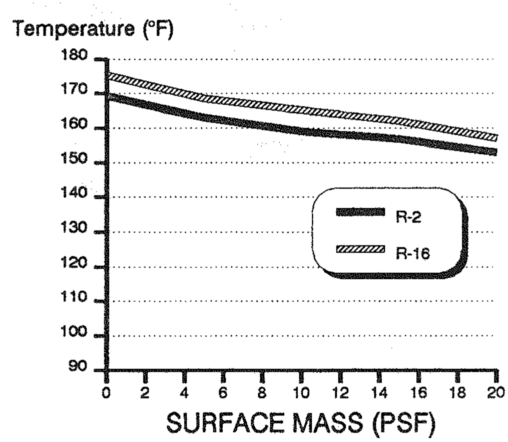


Figure 7—Effect of surface mass. Using the same data as in Figs. 4 and 5, the effect of surface mass on peak membrane temperature during a week was modeled, and the results are shown here.

ROOF SURFACE MASS

When mass is added to the surface of a roof, such as with paver blocks or gravel ballast, it acts as a thermal flywheel. Its effect on roof temperatures is to smooth out the variations from day to night. This results in lower peak temperatures than would be found with a bare roof. Figure 7 shows peak membrane temperatures calculated for roofs with various amounts of surface mass. This figure shows that peak membrane temperature is reduced as the amount of surface mass increases and added surface mass has a substantially larger effect than the effect of changes in roof insulation level.

Section 3

FACTORS THAT AFFECT THE ENERGY SAVINGS AVAILABLE FROM CHANGING ROOF SOLAR REFLECTANCE

The energy savings achievable by changing roof reflectance is predominantly influenced by:

R-value of roof insulation
Climate
Building type and use
Roof surface property changes

Each of these factors have varying degrees of influence on the potential for energy cost reductions resulting from reflectance change. The effect of surface mass (e.g., ballast) is discussed in Appendix E.

R-VALUE OF ROOF INSULATION

The amount of roof insulation is a major factor influencing the energy savings potentially available from a change in roof reflectance. If a roof is well insulated, little heat is transported between the roof surface and the building interior. Thus, although a change in roof reflectance changes the roof surface temperature, the building energy use will experience little impact.

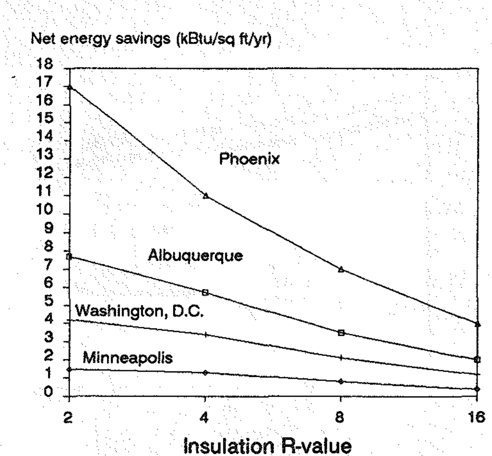


Figure 8—Effect of R-value on net energy savings for an increase of 0.5 in roof reflectance.
The effect of R-value on the net energy savings (cooling savings minus heating penalty) due to changing roof reflectance is dramatic. These impacts are shown here for four diverse climates.

The influence of insulation on the savings from changes in roof reflectance is shown in Fig. 8. Reflectance change will reduce energy costs the most for lower roof insulation levels. In cooling dominated climates, reductions in energy savings can also be significant for higher levels of roof insulation.

CLIMATE

Climate has a strong influence on both building energy use and on the resulting energy savings available from changing roof reflectance. Since climate often dicates the size of the energy bill, it also affects the size of potential savings from reflectance change. Outdoor temperatures, solar radiation, and wind speed are significant climate factors.

Increasing roof reflectance results in a reduced summer cooling load and an increased winter heating load. Since there is a tradeoff, an increase in roof reflectance is typically most beneficial in hot climates where cooling load dominates most of the the year. Climate effects on energy savings from reflectance change is illustrated in Fig. 9. This figure shows that potential savings are greatest in cooling season dominated climates. For the building configurations and climates examined for this work, the reduction in cooling load always exceeded the increase in heating load, but the distinction was small in nothern climates. This trend does not imply that white is always better than black, because the benefits of savings must be compared to the relative costs of the white and black materials.

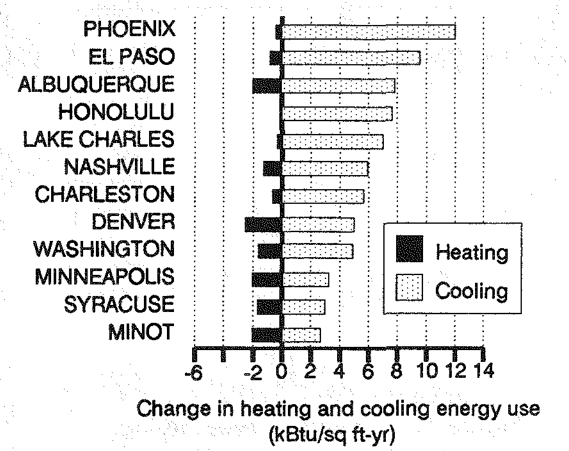


Figure 9 – Climate effect on energy savings for a change of 0.5 in roof reflectance. These results are for a roof R-value of 4.

BUILDING TYPE AND USE

Different buildings use differing amounts of energy and, therefore, will benefit differently from roof reflectance change. Energy intensive buildings such as office or retail buildings often have large internal loads which extend the buildings cooling season. These building types could benefit even more from increasing roof reflectance since energy savings are most significant in cooling dominated climates.

In high-rise buildings, the roof makes up a small portion of the above-ground building shell. Although savings can justify a reflectance change for these buildings, the magnitude of savings will be small in comparison to the buildings total energy bill. In low-rise buildings, however, the roof area can easily compose from 50 to 75% of the above-ground shell. Thus, the roof can be a major contributor to energy losses and gains, and savings from roof reflectance change may significantly reduce the buildings total energy bill (Fig. 10).

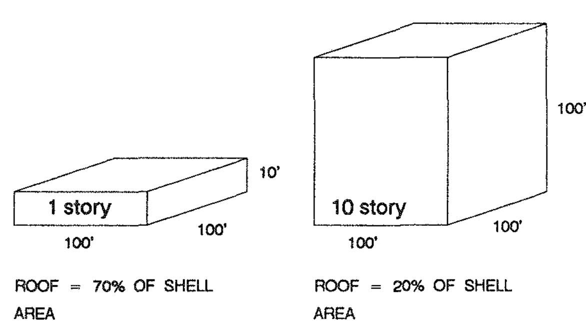


Figure 10 – Comparison of relative roof area. A savings will result for both buildings for a given roof reflectance change, but the relative savings for a low-rise building will be larger.

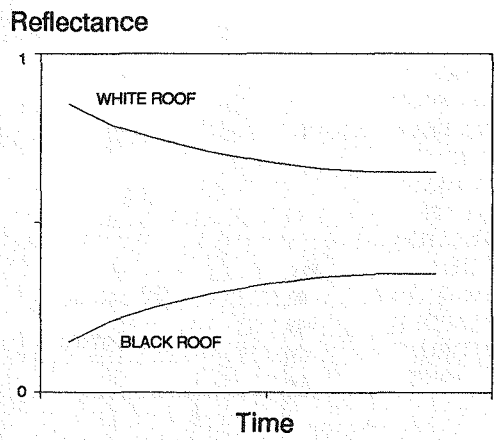


Figure 11 – Effects of weathering. Weathering tends to reduce the reflectance of a light roof and increase the reflectance of a dark roof.

ROOF SURFACE PROPERTY CHANGES

The solar reflectance of a roof changes over time, thus changing the performance of the roof as orignally installed. ORNL experience has shown that a black asphaltic surface becomes more reflective and that a white roof surface tends to become less reflective. This change is likely due to surface contamination, chemical reactions, and other factors. These changes can be either beneficial or detrimental to a building's energy demands.

Quantifying the change in a roof's reflectance during its life can be very difficult. If this change can be quantified, then this guide provides a method for evaluating its impact on energy use. If a user wishes to make estimates of the degradation of roof reflectance, this guide can also be used to study energy use impacts of a range of estimated changes in reflectance.

Section 4

EVALUATING ENERGY COST SAVINGS FROM A CHANGE IN ROOF REFLECTANCE

This guide provides a method for the user to estimate the cost savings from a change in roof reflectance. Steps to estimating these savings include:

- Selection of building type and climate data
- Determination of roof insulation R-value
- Determination of local energy costs and HVAC system efficiencies
- Determination of the change in roof reflectance
- Selection of the heating and cooling factors
- Completing the savings worksheet to estimate annual energy and cost ($) savings

DATA REQUIREMENTS

Selection of Building Type and Climate Data

A building type, Ia, Ib, IIa, IIb, or III should be selected that best represents the building being evaluated. The building types are:

I. A building with a ceiling plenum space (typically used for concealing HVAC duct and related equipment between the ceiling and the roof)
(a) Normal activity, e.g., normal occupancy and equipment loads
(b) High activity, e.g., high occupancy or high equipment loads

II. A building without a ceiling plenum
(a) low activity and loads, e.g., a conditioned storage area
(b) high activity and loads, e.g., a retail area

III. Energy intensive buildings or spaces (with or without a ceiling plenum), i.e., buildings which normally consume large amounts of energy per square foot such as:
a) restaurant areas with high cooking loads
b) office building areas with high equipment loads
c) industrial building areas with high equipment loads
d) some hospital areas, and potentially other buildings.

The building choice determines which of the sets of Cooling/Heating Factors tables (or figures) listed in Appendix D should be used.

Based on simulation results, these five building categories should represent most buildings reasonably well for an evaluation of energy savings related to roof reflectance change (see Appendix F).

The appropriate climate data, heating and cooling degree days and solar radiation values, can be selected from Appendix A. If the particular city of interest is not listed, data for the nearest city listed would be appropriate provided that a dramatic difference does not exist between climates. Solar radiation data listed in Appendix A do not consider the effects of water, snow, or shading on the annual global radiation received by a roof. The presence of snow tends to increase the benefits of a higher roof solar reflectance relative to a lower solar reflectance. Rain and shading tend to decrease the benefits. (See Interpreting Results discussion at the end of this section.)

Determination of Roof Insulation R-Value

The R-value required is the value for the roof insulation only since in most cases, insulation R-value dominates the total R-value of a roof. Typical R-values of common roofing materials are provided in the sidebar. These values are on a per inch basis and therefore must be multiplied by the insulation thickness if the table is used. Various sources are available if a more detailed list of roofing materials is needed. The NRCA *Roofing Materials Guide*[1] is a suggested source. If the roof has multiple layers of insulation, the total R-value is the sum of individual R-values for each layer, i.e., R (total) = R1 + R2 + ..., etc.

