CHANGES IN BUILDING HEATING AND COOLING REQUIREMENTS DUE TO A REDUCTION IN THE ROOF'S SOLAR ABSORPTANCE

E.I. Griggs
ASHRAE Member

G.E. Courville
ASHRAE Member

ABSTRACT

Sunlit surfaces of buildings experience higher temperatures during hours of solar exposure than those experienced by unexposed surfaces. The solar radiation incident on building exterior surfaces may, in turn, affect the heating and cooling loads imposed on the building's HVAC system. An increase in surface temperature due to insolation increases heat gain during the summer and reduces heating loss during the winter. Since this is a counteracting influence with regard to energy usage, questions arise as to how annual HVAC energy requirements are changed when a surface's radiative properties are altered.

The study reported here focused specifically on changes in heating and cooling loads when the roof's solar absorptance was reduced from 0.8 to 0.3. Calculations were made using DOE-2.1B for two different buildings at twenty different cities. A third building type was examined for five of the locations.

The paper presents the calculated load changes in the form of bar graphs. The magnitude of the load changes is shown to be significantly influenced by the convective coefficient. For locations of high solar intensity and low heating requirements, use of roofs with low solar absorptance can represent meaningful energy savings.

INTRODUCTION

Building surfaces exposed to the sun experience higher temperatures than do similar unexposed exterior surfaces. The resultant temperature of an exposed surface is affected by the solar intensity, radiative characteristics of the surface, wind speed, ambient temperature, surrounding objects, and the thermal properties of the associated building component.

An increase in a building's surface temperature by insolation can increase heat gain during the summer or reduce heat loss during the winter. Accordingly, if the solar absorptance of a sunlit surface is lowered, the cooling load and heating load imposed on the building's HVAC system may be altered. Since the effects are counteracting, questions arise as to how HVAC load requirements are changed when a surface's radiative properties are altered.

This study focused specifically on changes in a building's annual heating and cooling loads caused by reducing the solar absorptance of it's roof surface. The energy-saving potential associated with roof construction and the need for further research has been established and reported (Robinson 1981; Chang and Busching 1983). The possibility of conserving energy by using reflective materials for the outermost roof layer represents one area of interest. In this work, the computer code DOE-2.1B was used to calculate HVAC load changes.

Prior to presentation and discussion of results, some relevant background is outlined in the literature review and in related concepts.

E.I. Griggs, Professor, Department of Mechanical Engineering, Tennessee Technological University, and G.E. Courville, Program Manager, Building Thermal Envelope Systems and Materials (BTESM) Program, Oak Ridge National Laboratory.

LITERATURE REVIEW

Several workers have discussed how roof surface temperature and/or heat transfer through a roof are affected by the radiative characteristic of the roof's surface. Quantifying these effects is dependent on reliable solar absorptance values for roof coverings. A brief review of works dealing with these considerations follows.

Reported Solar Absorptance Values

In discussing energy-conserving aspects of roof design, Probert and Thirst (1980) stated that summer heat gain can be reduced by judicious selection of roof color, which in the technical context of this study is related to the roof's solar absorptance. Reported solar absorptance values ranged from 0.45 for a "white" surface to 0.95 for a "black" surface. This range of solar absorptances agreed well with that given in the treatise on roofs by Baker (1980).

Reagan and Acklam (1979) observed that solar reflectance data for common building materials were rather sparse. Reflectance measurements were made on a variety of wall and roofing materials using their own probe reported to have an effective spectral range of 0.44 to 0.96 microns. The reported reflectance values for coated and built-up roof materials correspond to an absorptance range from 0.25 to 0.88.

Talbert has also reported solar reflectance and thermal emittance data for several types of roof surfaces. The corresponding absorptance values range from 0.285 to 0.942.

In studying buildings with DOE-2.1B, the solar absorptance of exterior surfaces is an input parameter. Solar absorptance values given in the DOE-2.1B Reference Manual (DOE 1980) range from 0.02 to 0.98.

Surface Temperature

Insulation and surface color are both considered important factors affecting roof membrane temperature. Rossiter and Mathey (1976) calculated steady-state surface temperatures of black (α = 0.9), gray (α = 0.7), and white (α = 0.5) roofs. Several thicknesses of roof insulation and three different thermal conductivity values were used. The R-values ranged from 1.25 $hr \cdot ft^2 \cdot F/Btu$ (0.22 m^2k/W) to infinity. The color distinction caused a 30 F (15.5°C) difference in predicted roof temperatures at the highest level of insulation.