INSULATION R-VALUES*

Insulation Type	R/inch (nominal) (hr-ft^2-°F/Btu-in)
Fiberglass	4.0
Expanded polystyrene	3.8
Extruded polystyrene	5.0
Phenolic	8.3
Isocyanurate	5.8-7.2
Fiberboard	2.8
Perlite	2.8

For homogenous insulation, the total R-value is:

Total R = R/inch x thickness (inches)

*The R/inch values vary for different manufacturers. Actual values should be obtained from manufacturer literature or the Roofing Materials Guide published by the NRCA (see footnote below).

Determination of Local Energy Costs and HVAC System Efficiencies

The energy cost savings that result from a change in roof reflectance will vary with local energy rates. Doubling the local cost for energy would double the estimate of savings. Thus, savings will be dependent on local per unit energy costs and any

1 *Roofing Materials Guide* (semiannual). National Roofing Contractors Association, Sect. 3, Rosemont, Illinois

reduction in demand-related charges. Savings estimated using this guide include demand-related savings if energy costs in Appendix B are used. If local energy costs are used and demand reductions are not accounted for, savings estimates generated using this guide will be conservative.

If a particular building uses different fuel types for summer cooling and winter heating, such as electric cooling and gas heating, increasing roof reflectance may be desirable even in an area where there is a substantial heating season. This could occur if the cost per unit of energy is significantly less for the heating fuel (e.g., gas) than for the cooling fuel (e.g., electricity), thus reducing the heating penalty relative to the cooling dollars saved as a result of increasing roof reflectance. If there is a substantial difference between cooling and heating fuels, a building in a climate that is not dominated significantly by the heating or cooling season may still produce substantial savings from roof reflectance change.

Energy costs should be obtained from local utilities. For electricity, the average cost per kWh should be obtained for the particular building size. This number is an average kWh cost based on standard kWh cost and typical demand costs for the particular building size. For rough approximations, average per unit energy costs can be taken from Appendix B. Note that these costs are for 1985 and may not be appropriate as listed. If these values are slightly out of date, an estimated escalation (a percent increase) could be applied to approximate current values. Cost histories may need to be examined here since projecting energy cost increases over long periods can lead to major errors.

Heating and cooling (HVAC) system operational costs are based on the amount of energy consumed by the heating or cooling system, but the increase in heating and decrease in cooling energy computed here represent what the HVAC system must add or remove from the building space. The energy added to or removed from the building space divided by the energy consumed by the HVAC system may be called the efficiency (heating) or COP (cooling). Efficiencies and COPs can have a wide range of values, depending on the type, age, condition, and size of the HVAC equipment. The efficiencies or COPs for the building systems being evaluated should be obtained from actual data on the systems if possible. If these are not available, using a cooling COP of 1.7 for older unitary (cooling) equipment or 2.2 for newer unitary equipment and a heating system efficiency of 75% for fossil fuel systems or 190% for heat pumps is recommended.

Determination of the Change in Roof Reflectance

The change in roof reflectance to be examined is determined based on manufacturer's data, values from Appendix C, or other estimates. Changes in surface infrared emittance are not considered in this guide for evaluating savings. This is done since surface infrared emittance has little dependence on surface color (solar reflectance).

Selection of the Heating and Cooling Factors

Heating and cooling energy factors can be selected from Appendix D. Using the appropriate table, these factors should be determined based on heating degree days, cooling degree days, and insulation R-value. Heating and cooling energy factors were developed using the computer-based building energy use simulation program DOE-2.1B (see Appendix F). This program incorporates a dynamic model which simulates building performance on an hourly basis. The program accounts for dominant factors that influence the energy use of a building including building construction, building mass, HVAC systems, weather, internal loads, and operational schedules. The variations found in these factors for different buildings resulted in the generalized building types of this guide.

COMPLETING THE SAVINGS WORKSHEET

The savings worksheet for calculating energy cost savings as a result of roof reflectance change is shown on the next page. The worksheet should be completed as follows:

Site Information

Enter the selected building type.

Enter the building location and corresponding climate data (the solar radiation value is entered in box [1] of Calculation of Estimated Energy Savings).

Enter the roof's insulation R-value and its surface area (surface area is entered in box [2] of Calculation of Estimated Energy Savings).

Cost of Energy for Heating and Cooling

A-B. Enter HVAC system performance data, COP and efficiency.

C-D. Enter energy costs by type in $/million Btu's
(1 therm = 0.1 million Btu and 293 kWh or 7.15 gal. of #2 oil = 1 million Btu).

E-F. Calculate cooling and heating energy costs.

Calculation of Estimated Energy Savings

3. Enter the proposed change in roof reflectance.

4-5. Enter the appropriate heating and cooling factors from Appendix D.

6-7. Calculate estimated changes in heating and cooling energy.

Annual Cost Savings Estimate

8-10. Calculate estimated cooling cost reduction, heating cost increase, and net annual savings in dollars.

ENERGY SAVINGS ESTIMATES FOR HIGHER ROOF SOLAR REFLECTANCE

WORKSHEET

SITE INFORMATION

Building Type: ________________ Cooling Degree Days ________ (Appendix A)

Location: ____________________ Heating Degree Days ________ (Appendix A)

Roof Insulation R-value (hr-ft^2-^{o}F/Btu): ____ Solar Radiation ________ (Appendix A)

COST OF ENERGY FOR HEATING AND COOLING

(A) COOLING SYSTEM COP	(B) HEATING SYSTEM EFFICIENCY (%)	(C) COOLING FUEL COST ($/10^6 Btu)	(D) HEATING FUEL COST ($/10^6 Btu)	(E) COOLING ENERGY COST ($/10^6 Btu) [C / A]	(F) HEATING ENERGY COST ($/10^6 Btu) [(D / B) x 100]
specified by user	specified by user	specified by user or App. B	specified by user or App. B		

For calculation of energy costs: electricity – $/10^6 Btu = ¢/kWh x 2.93
natural gas – $/10^6 Btu = ($/therm or $/CCF) x 10 #2 fuel oil – $/10^6 Btu = $/gal x 7.15

CALCULATION OF ESTIMATED ENERGY SAVINGS

(1) SOLAR RADIATION (Btu/ft^2/day)	(2) ROOF AREA (ft^2)	(3) CHANGE IN REFLEC-TANCE	(4) COOLING ENERGY FACTOR	(5) HEATING ENERGY FACTOR	(6) DECREASE IN COOLING ENERGY (10^{6}Btu/yr) (1 x 2 x 3 x 4) / 10^6	(7) INCREASE IN HEATING ENERGY (10^{6}Btu/yr) (1 x 2 x 3 x 5) / 10^6
App. A	specified by user	specified by user	App. D	App. D		

ANNUAL COST SAVINGS ESTIMATE

(8) COOLING COST REDUCTION ($/YR) 6 x E	(9) HEATING COST INCREASE ($/YR) 7 x F		(10) NET COST SAVINGS ($/YR) 8 – 9
		=	

EXAMPLE: Roof Reflectance Change for an Office Building

A small office building in Albuquerque has 5,000 square feet of low-sloped roof. Re-roofing is being planned and use of a light-colored membrane having an estimated solar reflectance of 0.7 is being considered as opposed to a dark membrane with an estimated solar reflectance of 0.2. The lighter membrane will cost 20 cents more per sq. ft. ($1000 added). The insulation R-value of the new roof will be 4 ft^2-hr-°F/Btu. The building is electrically cooled and gas heated. The building has a ceiling plenum used to conceal air distribution ducts.

Part A. Will energy cost savings from the light-colored membrane pay back it's added cost within five years?

Solution

The building has a ceiling plenum and is not an intensive energy user. Thus, building Type Ia most nearly matches this building. Instead of obtaining current local energy costs, the user decides to use the energy cost rates provided in Appendix B as approximations. The estimated change in solar reflectance is 0.7 - 0.2 = 0.5. The worksheet is completed as shown on the opposing page.

Conclusions

The roof reflectance change reduces energy use by 26.9 MBtu/year providing a net annual energy cost savings of approximately $644/year. Payback of the additional expense of the light membrane will occur in 1.6 years ($1000 / $644). Although Albuquerque has a heating-season dominated year, savings from increasing roof reflectance are still substantial, and the payback period is less than five years.

Part B. Assume that the roof insulation for this building was R-8 instead of R-4 as in Part A above. Will the energy cost savings from the light-colored membrane still pay back within five years?

Solution

The new values needed in Part A as a result of the increased R-value of the roof are:

R-Value = 8
Cooling Factor = 5.2 (Appendix D)
Heating Factor = 1.25 (Appendix D)

Conclusions

Changing these values on the worksheet results in a savings of $410 as a result of the reflectance change. Payback of the additional expense of the light membrane occurs in 2.5 years ($1000 / $410 = 2.5). The payback occurs within five years for a roof R-value of 8 as well.

ENERGY SAVINGS ESTIMATES FOR HIGHER ROOF SOLAR REFLECTANCE
WORKSHEET

SITE INFORMATION

Building Type: Iq - Office

Location: Albuquerque

Roof Insulation R-value (hr-ft^2-°F/Btu): 4

Cooling Degree Days: 1316 (Appendix A)

Heating Degree Days: 4291 (Appendix A)

Solar Radiation: 1828 (Appendix A)

COST OF ENERGY FOR HEATING AND COOLING

(A) COOLING SYSTEM COP	(B) HEATING SYSTEM EFFICIENCY (%)	(C) COOLING FUEL COST ($/10^6 Btu)	(D) HEATING FUEL COST ($/10^6 Btu)	(E) COOLING ENERGY COST ($/10^6 Btu) [C / A]	(F) HEATING ENERGY COST ($/10^6 Btu) [(D / B) x 100]
1.7	75	31.9 (elec.)	4.7 (gas)	18.8	6.27
specified by user	specified by user	specified by user or App. B	specified by user or App. B		

For calculation of energy costs: electricity – $/10^6 Btu = ¢/kWh x 2.93

natural gas – $/10^6 Btu = ($/therm or $/CCF) x 10 #2 fuel oil – $/10^6 Btu = $/gal x 7.15

CALCULATION OF ESTIMATED ENERGY SAVINGS

(1) SOLAR RADIATION (Btu/ft^2/day)	(2) ROOF AREA (ft^2)	(3) CHANGE IN REFLEC-TANCE	(4) COOLING ENERGY FACTOR	(5) HEATING ENERGY FACTOR	(6) DECREASE IN COOLING ENERGY (10^{6}Btu/yr) (1 x 2 x 3 x 4) / 10^6	(7) INCREASE IN HEATING ENERGY (10^{6}Btu/yr) (1 x 2 x 3 x 5) / 10^6
1828	5,000	0.5	8.3	2.4	37.9	11.0
App. A	specified by user	specified by user	App. D	App. D		

ANNUAL COST SAVINGS ESTIMATE

(8) COOLING COST REDUCTION ($/YR) 6 x E	(9) HEATING COST INCREASE ($/YR) 7 x F		(10) NET COST SAVINGS ($/YR) 8 – 9
712	69	=	643

EXAMPLE: Roof Reflectance Change for Industrial and Retail Buildings

A supplier has suggested that he can coat smooth-surfaced roofs with a highly-reflective coating that will have attractive savings. The supplier claims the coating can be applied for a total cost of 20 cents/ sq. ft. and will increase the solar reflectance of a black roof by 0.6.

The owner of a manufacturing and retailing business is interested in the product. The specifications of the owner's buildings are:

Case 1. Industrial manufacturing building located in Minneapolis, Minn. The building has 7,000 sq. ft. of roof insulated to R-8 and does not have a ceiling plenum.

Case 2. Retail sales building located in Dallas, Texas. The building has 10,000 sq. ft. of roof insulated to R-8 and has a ceiling plenum.

Both buildings are electrically cooled and gas heated. If the owner requires a payback on the investment of two years, will the coating be acceptable to the owner if it can perform as claimed?

Solution: Case 1

The building is for industrial manufacturing and has extensive machinery. The building is best described by Building Type III. The coating will cost $1400 ($0.20/sq. ft. x 7,000 sq. ft.). The worksheet is completed as shown on the opposing page.

Conclusion: Case 1

Using the heating and cooling costs provided in Appendix B, the roof reflectance change reduces the net annual energy cost for the building by approximately $285. The payback is substantially longer than the two years required by the owner ($1400 / $285 = 4.9 years).

Solution: Case 2

The building has a ceiling plenum, is operated 7 days per week, and has large cooling loads due to extensive lighting. The building is best described by Building Type Ib. Per Appendix B, average energy costs are 9.9 cents/kWh for electricity and 54 cents/CCF for gas. The appropriate worksheet data for this building is enclosed in parentheses on the opposing worksheet for comparison to Case I.

Conclusions: Case 2 and Comparison

Using the heating and cooling costs provided in Appendix B, the roof reflectance change reduces the net annual energy cost for the Case 2 building by approximately $1175. The coating will cost $2000 ($0.20/sq. ft. x 10,000 sq. ft.). If the roof's reflectance is increased by 0.6, the energy cost savings will easily meet the owners requirement of investment payback within two years ($2000 / $1175 = 1.7) if local energy costs are comparable to those used from Appendix B. Although the building types are different, the difference in climate is the main reason for the dramatic savings difference between Cases 1 and 2.

ENERGY SAVINGS ESTIMATES FOR HIGHER ROOF SOLAR REFLECTANCE
WORKSHEET

SITE INFORMATION

Building Type: III Industrial (Ib) (Retail)   Cooling Degree Days 585 (2754) Appendix A

Location: Minneapolis (Dallas)   Heating Degree Days 8158 (2290) Appendix A

Roof Insulation R-value (hr-ft^2-°F/Btu): 8   Solar Radiation 1170 (1468) Appendix A

COST OF ENERGY FOR HEATING AND COOLING

(A) COOLING SYSTEM COP	(B) HEATING SYSTEM EFFICIENCY (%)	(C) COOLING FUEL COST ($/10^6 Btu)	(D) HEATING FUEL COST ($/10^6 Btu)	(E) COOLING ENERGY COST ($/10^6 Btu) [C / A]	(F) HEATING ENERGY COST ($/10^6 Btu) [(D / B) x 100]
1.7	75	19.8 (29.0)	6.08 (5.4)	11.6 (17.1)	8.1 (7.2)
specified by user	specified by user	specified by user or App. B	specified by user or App. B		

For calculation of energy costs: electricity – $/10^6 Btu = ¢/kWh x 2.93

natural gas – $/10^6 Btu = ($/therm or $/CCF) x 10   #2 fuel oil – $/10^6 Btu = $/gal x 7.15

CALCULATION OF ESTIMATED ENERGY SAVINGS

(1) SOLAR RADIATION (Btu/ft^2/day)	(2) ROOF AREA (ft^2)	(3) CHANGE IN REFLECTANCE	(4) COOLING ENERGY FACTOR	(5) HEATING ENERGY FACTOR	(6) DECREASE IN COOLING ENERGY (10^{6}Btu/yr) (1 x 2 x 3 x 4) / 10^6	(7) INCREASE IN HEATING ENERGY (10^{6}Btu/yr) (1 x 2 x 3 x 5) / 10^6
1170 (1468)	7000 (10,000)	0.6	5 (7.8)	0 (0)	24.6 (68.7)	0 (0)
App. A	specified by user	specified by user	App. D	App. D		

ANNUAL COST SAVINGS ESTIMATE

(8) COOLING COST REDUCTION ($/YR) 6 x E	(9) HEATING COST INCREASE ($/YR) 7 x F		(10) NET COST SAVINGS ($/YR) 8 – 9
285 (1175)	0 (0)	=	285 (1175)

INTERPRETING RESULTS

The information included in this document provides a method for estimating the savings for a change in roof solar reflectance and shows that savings decrease with increased roof insulation R-value. However, the factors provided here do not account for changes in heating or cooling energy use caused by changes in R-value of roof insulation. The factors do account for the interactive effect of roof insulation R-value on potential savings from a change in roof solar reflectance. Therefore, the data presented here cannot be used to evaluate effects of insulation R-value on energy use or costs, and the user can only evaluate impacts from solar reflectance given a roof insulation R-value as a starting point.

In terms of dollar savings, increasing roof reflectance may or may not be cost effective. A positive dollar savings indicates reduced energy costs from the reflectance increase. A negative result indicates an increase in energy costs and thus a penalty for the increase in roof reflectance. Users must evaluate the benefits of the cost savings and the costs of achieving the increased roof reflectance to determine whether an investment in the increased reflectance is attractive.

Because the effects of snow, rain, and shading are not explicitly addressed in the heating and cooling factors or in the solar radiation data, some adjustments to the estimates of changes in heating and cooling energy due to increased roof reflectance may be required if snow, rain, or shading are judged to have a significant impact. Snow tends to increase benefits, and thus the savings estimates will be more conservative if snow is ignored. Rain will have an impact on savings, but if most of the daytime hours during the cooling season do not have rainfall, the effects of rain can usually be ignored. Significant shading on the roof (more than 10% shaded for most of the middle six hours of the day) by trees, buildings, or other causes must be considered, and the judgment of a professional is probably required to make an estimate of the impacts of significant shading.

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Appendix A
WEATHER DATA

(Data are from Knapp et al, 1980 – see Bibliography. More specific data may be obtained from NOAA, Asheville, NC, a utility, or a local university.)

	Annual Cooling Degree Days (65 base)	Annual Heating Degree Days (65 base)	Annual Average Solar Radiation (avg. total daily, Btu/ft^2-day)
ALABAMA			
Birmingham	1928	2844	1344.7
Mobile	2576	1683	1384.7
Montgomery	2237	2268	1387.9
ALASKA			
Annette	13	7052	794.6
Barrow	0	20264	595
Bethel	0	13203	732.4
Bettles	16	15925	765.4
Big Delta	32	13698	811.5
Fairbanks	50	14342	767.8
Gulkana	9	13936	832.2
Homer	0	10363	837.6
Juneau	0	9005	682.7
King Salmon	0	11584	793.9
Kodiak	0	8860	796.7
Kotzebue	0	16038	744.8
McGrath	13	14486	733.5
Nome	0	14324	737.6
Summit	0	14368	761.3
Yakutat	0	9533	663.9
ARIZONA			
Phoenix	3506	1552	1869.4
Prescott	882	4455	1813.3
Tucson	2813	1751	1872.3
Winslow	1202	4732	1801.9
Yuma	4194	1010	1923.7
ARKANSAS			
Fort Smith	2021	3335	1404.1
Little Rock	1924	3353	1404.4
CALIFORNIA			
Bakersfield	2178	2183	1749.2
Daggett	2729	2201	1842.8
Fresno	1670	2650	1710.8
Long Beach	985	1606	1597.7
Los Angeles	614	1818	1593.8
Mount Shasta	284	5890	1491
Needles	4235	1427	1861
Oakland	128	2909	1535.2
Red Bluff	1903	2687	1581.1
Sacramento	1157	2842	1642.9
San Diego	722	1507	1598
San Francisco	108	3042	1552.8
Santa Maria	83	3053	1607.9
COLORADO			
Colorado Springs	461	6473	1594.1
Denver	625	6016	1568.4
Eagle	117	8426	1594.3
Grand Junction	1139	5603	1658.7
Pueblo	981	5393	1622.7
CONNECTICUT			
Hartford	583	6349	1058.3
DELAWARE			
Wilmington	992	4939	1207.7
DISTRICT OF COLUMBIA			
Washington	940	5009	1208.4
FLORIDA			
Apalachicola	2662	1361	1473.8
Daytona Beach	2918	902	1458.1
Jacksonville	2596	1327	1438.2
Miami	4037	205	1472.9
Orlando	3226	733	1486.7
Tallahassee	2561	1562	1432.6
Tampa	3366	716	1492.1
West Palm Beach	3785	299	1438.1
GEORGIA			
Atlanta	1588	3094	1345.3
Augusta	1994	2547	1361.6
Macon	2293	2239	1379.2
Savannah	2317	1951	1364.5

HAWAII			
Hilo	3065	0	1385.1
Honolulu	4221	0	1638.7
Lihue	3719	0	1524.2
IDAHO			
Boise	713	5832	1495.5
Lewiston	657	5463	1210.1
Pocatello	436	7061	1529.2
ILLINOIS			
Chicago	923	6125	1215.1
Moline	893	6394	1223.6
Springfield	1116	5557	1301.5
INDIANA			
Evansville	1363	4628	1261.8
Fort Wayne	747	6208	1122.7
Indianapolis	974	5576	1165
South Bend	695	6462	1138
IOWA			
Burlington	994	6149	1306
Des Moines	927	6709	1311.8
Mason City	580	7900	1288.5
Sioux City	931	6952	1310.2
KANSAS			
Dodge City	1409	5045	1560.2
Goodland	923	6118	1528.6
Topeka	1361	5242	1384.8
Wichita	1672	4685	1502.3
KENTUCKY			
Lexington	1197	4729	1219.4
Louisville	1267	4644	1215.7
LOUISIANA			
Baton Rouge	2585	1669	1378.5
Lake Charles	2738	1498	1364.6
New Orleans	2705	1463	1437
Shreveport	2538	2165	1426.1
MAINE			
Caribou	128	9632	1063.1
Portland	252	7497	1050.6