In a study of two contiguous buildings, Shuman (1980) compared heat flow through wet and dry insulated roof constructions; he also measured thermal effects associated with three roof coverings, which included slag, white marble containing dark constituents of about 15%, and slag coated with an experimental water-paint of white portland cement with plasticizer. Concluding that roof reflectance should be considered in design, he emphasized the need for reliable reflectance data and the importance of an acceptable service life.

Baker (1980) stated that temperatures experienced by roofing materials during their service life may well determine the success or failure of a roof system. He reports that the surface temperature of a roof may reach 190 F (88°C) for a flat roof having an unobstructed view of the sky. Some simple formulae for estimating roof temperature during both day and night operation are given in his book.

Keeton and Alumbaugh (1981) experimentally investigated thermal performance of built-up roofs using three temperature-controlled buildings designed to accomodate testing of 8 ft x 8 ft (2.44 m x 2.44 m) panels. Tests encompassed surfacings classified as white, white gravel, gray gravel, aluminum gray, and black. They concluded that serious consideration should be given to changing the surfacing of a roof to a lighter color as an alternative to more expensive re-roofing when it is necessary to improve thermal resistance of an existing roof to lower energy consumption.

Energy Use Considerations

Since heat transfer through a roof depends on surface temperature, the influence of solar absorptance on a sunlit surface temperature in turn affects the heat transfer. In contemporary methods for estimating air-conditioning cooling loads, such as the procedure outlined in the ASHRAE Handbook--Fundamentals (ASHRAE 1985), calculation of loads depends on specification of the color of exterior wall and roof surfaces. Color consideration is typically discussed only in connection with cooling loads since traditional load calculation schemes determine the maximum loads for purposes of sizing equipment. The maximum cooling load will include solar contribution; however, the maximum heating load will occur in the absence of solar exposure. As attention is directed more specifically to energy utilization, the impact of solar influences on both heating and cooling energy use needs to be evaluated.

Attention has been given to the role that roof "color" has in altering energy requirements for the heating and cooling of buildings. In an extensive treatise on energy conservation, Dubin and Long (1978) presented nomographs for heat gain and heat loss. These nomographs facilitate comparing roof heat gain and loss for solar absorptance values of 0.8 to 0.3.

In an assessment of the energy-saving potential of roofing research within the United States, Chang and Busching (1983) used Dubin's nomographs to estimate heat gains and losses for numerous locations. They noted that the annual heat loss through a roof with a surface absorptance of 0.8 is approximately 12% to 25% less than the annual heat loss through a similar roof with a surface absorptance of 0.3 and that the annual heat gain for α = 0.8 is approximately two to four times that for α = 0.3. Surface solar absorptance of a low-slope roof was concluded to be an important factor affecting heat loss and gain.

The influence of surface solar absorptance on heat transfer through opaque building elements was also addressed by Reagan and Acklam (1979). They discussed results of heat gain/loss calculations made for several residences in Tucson, Arizona. Comparative results for daily average heat gain were given for one residence; values of α for the roof of 0.75 and 0.35 were used. One case corresponded to what they classified as a poorly insulated home; the other case was for what they termed a more modern, better insulated home. They concluded that changing the roof color from dark to light reduces the roof heat gain of a typical southwestern house during the summer. For the cases which they examined, it was stated that such a reduction has little effect on the summer total house heat gain because the roof's contribution was only a small part of the total.

Griffin (1980) outlined a scheme for estimating cooling-energy cost savings with the use of heat-reflective, aluminum asbestos-fibrated coatings instead of conventional black asbestos-fibrated coatings, on smooth-surfaced built-up bituminous membranes. His estimation scheme was based on use of the total equivalent Cooling Load Temperature Difference (CLTD) as described in the ASHRAE Handbook--1985 Fundamentals (ASHRAE 1985). Tabulated CLTD values were corrected by a color adjustment factor. For climates with long cooling seasons, Griffin reported that a savings of 0.25 $\$/ft^2$ (2.69 $\$/m^2$) in present worth can be achieved over 20 years; it was, however, noted that other climatic conditions tend to complicate the impact of changing α on heating energy consumption.

Talbert summarized a brief study that focused on potential energy savings with buildings whose roofs are coated with aluminum flakes exhibiting high solar reflectance and low thermal emittance. The report includes estimated cooling energy savings that might be realized in Phoenix, Arizona, by use of the aluminum flakes. Estimates were made by two methods. The first was based on the scheme reported by Griffin (1980). The second was based on use of an average daily sol-air temperature and steady-state calculation. Noting that the methods were developed to determine design loads for equipment sizing, Talbert cautioned that predicted energy savings may not be very accurate. He suggested that a better method would be to utilize one of the more sophisticated computer models.

RELATED CONCEPTS

Certain concepts related to this study are discussed in this section.

Thermal Radiation Considerations

This work focused on the change in heat transfer through a roof caused by changing its solar absorptance.

The radiative character of a surface is often discussed in terms of color. Color generally relates to the visible portion (0.35 - 0.7 μ) of the electromagnetic spectrum; hence, color may not adequately characterize the total thermal-radiation band. Radiative heat transfer between objects at low temperatures involves long-wavelength (>8 μ) radiation. The energy transmitted as solar radiation is concentrated in a band of shorter wavelengths. For example, modeling the sun as a blackbody emitter at 6000°K, 99.5% of the emitted energy lies between 0.1 and 5 microns and 43.2% lies in the visible spectrum (0.35 to 0.7 μ).

When a material layer is exposed to radiant energy, a portion is reflected, a portion may be transmitted and the remainder is absorbed. An energy accounting for radiant energy of any wavelength leads to

$$\alpha_\lambda + \rho_\lambda + \tau_\lambda = 1. \tag{1}$$

Radiative properties of materials are directional and spectrally dependent; however, many engineering analyses are made using hemispherical values and involve opaque material layers, which means that none of the incident radiant energy is transmitted through the layer (i.e., $\tau = 0$). The absorption and reflection processes are treated as surface phenomena. In terms of hemispherical properties, the accounting of radiant energy impinging upon an opaque layer is given by

$$\alpha + \rho = 1. \tag{2}$$

According to Kirchhoff's law, absorptance equals emittance under conditions of thermal equilibrium, but this equality is often assumed in engineering analyses of nonequilibrium situations. When this is done, $\alpha = \varepsilon$ and Equation 2 becomes

$$\varepsilon = 1 - \rho. \tag{3}$$

Equation 3 is not strictly valid for all real situations; however, data relating α and ε for common roof coverings seem to be scarce.

Sol-Air Temperature

The net heat transfer from the sun and other exterior surroundings to a roof's surface involves absorption of solar energy, convective exchange with the environment, and an infrared radiative exchange with low-temperature surroundings. The sol-air temperature is defined as the "hypothetical" air temperature that would result in the same net heat transfer to the surface using a combined radiative and convective heat transfer coefficient. The sol-air temperature (ASHRAE 1985) is given by

$$T_{sa} = T_\infty + \frac{\alpha G}{h_o} - \frac{\varepsilon \Delta R}{h_o}. \tag{4}$$

Although the sol-air temperature is useful for illustrating the effect of solar loading, it is not an independent property of the climate because of its dependence on the parameters α, ε, h_o and ΔR.

Building Load Considerations

Definition and Illustration of Terms. If α of a roof's surface is lowered, the energy required for cooling the contiguous building will most likely be reduced because the heat gain will be smaller following the reduction in surface temperature during sunlit hours. In the winter, high surface temperatures may tend to impede heat loss through a roof. Hence, using a reduced surface α during the winter may likely result in an increase in the energy requirements for heating. Figure 1(a) illustrates the possibility of reducing annual cooling energy per unit roof area (ACE) by lowering the roof's α. Similarly, Figure 1(b) shows the converse for the possibility of increasing annual heating energy per unit roof area (AHE) by lowering α of the roof. A principal goal of this study was to assess changes in ACE and AHE due to a discrete reduction in α. For this purpose ACES denotes the magnitude of annual cooling energy saving and AHEP denotes the magnitude of annual heating energy penalty, both based on unit roof area. With reference to Figure 1, ACES and AHEP are expressed by

$$\text{ACES} = \text{ACE}_1 - \text{ACE}_2 \tag{5}$$

$$\text{AHEP} = \text{AHE}_2 - \text{AHE}_1. \tag{6}$$

Both ACES and AHEP represent changes in annual energy requirements due to a lowering of a roof's α. Both are defined in the positive sense.