MARYLAND			
Baltimore	1107	4729	1215
MASSACHUSETTS			
Boston	661	5620	1104.7
MICHIGAN			
Alpena	207	8518	1086.1
Detroit	742	6228	1120
Flint	437	7040	1075.1
Grand Rapids	574	6800	1135.3
Sault Ste. Marie	139	9193	1041.9
Traverse City	374	7697	1083.2
MINNESOTA			
Duluth	175	9756	1064.3
International Falls	175	10546	1088.2
Minneapolis/ St. Paul	585	8158	1170.2
Rochester	473	8226	1156.1
MISSISSIPPI			
Jackson	2320	2299	1408.6
Meridian	2230	2387	1369.9
MISSOURI			
Columbia	1269	5081	1327.6
Kansas City	1283	5357	1340
Springfield	1381	4568	1362.1
St. Louis	1474	4748	1326.6
MONTANA			
Billings	497	7265	1324.7
Cut Bank	139	9032	1237.6
Dillon	198	8354	1369.6
Glasgow	437	8968	1217.8
Great Falls	338	7652	1262.3
Helena	256	8190	1262.4
Lewistown	254	8586	1240.2
Miles City	751	7888	1299.7
Missoula	187	7931	1168.5
NEBRASKA			
Grand Island	1035	6424	1405
North Omaha	949	6601	1320.5
North Platte	801	6743	1444.6
Scottsbluff	666	6773	1424.7

NEVADA			
Elko	342	7483	1625.5
Ely	207	7814	1672.3
Las Vegas	2945	2601	1864.2
Lovelock	684	5989	1790.5
Reno	328	6021	1760.7
Tonopah	630	5899	1845.5
Winnemucca	407	6628	1647.6
NEW HAMPSHIRE			
Concord	347	7358	1053
NEW JERSEY			
Newark	1022	5033	1165.3
NEW MEXICO			
Albuquerque	1316	4291	1827.5
Clayton	767	5211	1669.8
Farmington	749	5711	1766.3
Roswell	1559	3695	1810
Truth or Consequences	1557	3391	1859.9
Tucumcari	1355	4046	1723.5
Zuni	472	5814	1744
NEW YORK			
Albany	572	6887	1065.8
Binghamton	369	7285	995.6
Buffalo	436	6926	1034.3
Massena	342	8237	1041.7
New York City (Central Park)	1067	4847	1098.9
New York City (LaGuardia)	1048	4909	1171.4
Rochester	531	6718	1043
Syracuse	551	6678	1034.5
NORTH CAROLINA			
Asheville	871	4235	1311.9
Cape Hatteras	1550	2731	1375
Charlotte	1595	3217	1344.4
Greensboro	1341	3825	1343.3
Raleigh/Durham	1393	3514	1295.5
NORTH DAKOTA			
Bismarck	486	9043	1248.4
Fargo	472	9270	1203.4
Minot	369	9407	1178.3

OHIO			
Akron/Canton	6223	634	1110.5
Cincinnati (Covington,KY)	1080	5069	1158.5
Cleveland	612	6152	1090.6
Columbus	808	5701	1122.9
Dayton	936	5639	1160.8
Toledo	684	6381	1133
Youngstown	517	6426	1045.2
OKLAHOMA			
Oklahoma City	1876	3694	1461.3
Tulsa	1948	3679	1373.3
OREGON			
Astoria	13	5294	1000.2
Burns	288	7211	1389.9
Medford	562	4928	1352.9
North Bend	0	4687	1219.2
Pendleton	655	5240	1259.1
Portland	299	4792	1066.8
Redmond	169	6642	1383.4
Salem	230	4851	1127.2
PACIFIC ISLANDS			
Koror Island	6007	0	1503.9
Kwajalein Island	6163	0	1620.5
Wake Island	5454	0	1720.1
PENNSYLVANIA			
Allentown	770	5827	1138.9
Erie	373	6851	1058.7
Harrisburg	1024	5224	1149.8
Philadelphia	1103	4864	1168.7
Pittsburgh	646	5929	1068.9
Wilkes-Barre/ Scranton	607	6277	1086.4
PUERTO RICO			
San Juan	4981	0	1639.6
RHODE ISLAND			
Providence	531	5971	1112.2
SOUTH CAROLINA			
Charleston	2077	2146	1345.1
Columbia	2086	2597	1380.4
Greenville/ Spartanburg	1571	3163	1346.6

SOUTH DAKOTA			
Huron	711	8053	1276.1
Pierre	857	7677	1349.2
Rapid City	6661	7322	1341.3
Sioux Falls	718	7837	1290.1
TENNESSEE			
Chattanooga	1634	3505	1245.1
Knoxville	1568	3478	1273.4
Memphis	2029	3226	1365.9
Nashville	1694	3695	1269.7
TEXAS			
Abilene	2466	2610	1554.3
Amarillo	1433	4181	1659.2
Austin	2907	1737	1476.4
Brownsville	3874	650	1547.9
Corpus Christi	3474	929	1520.5
Dallas	2754	2290	1468.1
Del Rio	3362	1523	1515.9
El Paso	2097	2677	1899.7
Fort Worth	2587	2381	1474.9
Houston	2889	1433	1351.1
Laredo	4136	875	1550.5
Lubbock	1647	3544	1766
Lufkin	2592	1939	1438.8
Midland/Odessa	2250	2621	1802.4
Port Arthur	2797	1517	1404.4
San Angelo	2702	2239	1567.9
San Antonio	2993	1570	1499
Sherman	2336	2864	1441.1
Waco	2862	2057	1467.1
Wichita Falls	2610	2903	1520.2
UTAH			
Bryce Canyon	40	9131	1739.5
Cedar City	614	6136	1742.8
Salt Lake City	927	5981	1603.1
VERMONT			
Burlington	396	7875	1020.7
VIRGINIA			
Norfolk	1440	3487	1325.2
Richmond	1352	3938	1248
Roanoke	1030	4306	1269.5
WASHINGTON			
Olympia	101	5530	1001.1
Seattle/Tacoma	128	5184	1052.7
Spokane	387	6835	1223.8
Yakima	479	6008	1281.2
WEST VIRGINIA			
Charleston	1055	4590	1123.3
Huntington	1098	4622	1176.2
WISCONSIN			
Eau Claire	459	8388	1132.3
Green Bay	385	8096	1142.5
La Crosse	695	7416	1160.6
Madison	459	7729	1190.9
Milwaukee	450	7443	1191.2
WYOMING			
Casper	457	7555	1564.7
Cheyenne	326	7254	1490.7
Rock Springs	227	8410	1635
Sheridan	445	7708	1330.1

Appendix B
ENERGY COSTS FOR SPECIFIC CITIES (1985)

Local energy costs should be used for the calculations in this manual. The data here are for illustrative use in the examples or for quick estimates that will be verified later.

SMALL COMMERCIAL ELECTRICITY	Cost Per kWh (¢/kWh)	
	Cooling	**Heating**
Albuquerque, New Mexico		
Small Commercial Basic Electricity Without Demand	9.295	7.471
Small Commercial Time-of-use With Demand	10.884	8.424
Atlanta, Georgia		
Small Commercial Basic Electricity Without Demand	10.723	10.577
Birmingham, Alabama		
Small Commercial Basic Electricity With Demand	8.464	8.191
Boston, Massachusetts		
Small Commercial Basic Electricity With Demand	14.090	12.872
Small Commercial Time-of-use With Demand	16.184	14.454
Chicago, Illinois		
Small Commercial Basic Electricity With Demand	11.233	10.104
Dallas, Texas		
Small Commercial Basic Electricity With Demand	9.899	9.545
Denver, Colorado		
Small Commercial Basic Electricity With Demand	8.370	8.994
Detroit, Michigan		
Small Commercial Basic Electricity Without Demand	9.016	8.891
Kansas City, Missouri		
Small Commercial Basic Electricity With Demand	8.212	8.212
Los Angeles, California		
Small Commercial Basic Electricity With Demand	7.381	7.381
Small Commercial Time-of-use With Demand	8.844	9.917
Louisville, Kentucky		
Small Commercial Basic Electricity Without Demand	7.740	6.470
Minneapolis, Minnesota		
Small Commercial Basic Electricity With Demand	6.762	5.909
Small Commercial Time-of-use With Demand	5.850	5.767
New York, New York		
Small Commercial Basic Electricity Without Demand	21.175	18.013

Philadelphia, Pennsylvania		
Small Commercial Basic Electricity Without Demand	12.118	10.046
San Francisco, California		
Small Commercial Basic Electricity Without Demand	4.574	7.807
Small Commercial Basic Electricity With Demand	7.472	7.472
Small Commercial Time-of-use Without Demand	8.358	8.580
Small Commercial Time-of-use With Demand	7.924	7.920
Seattle, Washington		
Small Commercial Basic Electricity With Demand	2.180	2.320
Tulsa, Oklahoma		
Small Commercial Basic Electricity Without Demand	4.277	4.485
Washington, D. C.		
Small Commercial Basic Electricity Without Demand	10.451	8.277
Small Commercial Basic Electricity With Demand	11.063	8.753

SMALL COMMERCIAL NATURAL GAS

	Cost Per CCF ($/CCF)	
	Cooling	**Heating**
Albuquerque, New Mexico	$0.49855	$0.47323
Atlanta, Georgia	$0.59065	$0.60910
Birmingham, Alabama	$0.55582	$0.56414
Boston, Massachusetts	$0.67943	$0.70316
Chicago, Illinois	$0.51424	$0.54919
Dallas, Texas	$0.48845	$0.53510
Denver, Colorado	$0.43689	$0.43891
Detroit, Michigan	$0.60905	$0.65255
Kansas City, Missouri	$0.48318	$0.49832
Los Angeles, California	$0.79649	$0.79649
Louisville, Kentucky	$0.47487	$0.47112
Minneapolis, Minnesota	$0.60842	$0.60842
New York, New York	$1.03778	$1.00809
Philadelphia, Pennsylvania	$0.72775	$0.67440
San Francisco, California	$0.66949	$0.66766
Seattle, Washington	$0.68088	$0.65088
Tulsa, Oklahoma	$0.49996	$0.48399
Washington, D. C.	$0.77432	$0.81131

Appendix C
REFERENCE REFLECTANCES

The reflectance values listed here are illustrative of typical ranges and were obtained from the sources indicated (see Bibliography). Reflectance values for a specific product that are known or can be measured should be used when available.

COLOR CLASSIFICATION FOR OPAQUE BUILDING MATERIALS
(from Reagan and Acklam, 1979)

Surface Color Code	Reflectance
Very light	0.75
Light	0.65
Medium	0.45
Dark	0.25
Very dark	0.10

Very light:
Smooth building material surfaces covered with a fresh or clean stark white paint or coating

Light:
Masonry, textured, rough wood, or gravel (roof) surfaces covered with a white paint or coating

Medium:
Off-white, cream, buff or other light colored brick,concrete block, or painted surfaces and white-chip marble covered roofs

Dark:
Brown, red or other dark colored brick, concrete block, painted or natural wool walls and roofs with gravel, red tile, stone, or tan to brown shingles

Very dark:
Dark brown, dark green or other very dark colored painted, coated, or shingled surfaces

GENERAL SURFACES

Surface Color Or Material	Reflectance
(from Probert and Thirst, 1980)	
Black	0.05
Dark Grey	0.15-.20
Light Grey	0.35
White	0.55
Copper-tarnished	0.20
Copper-oxidized	0.35
(from Baker, 1980)	
Copper	0.35
Aluminum	0.40
Galvanized Iron	0.10
Asbestos-Cement	0.20
Smooth-surface Asphalt	0.07
Grey Gravel	0.25
White Gravel	0.50
Concrete Paving	0.35

COATED AND BUILT-UP ROOFS
(from Reagan and Acklam, 1979)

Description	Reflectance
Pea gravel covered	
Dark blend	0.12
Medium blend	0.24
Light blend	0.34
White coated	0.65
Crushed used brick, red, covered	0.34
White marble chips covered	0.49
Flexstone or mineral chip roof type, white	0.26
Polyurethane foam, white coated	0.70
Same with tan coating	0.41
Silver, aluminum painted tar paper	0.51
Tarpaper, "weathered"	0.41

SAMPLES OF MATERIALS USED ON ROOFS

Description	Reflectance
(from Coursey)	
White hypalon	0.780
(from Talbert)	
Trocal SMA (PVC base)	0.285
Derbigum HPS (Modified Bitumen)	0.580
Sure Seal, Design A (EPDM)	0.124
SPM System (EPDM)	0.108
Awaplan Regular (Modified Bit.)	0.067
Awaplan Welding (Modified Bit.)	0.244
SPM 60 (EPDM)	0.076
Aluminum Fiber Coating, 1.5#	0.530
Aluminum Fiber Coating, 3.0#	0.364
Rolled Aluminum Flake	0.695
Unrolled Aluminum Flake	0.584
Rolled Coated Aluminum Flake	0.542
Unrolled Coated Aluminum Flake	0.536
Plain Steep Asphalt	0.156
Gravel Coated Asphalt	0.234

Appendix D
COOLING AND HEATING FACTORS

The cooling and heating factors are given in this appendix for the five building types (Ia, Ib, IIa, IIb, III) listed in Section 4 (also see Appendix F). The same data are given first in tabular form and then repeated graphically. The values are developed from simulations of the buildings using the DOE-2.1B computer code. Annual heating and cooling energies were calculated for different solar reflectances and fixed roof insulation. Calculations were made for a minimum of 12 locations. Heating and cooling factors were derived by dividing the heating and cooling energy values by roof area and average daily solar flux. Curve fits were made of these factors, and the data presented here are from the fitted curves.

CDD = Cooling Degree Days
HDD = Heating Degree Days

COOLING FACTORS FOR BLDG. Ia

CDD	R=2	R=4	R=8	R=16
350	6.53	4.17	2.56	1.45
550	8.33	5.93	3.74	2.10
750	9.48	6.80	4.30	2.41
950	10.36	7.42	4.69	2.62
1150	11.08	7.91	4.99	2.79
1350	11.71	8.31	5.25	2.93
1550	12.26	8.67	5.47	3.05
1750	12.75	8.98	5.66	3.16
1950	13.20	9.26	5.84	3.25
2150	13.62	9.51	6.00	3.34
2350	14.00	9.75	6.15	3.42
2550	14.36	9.97	6.28	3.49
2750	14.70	10.17	6.41	3.56
2950	15.02	10.37	6.53	3.63
3150	15.33	10.55	6.64	3.69
3350	15.62	10.72	6.75	3.75
3550	15.90	10.89	6.85	3.81
3750	16.16	11.04	6.95	3.86
3950	16.42	11.19	7.04	3.91
4150	16.67	11.34	7.13	3.96
4350	16.90	11.48	7.22	4.00

HEATING FACTORS FOR BLDG. Ia

HDD	R=2	R=4	R=8	R=16
0	0.00	0.00	0.00	0.00
400	0.36	0.23	0.12	0.06
800	0.72	0.45	0.24	0.12
1200	1.06	0.67	0.36	0.18
1600	1.39	0.88	0.48	0.24
2000	1.71	1.08	0.59	0.29
2400	2.02	1.28	0.70	0.35
2800	2.32	1.47	0.81	0.40
3200	2.61	1.66	0.92	0.46
3600	2.89	1.84	1.02	0.51
4000	3.15	2.02	1.12	0.56
4400	3.41	2.19	1.22	0.61
4800	3.65	2.35	1.32	0.66
5200	3.88	2.51	1.41	0.71
5600	4.11	2.66	1.50	0.76
6000	4.32	2.81	1.59	0.81
6400	4.52	2.95	1.68	0.86
6800	4.71	3.08	1.76	0.90
7200	4.89	3.21	1.84	0.95
7600	5.06	3.34	1.92	0.99
8000	5.21	3.45	2.00	1.03
8400	5.36	3.56	2.07	1.08
8800	5.50	3.67	2.14	1.12
9200	5.62	3.77	2.21	1.16

COOLING FACTORS FOR BLDG. Ib

CDD	R=2	R=4	R=8	R=16
350	9.97	6.63	3.78	2.02
550	12.17	8.05	4.64	2.49
750	13.67	9.02	5.23	2.81
950	14.82	9.77	5.68	3.06
1150	15.75	10.37	6.04	3.26
1350	16.52	10.87	6.34	3.43
1550	17.19	11.30	6.60	3.57
1750	17.78	11.69	6.83	3.70
1950	18.31	12.02	7.04	3.81
2150	18.78	12.33	7.22	3.91
2350	19.21	12.61	7.39	4.00
2550	19.61	12.87	7.55	4.09
2750	19.97	13.10	7.69	4.17
2950	20.32	13.33	7.82	4.24
3150	20.63	13.53	7.95	4.31
3350	20.93	13.72	8.06	4.37
3550	21.21	13.91	8.17	4.43
3750	21.48	14.08	8.28	4.49
3950	21.73	14.24	8.38	4.54
4150	21.97	14.40	8.47	4.59
4350	22.20	14.55	8.56	4.64

HEATING FACTORS FOR BLDG. Ib

HDD	R=2	R=4	R=8	R=16
0	0.00	0.00	0.00	0.00
400	0.27	0.00	0.00	0.00
800	0.56	0.00	0.00	0.00
1200	0.87	0.00	0.00	0.00
1600	1.20	0.16	0.00	0.00
2000	1.54	0.27	0.00	0.00
2400	1.89	0.40	0.00	0.00
2800	2.24	0.55	0.00	0.00
3200	2.61	0.72	0.13	0.00
3600	2.97	0.90	0.17	0.02
4000	3.33	1.08	0.22	0.02
4400	3.68	1.28	0.27	0.03
4800	4.02	1.47	0.32	0.04
5200	4.35	1.67	0.37	0.05
5600	4.67	1.85	0.43	0.06
6000	4.96	2.04	0.49	0.07
6400	5.24	2.21	0.55	0.08
6800	5.49	2.36	0.60	0.09
7200	5.71	2.50	0.66	0.11
7600	5.90	2.62	0.72	0.13
8000	6.05	2.72	0.77	0.14
8400	6.17	2.78	0.82	0.16
8800	6.25	2.82	0.87	0.18
9200	6.28	2.83	0.92	0.20

COOLING FACTORS FOR BLDG. IIa

CDD	R=2	R=4	R=8	R=16
350	9.62	6.01	3.34	1.76
550	10.92	6.90	3.93	2.09
750	12.16	7.73	4.49	2.40
950	13.32	8.51	5.00	2.69
1150	14.40	9.24	5.47	2.95
1350	15.41	9.92	5.89	3.18
1550	16.34	10.55	6.27	3.40
1750	17.20	11.13	6.61	3.59
1950	17.98	11.65	6.90	3.75
2150	18.69	12.13	7.15	3.89
2350	19.32	12.55	7.36	4.01
2550	19.88	12.92	7.53	4.11
2750	20.36	13.24	7.65	4.18
2950	20.77	13.51	7.73	4.22
3150	21.10	13.72	7.76	4.25
3350	21.36	13.89	7.75	4.25
3550	21.54	14.00	7.70	4.22
3750	21.65	14.06	7.61	4.17
3950	21.68	14.07	7.47	4.10
4150	21.63	14.03	7.29	4.01
4350	21.52	13.94	7.06	3.89

HEATING FACTORS FOR BLDG. IIa

HDD	R=2	R=4	R=8	R=16
0	0.00	0.00	0.00	0.00
400	0.83	0.50	0.28	0.17
800	1.65	0.98	0.54	0.33
1200	2.47	1.43	0.79	0.48
1600	3.29	1.86	1.02	0.62
2000	4.10	2.26	1.24	0.75
2400	4.91	2.63	1.45	0.87
2800	5.71	2.99	1.65	0.99
3200	6.51	3.31	1.83	1.09
3600	7.31	3.61	1.99	1.18
4000	8.10	3.89	2.15	1.27
4400	8.89	4.14	2.29	1.34
4800	9.67	4.36	2.41	1.41
5200	10.45	4.56	2.52	1.47
5600	11.23	4.74	2.62	1.51
6000	12.00	4.89	2.71	1.55
6400	12.76	5.01	2.78	1.58
6800	13.53	5.11	2.84	1.60
7200	14.29	5.18	2.88	1.61
7600	15.04	5.23	2.91	1.61
8000	15.79	5.26	2.93	1.60
8400	16.54	5.25	2.93	1.58
8800	17.28	5.23	2.92	1.55
9200	18.02	5.18	2.90	1.51
9600	18.76	5.10	2.86	1.46

COOLING FACTORS FOR BLDG. IIb

CDD	R=2	R=4	R=8	R=16
350	10.22	6.30	3.58	2.00
550	13.01	8.11	4.60	2.55
750	14.93	9.34	5.30	2.92
950	16.39	10.29	5.83	3.21
1150	17.57	11.05	6.26	3.44
1350	18.57	11.69	6.62	3.63
1550	19.42	12.24	6.93	3.80
1750	20.17	12.72	7.20	3.95
1950	20.84	13.16	7.45	4.08
2150	21.44	13.54	7.67	4.20
2350	21.99	13.90	7.87	4.30
2550	22.50	14.23	8.05	4.40
2750	22.97	14.53	8.22	4.49
2950	23.40	14.81	8.38	4.58
3150	23.81	15.07	8.52	4.66
3350	24.19	15.31	8.66	4.73
3550	24.55	15.55	8.79	4.80
3750	24.88	15.76	8.92	4.87
3950	25.21	15.97	9.03	4.93
4150	25.51	16.17	9.14	4.99
4350	25.80	16.36	9.25	5.05