Steady-State Calculation of Roof Heat Transfer Using Sol-Air Temperature. A steady-state calculation of roof heat transfer gives some insight into how changing α affects energy use. Consider unit area of a roof over a conditioned space, which for the purpose of this evaluation is to be maintained at a constant temperature, T_i, around the clock. Using sol-air temperature, the net annual heat gain through the roof per unit area is given by

$$\text{Net Annual Gain Per Unit Roof Area} = \int U_o(T_{sa} - T_i)dt \quad (7)$$

where U_o represents the overall heat transfer coefficient for heat transfer between air at the sol-air temperature and inside at T_i. The integral is to be evaluated over one year. Specific separation of the net gain into ACE and AHE requires more detailed insight into hour-by-hour building operation. For example, heat gain through the roof may contribute to a cooling load or may reduce a heating load, depending on which mode prevails within the space at that time.

The definition of sol-air temperature given in Equation 4 can be used in Equation 7. The net gain can then be evaluated for a large value of α and also for a lower value of α. An approximation for ACES + AHEP can be obtained by subtracting the net gain for the lower α from that corresponding to the higher α, assuming that ε, h_o, and ΔR are unaffected by the changed α. The result is

$$\text{ACES} + \text{AHEP} = \int \frac{\Delta\alpha \; U_o \; G}{h_o} dt. \quad (8)$$

The left side of Equation 8 is written as the sum (ACES + AHEP) since the net reduction in energy gain, represented by this sum, may be composed of both a saving in cooling energy and a penalty in heating energy. If a particular location is characterized by essentially no annual heating requirement, such as southern Florida, then the net reduction is manifested almost totally in ACES. Conversely, should a particular location be characterized by essentially no cooling requirements, then the net reduction would be manifested almost totally in AHEP.

If U_o and h_o are assumed constant, the steady-state value given by Equation 8 may be expressed as

$$\text{ACES} + \text{AHEP} = \left(\frac{\Delta\alpha \; U_o}{h_o}\right)(365\ \overline{G}_{SD}) \quad (9)$$

where $\overline{G}_{SD}$ represents the average daily solar flux on a horizontal surface. The approximation of Equation 9 suggests that the net reduction in energy gain (ACES + AHEP), due to a reduction in a roof's solar absorptance by the amount $\Delta\alpha$, should vary linearly with $\overline{G}_{SD}$. Also, with other parameters unchanged, an increase in h_o causes a decrease in the sum (ACES+AHEP), an observation that illustrates the important role of the factors that control h_o such as wind velocity.

While Equations 8 and 9 indicate steady-state behavior, the net effect for real building operation should be expected to differ quantitatively from that estimated by the steady-state calculations. Such features as structural energy storage, thermostat set points, HVAC equipment operating characteristics, the distinction between instantaneous heat transfer rates and coil loads, the coupling between internal loads and external loads, and other interrelated effects serve to make the calculation of actual energy requirements a more formidable problem than that of making simple steady-state calculations. Division of the net reduction into separate values for ACES and AHEP for a real building operating in a location having both significant heating and cooling loads is dependent on local climate, building type, and HVAC operation. ACES and AHEP values computed in this study using DOE-2.1B are presented and discussed in the next section.

COMPUTATIONAL RESULTS

All load-change computations made in this study correspond to a discrete reduction in the roof's α from 0.8 to 0.3. The study focused on two buildings; a few computations were also made for a third one. Twenty locations were used for many of the calculations; however, some runs were made for only fifteen locations. Prior to presentation of results, DOE-2.1B is briefly discussed along with some special considerations.

DOE-2.1B

DOE-2.1B is a computer code widely used for modeling buildings and their HVAC systems. It is a versatile code, which can simulate hour-by-hour performance throughout a year. It contains several subprograms, two of which are the LOADS program and the SYSTEMS program. In the LOADS program, hourly heat gains and losses through the building envelope components are first calculated separately. Weighting factors are then used to convert gains into loads.