HEATING FACTORS FOR BLDG. IIb

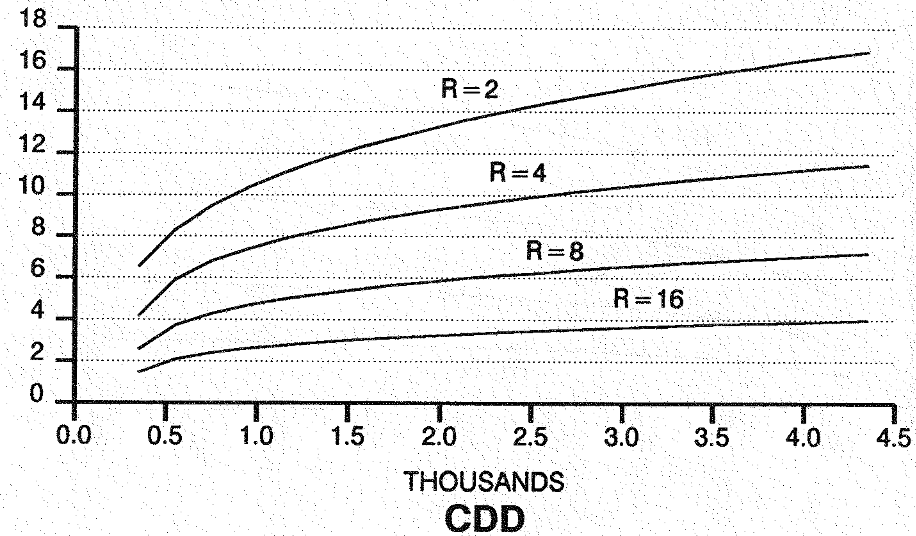
HDD	R=2	R=4	R=8	R=16
0	0.00	0.00	0.00	0.00
200	0.10	0.02	0.00	0.00
400	0.19	0.04	0.00	0.00
600	0.29	0.06	0.00	0.00
800	0.38	0.09	0.01	0.00
1000	0.48	0.12	0.01	0.00
1200	0.57	0.15	0.02	0.00
1400	0.67	0.19	0.03	0.00
1600	0.76	0.22	0.05	0.01
1800	0.85	0.26	0.06	0.01
2000	0.95	0.30	0.08	0.02
2200	1.04	0.35	0.10	0.03
2400	1.13	0.39	0.12	0.04
2600	1.22	0.44	0.14	0.05
2800	1.31	0.48	0.16	0.06
3000	1.41	0.53	0.19	0.07
3200	1.50	0.58	0.21	0.09
3400	1.59	0.63	0.24	0.10
3600	1.68	0.68	0.27	0.11
3800	1.76	0.73	0.29	0.13
4000	1.85	0.78	0.32	0.14
4200	1.94	0.16	0.35	0.84
4400	2.03	0.17	0.38	0.89
4600	2.12	0.19	0.40	0.94
4800	2.20	0.99	0.43	0.20
5000	2.29	1.04	0.46	0.22
5200	2.38	1.10	0.49	0.23
5400	2.46	1.15	0.52	0.25
5600	2.55	1.20	0.54	0.26
5800	2.63	1.25	0.57	0.28
6000	2.72	1.30	0.59	0.29
6200	2.80	1.34	0.62	0.30
6400	2.89	1.39	0.64	0.32
6600	2.97	1.44	0.66	0.33
6800	3.05	1.48	0.69	0.34
7000	3.13	1.52	0.71	0.35
7200	3.22	1.56	0.72	0.36
7400	3.30	1.60	0.74	0.37
7600	3.38	1.64	0.76	0.38
7800	3.46	1.67	0.77	0.39
8000	3.54	1.70	0.78	0.39
8200	3.62	1.73	0.79	0.40
8400	3.70	1.76	0.80	0.40
8600	3.78	1.78	0.80	0.41
8800	3.86	1.80	0.80	0.41
9000	3.94	1.82	0.80	0.41
9200	4.01	1.84	0.80	0.41
9400	4.09	1.85	0.79	0.40

ALL HEATING FACTORS FOR BUILDING III = 0.

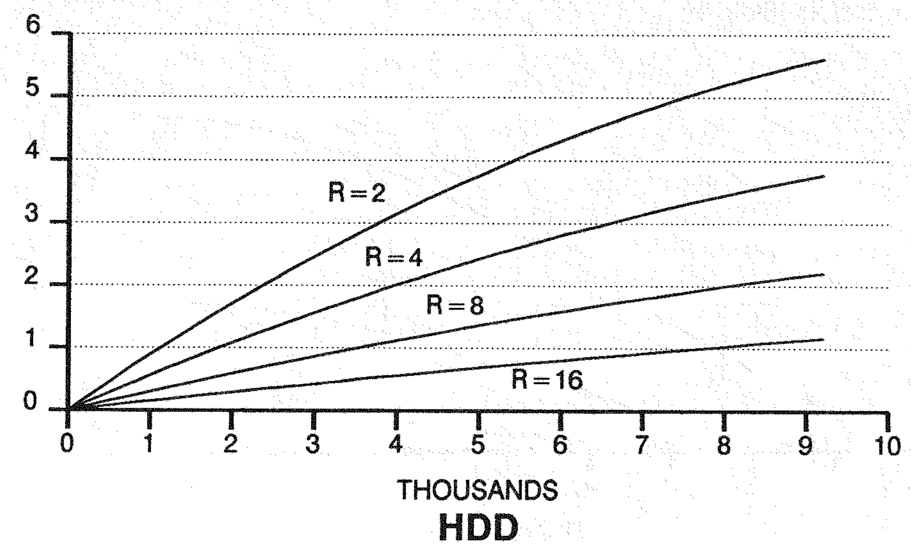
COOLING FACTORS FOR BLDG. III

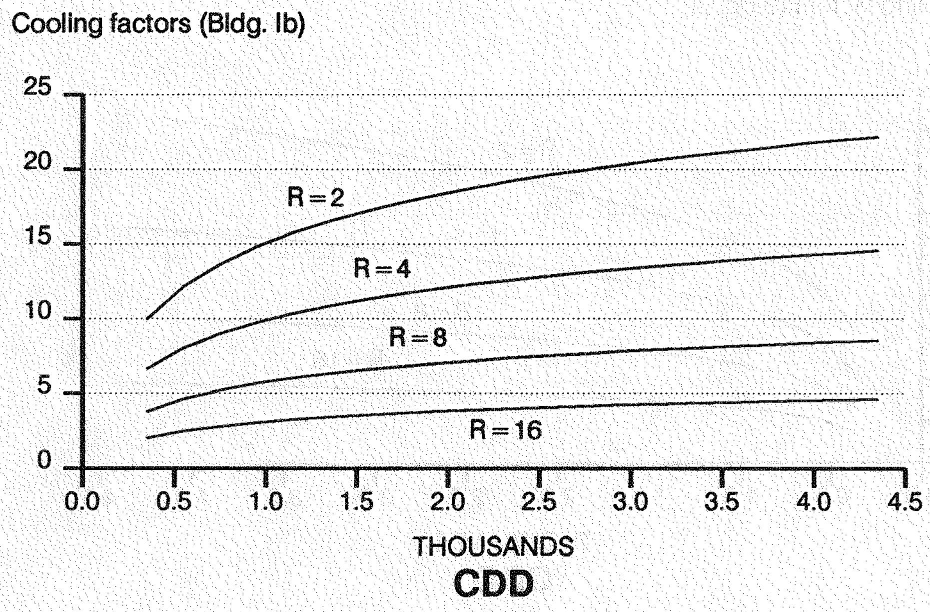
CDD	R=2	R=4	R=8	R=16
350	11.00	7.06	3.93	2.08
550	13.83	8.78	4.92	2.61
750	15.38	9.72	5.46	2.90
950	16.50	10.39	5.85	3.11
1150	17.38	10.93	6.16	3.28
1350	18.13	11.37	6.42	3.42
1550	18.77	11.75	6.64	3.54
1750	19.34	12.09	6.84	3.65
1950	19.85	12.40	7.02	3.74
2150	20.31	12.68	7.18	3.83
2350	20.74	12.93	7.33	3.91
2550	21.14	13.17	7.47	3.98
2750	21.51	13.39	7.60	4.05
2950	21.85	13.59	7.72	4.12
3150	22.18	13.79	7.83	4.18
3350	22.49	13.97	7.94	4.24
3550	22.79	14.15	8.04	4.29
3750	23.07	14.31	8.14	4.34
3950	23.34	14.47	8.23	4.39
4150	23.59	14.62	8.32	4.44
4250	23.72	14.70	8.36	4.46

Cooling factors (Bldg. Ia)



Heating factors (Bldg. Ia)




Cooling factors (Bldg. Ib)
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20
15
10
5
0
R = 2
R = 4
R = 8
R = 16
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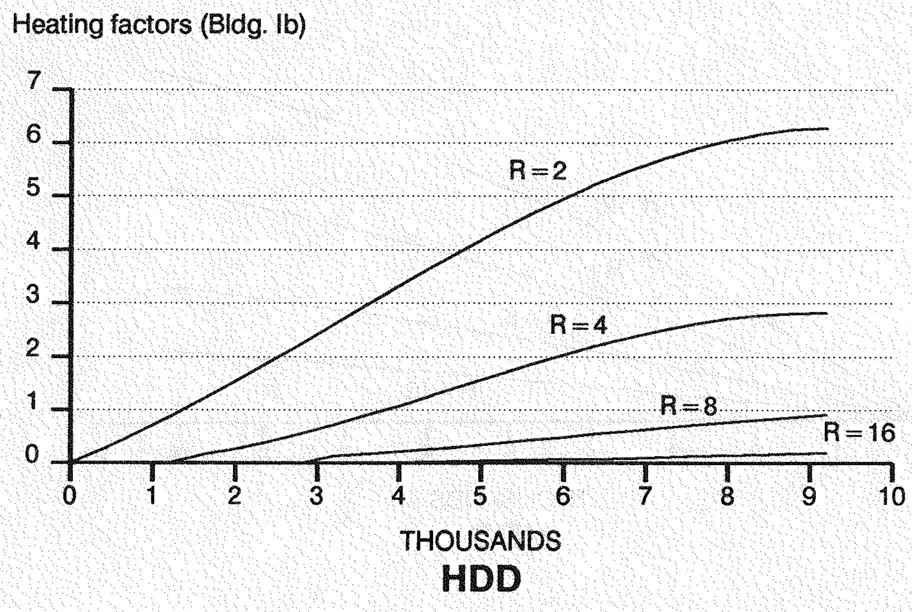
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
THOUSANDS
CDD


Heating factors (Bldg. Ib)
7
6
5
4
3
2
1
0
R = 2
R = 4
R = 8
R = 16
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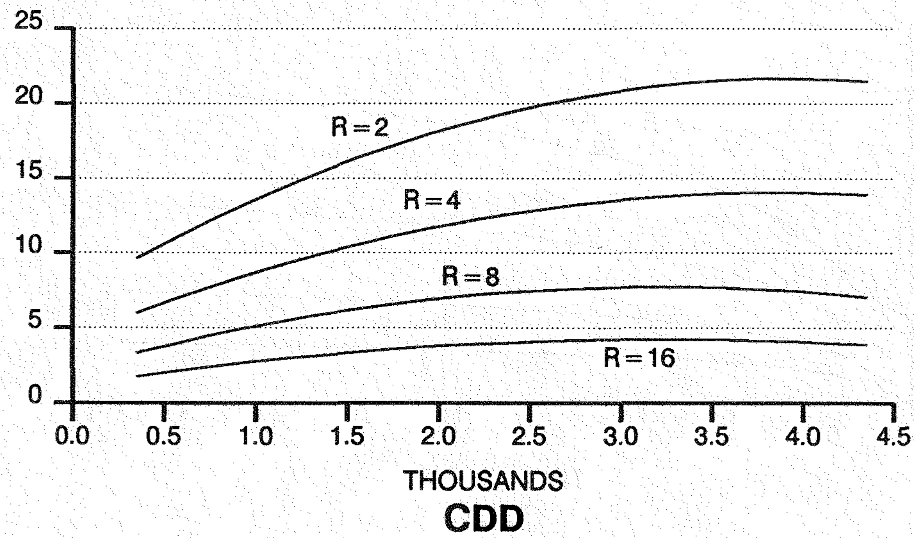
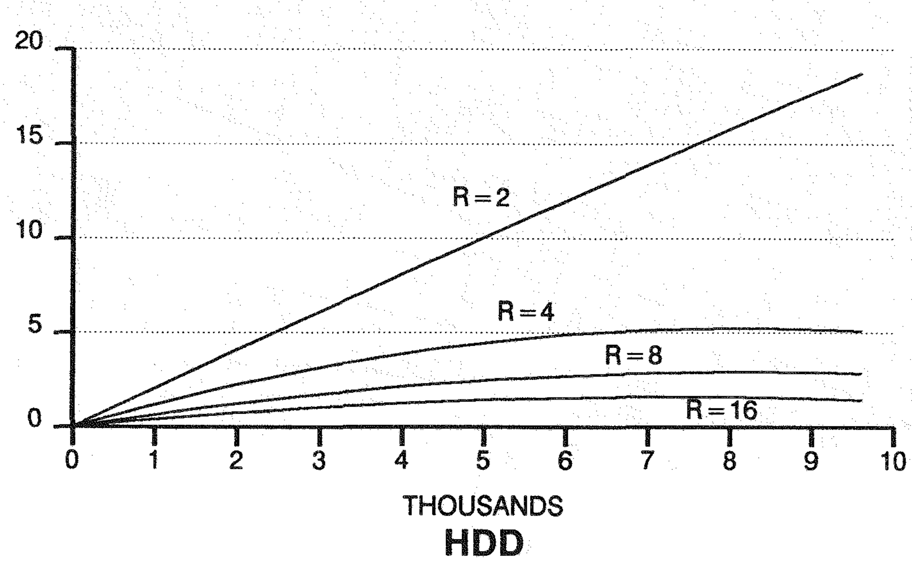
1
2
3
4
5
6
7
8
9
10
THOUSANDS
HDD

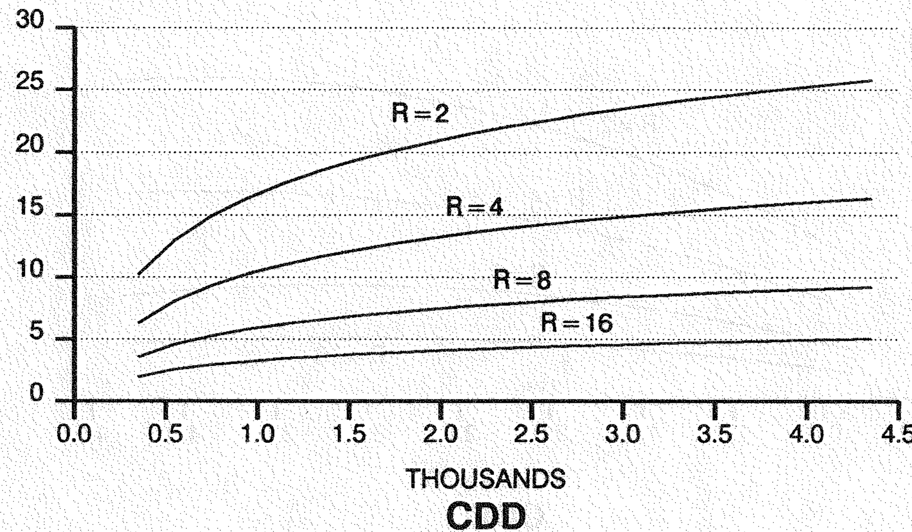
Cooling factors (Bldg. IIa)



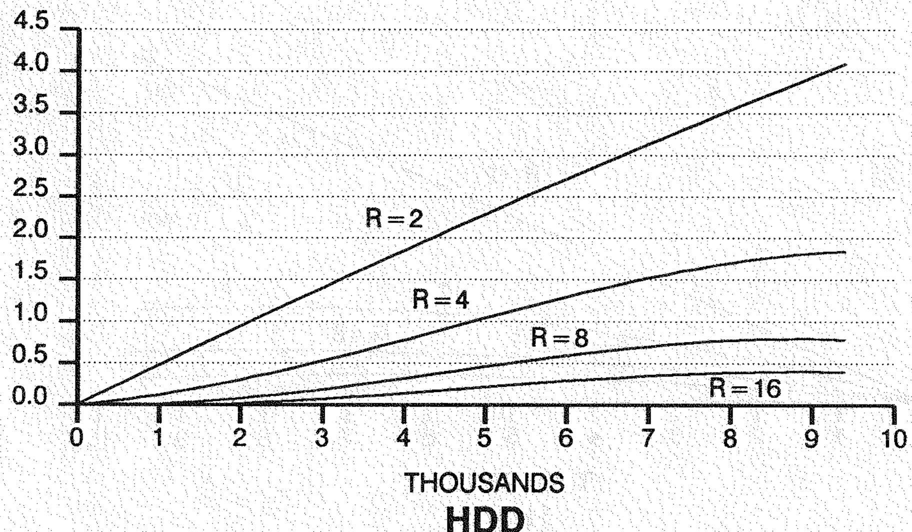
Heating factors (Bldg. IIa)



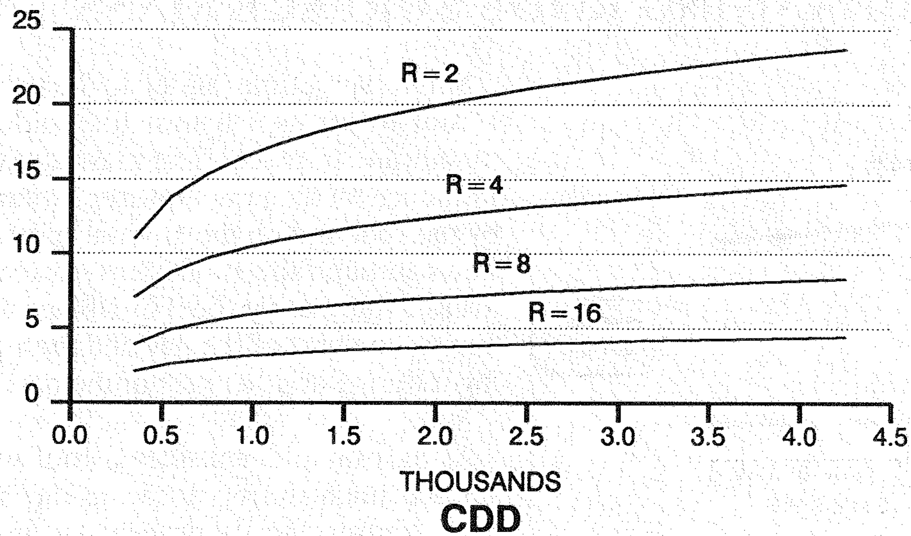
Cooling factors (Bldg. IIb)



Heating factors (Bldg. IIb)



Cooling factors (Bldg. III)



ALL HEATING FACTORS FOR BUILDING III = 0.

Appendix E
ENERGY SAVINGS AVAILABLE FROM CHANGING ROOF SURFACE MASS

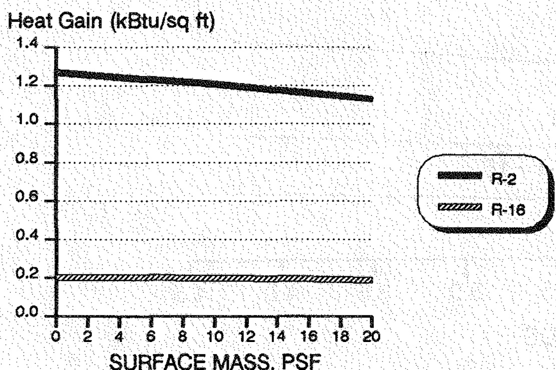


Figure E-1 – Effect of surface mass on heat gain.
Using data for the same week in May as shown in Fig. 4, the impacts of surface mass on heat gain during hot weather is shown.

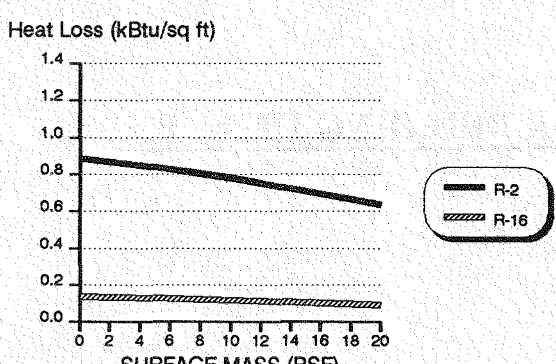


Figure E-2 – Effect of surface mass on heat loss.
The impact of roof surface mass on heat loss at night during the same week in May as above are shown in this figure.

Mass is sometimes added to the surface of a roof to act as a ballast for holding the membrane in place. The mass also has an influence on the temperatures experienced by the roof and on the amount of heat that flows through the roof. Surface mass can act as a thermal flywheel by storing up heat during one part of the day and then releasing it during another part of the day.

As an example, consider a roof with no surface mass during a spring day that is warm during the daytime hours and cool during the nighttime hours. During the daytime, the sun shines on the roof and drives heat into the building, while during the night heat flows out of the building because of the cool outdoor air. Now, if surface mass is added to the roof, part of the heat from the sun is stored in the surface mass and does not pass through the roof into the building. Thus the surface mass reduces the amount of heat gained through the roof during the daytime hours. During the nighttime hours, the mass is still somewhat warm because of its stored heat and thus acts to reduce the amount of heat that is lost from the roof during the nighttime hours.

Figures E-1 and E-2 show the total heat gains and losses calculated for roofs using weather data from a week in May in Oak Ridge, Tennessee. During this week, heat would flow into the building during the day (heat gains) and would flow out of the building during the night (heat losses). Adding mass to the surface would result in decreases in both the heat gains and heat losses, with the decreases being greater for greater amounts of mass. Mass is often added as ballast for single ply roof systems. Some typical ballast densities are 10 psf for loose-laid stones and 18–25 psf for paving blocks. The graphs show the changes in heat gains and losses due to mass at both low and high levels of insulation. Generally speaking, the effects of surface mass are considerably smaller than the effect of changing the insulation level. Whether or not these changes in heat gains and losses show up as energy savings depends upon the heat gain and loss picture for the rest of the building and the method of operating the heating and cooling equipment.

Two examples of energy changes due to roof surface mass are given in Figures E-3 and E-4. Figure E-3 shows the cooling energy for a building in Phoenix, where cooling loads are high and heating loads are small. The graph shows the effect of mass at both a high and a low level of surface reflectance. This shows that the effects of surface mass on annual cooling energy is relatively small compared with the effect of changing the surface reflectance. Figure F-4 shows the heating energy for a building in Minot, N.D., where heating loads are high and cooling loads are small. For this case, the energy change due to surface mass is still relatively small, but is not as much different from the effect of surface reflectance as it was for Phoenix. In general, when heating or cooling energies are significant, the changes due to surface mass are usually less than a few percent.

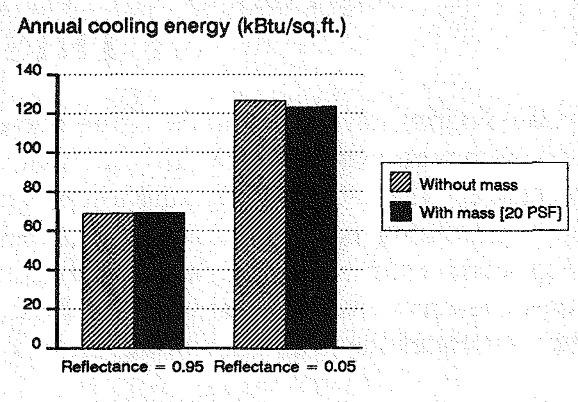


Figure E-3—Effect of surface mass on cooling energy (Phoenix, AZ).
This figure demonstrates that, although surface mass can have some impact on heat gain for buildings, the overall effect for a whole year is typically small compared to the effect of changing reflectance. The roof R-value is R-2, and the case with mass is for 20 PSF.

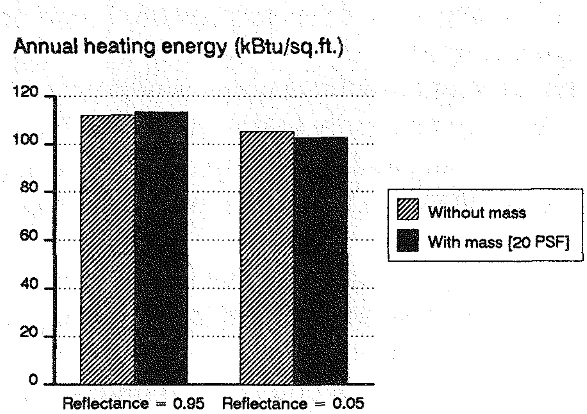


Figure E-4—Effect of surface mass on heating energy (Minot, N. D.).
The effect of surface mass on heating energy is shown in this figure for a building in Minot, N. D. The effect on heating energy is small compared to total loads in a climate with significant heating requirements. The roof R-value is R-2, and the case with mass is for 20 PSF.

Appendix F
NOTES ON THE DEVELOPMENT OF THIS GUIDE

Calculations have been made of the decrease in energy required to cool a building and the increase in energy required to heat a building when the roof's solar reflectance is changed. The DOE 2.1B simulation program was used to make multiple simulations for five building configurations, and the results are summarized in this document to help others estimate the impact of increasing roof reflectance on cooling and heating costs. Descriptions of the cases follow. First a steady-state based overview is presented that illustrates the problem and why more detailed computations are necessary.

STEADY-STATE BASED OVERVIEW

A building collects solar energy when it is exposed to the sun. The amount of solar energy available varies with location and is affected by atmospheric conditions, particularly cloud cover. The portion of available solar energy which ultimately ends up inside a building depends on many factors. A principal part of a building envelope which sees the sun is the roof. This document focuses on how an increase in the solar reflectance of a low slope roof affects that portion of available solar energy which ends up inside the building. Heat entering a building during hours of cooling is a penalty since it increases the amount of heat which must be removed by the cooling system. Heat which enters the building when heating is needed is beneficial, since it reduces the amount the heating system has to provide. Some of the heat entering a building through the roof due to solar effects may occur at times when neither cooling or heating is required, and consequently this energy is neither a cooling penalty nor a heating benefit. Thus, it becomes necessary to determine the heat gain that occurs during times of operation of the cooling and heating systems to make any judgement about the annual influence of solar heat gain through a low slope roof.

A simple estimate of the heat entering a building through a low slope roof can be made using a steady-state calculation. Suppose a building is conditioned continuously with the thermostat kept at the same setting throughout the year. The annual summation of heat which enters the building through the roof can be calculated by the steady-state equation two times, first for the case of a roof that reflects none of the incoming solar energy and secondly for the case of a roof that reflects all of the incoming solar energy. This scenario provides an upper limit on the effect of changing the roof's reflectance. The difference between these two summations is the maximum possible amount of heat which enters the building through the roof due to solar effects. Calculations via this steady-state scenario can be made, but real roofs do not operate in a steady-state mode. It is not feasible to achieve a change in roof solar reflectance from zero to unity. The interiors of buildings are not typically kept at a fixed thermostat set point throughout the year. Therefore, while the steady-state computations provide some insight regarding effects and limiting values, they do not account for real building effects and do not provide any insight into how to separate the annual summation into portions occurring during times of building cooling and heating. Consequently, evaluation of the impact of increasing a low sloped roof's solar reflectance on building energy use requires that a more sophisticated analysis be made. This is why the DOE 2.1B program was used to make the calculations summarized in this document.

COMPUTATIONAL METHODOLOGY

DOE 2.1B was used in making calculations in order to take into account real building effects and HVAC system operating effects. DOE 2.1B is a versatile, widely used code for modeling a complete building and its HVAC systems. Hour by hour performance is simulated for a user-specified period which can be up to one year in length. Hourly values of key climatic variables are required in an appropriately formatted data file as input to run the program.Typical meteorological year (TMY) weather data files were used for all locations included in the calculations summarized here. The files included available solar energy values for the locations.

DOE 2.1B is structured with several subprograms. Two of these are named LOADS and SYSTEMS. The LOADS subprogram calculates hourly heat gains and heat losses for each component of the building envelope. Gains from specified internal heat sources such as lights, equipment, and people are also included. Space weighting factors are used to convert the predicted gains into loads. All calculations in the LOADS subprogram are made on the basis of a fixed, user-specified inside temperature for each conditioned space within the building. The SYSTEMS subprogram uses the output of the LOADS subprogram, user-specified HVAC system(s), operating schedules, and thermostat set points for conditioned zones to determine hourly values of heat which the cooling coil must remove during periods of cooling and the heating coil must provide during hours when heating is needed. Accumulative sums over the simulation period for each of these quantities are stored and reported as specified. The energy quantities used for the results of this effort were based on the annual summations of the cooling energy that must be removed by the cooling system and of the heating energy that must be added by the heating system.

The scheme was to run the code for a particular building and roof R-value for different values of the roof's solar reflectance. After several simulation runs, it was observed that the annual cooling energy and the annual heating energy reported by the program varied linearly with the roof's solar reflectance. This is a key fact used in presenting the results. This relationship permits use of the results for different increments of solar reflectance and thereby accommodates more universal application than if only one particular change in the roof's solar reflectance were valid. This also means that aging effects can be accommodated if good estimates of how aging alters a roof's solar reflectance can be obtained.

The decrease in annual cooling energy divided by the product of the increase in roof solar reflectance and average daily solar radiation for the location is referred to herein as the cooling factor. Similarly, the increase in annual heating energy divided by the product of the increase in roof solar reflectance and average daily solar radiation for the location is referred to herein as the heating factor.

Use of these results reduces basically to determining the cooling factor and heating factor for specific locations. These factors are multiplied by the average daily solar radiation listed in Appendix A and the estimated increase in the roof's solar reflectance. The result of these two computations yields, respectively, the cooling energy savings and heating energy penalties for the building and location examined.

CASES EXAMINED

As discussed in relation to the steady-state scenario, reduction in the annual heat flow into a building through the roof caused by increasing its solar reflectance depends on location, roof construction and the magnitude of reflectance increase. The crucial issue is how the reduction in annual heat is divided into a heating penalty and a cooling benefit. All factors that play a role in determining when a building needs heating and when it needs cooling are influential in establishing this division.

In an attempt to cover selected practical situations, five building cases were simulated using DOE 2.1B. It was found after some initial calculations that building size did not significantly affect the results when other conditions were unchanged. Whether or not the building had a plenum space between the conditioned space and the roof and operating schedule and internal loading did influence the computed results. Summary descriptions of the five cases used to generate results for this document are given below.

For all the cases examined, the thermostat settings for cooling and heating were, respectively, 78°F and 72°F. Setback values were 84°F and 63°F for cooling and heating, respectively.

Building Ia:

The building for this case was 25 ft by 60 ft by 10 ft tall, providing a floor area of 1500 ft^2. The load schedule simulated office operation for weekdays only. Occupancy, lights, and equipment were specified for weekdays only. Peak loading included 10 people and 3 W/ft^2 for lights and equipment combined. Thermostat setback was used for nighttime and weekends. A suspended ceiling was included with the space between the roof and the suspended ceiling serving as a plenum.

Building Ib:

The building for this case was a two-story structure which simulated a retail store in a shopping mall. The building was not exactly rectangular. Gross floor area was 164,200 ft^2. The average floor-to-floor height was 19 ft. The exposed roof area was 76,240 ft^2. Peak loading on the first floor included 1102 people and 4.26 W/ft^2 for lighting. Peak loading on the second floor included 906 people, 4.26 W/ft^2 for lights, and 10 kW for equipment. There was a plenum between the conditioned top floor and the roof. A nighttime thermostat was used, but the building operated seven days a week.

Building IIa:

The building for this case consisted of two spaces. The large part was 120 ft by 322 ft by 24 ft tall. An adjacent office building was 32 ft by 66 ft by 12 ft tall. The combination has a gross area of 40,752 ft^2. The load schedule simulated a conditioned warehouse or light assembly plant. Occupancy, lights, and equipment were scheduled for weekdays and for Saturday morning in the office. Peak loading in the office included 16 people and combined 5.36 W/ft^2 for lights and equipment. Peak loading in the large building was less with 20 people and a combined 0.9 W/ft^2 for lights and equipment. Nighttime and weekend thermostat setback was used. The simulation did not include a plenum.

Building IIb:

The same building used for Building Ia was used in this case except the plenum was removed, internal loading was increased and operating time was extended. Loading schedule simulated office operation throughout the week and half a day on Saturday. No thermostat setback was used. Peak loading included 15 people and a combined 12.5 W/ft^2 for equipment and lights.

Building III:

The same building used for Building IIb was used in this case except internal loading and operating schedule were increased more. Loading schedule simulated a restaurant or fastfood operation. Peak loading included 30 people, 2.5 W/ft^2 for lights and 50 W/ft^2 for equipment. Occupancy, lights and equipment were scheduled for operation throughout the day and into late evening for every day of the week. No thermostat setback was used.

The five cases described above encompass buildings of different size, buildings with and without plenums, different schedules, and a range of internal loading. A few computations were made for Building Ia with the plenum removed. The results agreed almost exactly with computations made for Building IIa for the same locations and same roof R-value.

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