In the calculation of heat gains and losses through exterior walls and roofs, the effect of thermal storage can be included with use of thermal response factors. All computations in LOADS are made for a fixed temperature within conditioned spaces. The SYSTEMS program uses the output of the LOADS Program, HVAC system characteristics, and room air weighting factors to determine hourly HVAC system coil loads. The SYSTEMS program modifies the LOADS output to account for variable temperatures in each conditioned zone.

The flexibility of DOE-2.1B affords opportunity for comparing computed energy values corresponding to a rather wide range of modeling options. For example, the output of LOADS corresponds to a fixed space temperature. On the other hand, the output of SYSTEMS (e.g., coil loads) takes into account different thermostat setpoints for heating and cooling, scheduling of HVAC operation, scheduling of various internal loading, and HVAC equipment specifications. If the HVAC system capacity is not specified, DOE 2.1B sizes the equipment automatically from loads determined in the LOADS program. Thus, if a building-envelope parameter is changed between two runs, the change in computed loads may lead to a different size HVAC system for the second case than was determined for the first case. The user, however, has the option of inputing HVAC equipment capacity. Comparisons of building energy use between two runs where the HVAC equipment has been sized automatically would seem more appropriate for examining the effect of changing a building-envelope parameter in new building designs. Conversely, the effect of changing a building-envelope parameter for an existing building, for which the same HVAC equipment is to be used before and after the change, would seem best determined by specifying the same equipment capacities for both runs.

Special Considerations for This Study

Weather Data. DOE-2.1B is designed to receive climate-related variables from weather tapes. For this study Typical Meterological Year (TMY) weather tapes were used. Twenty locations were used for several runs; however, some cases involved only fifteen locations. Although selected partially on the basis of available TMY weather tapes, which had been configured for DOE-2.1B input, the locations were chosen to represent the range of heating and cooling requirements within the United States. Figure 2 shows cooling degree-days versus heating degree-days for more than 200 weather-reporting stations within the United States (Knapp et al. 1980). The 20 selected locations, indicated by the heavier darkened circles, are representative of the full range of reporting stations. Table 1 lists these 20 locations together with values for the cooling degree-days, heating degree-days, average daily solar flux, and average wind speed (Knapp et al. 1980; WERA 1980-83).

Values of Solar Absorptance. Values of 0.8 and 0.3 were used for the roof's solar absorptance. These values were considered to represent practical limits on absorptance. These two values were also used in the work of Dubin and Long (1978) and that of Chang and Busching (1983).

Overall Heat Transfer Coefficient. With load-calculating methods such as those outlined in the ASHRAE Handbook (ASHRAE 1985), air-film coefficients on the inside and outside of a roof, h_i and h_e respectively, are included with the roof resistance, R, in determining the overall thermal conductance, U. The expression is

$$U = \frac{1}{\frac{1}{h_i} + R + \frac{1}{h_e}} = \frac{1}{\frac{1}{U'} + \frac{1}{h_e}} . \qquad (10)$$

U of Equation 10 is the traditional value used for steady-state heat transfer calculations with the outside-air-to-inside-air temperature difference. When calculating steady-state heat transfer using sol-air-to-inside-air temperature difference, the appropriate conductance is U_o, which incorporates the combined exterior convective and radiative coefficient, h_o. The expression is

$$U_o = \frac{1}{\frac{1}{U'} + \frac{1}{h_o}} . \qquad (11)$$

The quantities R and h_i, thus U', remain constant during a particular DOE-2.1B run. The exterior surface energy balance incorporated within DOE-211B utilizes h_o, which varies with external environmental conditions. Since h_o varies, U' has been used to characterize the roof's level of insulation. A surface roughness parameter is input in a DOE-2.1B run to specify which of six different h_o-wind speed correlations is used. The one used for most calculations in this study corresponded to the most rough surface. A comparative case was run for the most smooth case.

Building Simulations

Three buildings, designated A, B, and C, were considered. Building A was selected to model a typical interior office module within a strip of contiguous identical units. Building B was specified to model an open-area repair shop or light manufacturing facility. Building C represented a multizone office building. All three modeled single-story buildings having concrete slab floors and brick-faced, concrete-block walls. The flat roof construction was specified to be the same for all three buildings. Buildings A and B involved only one interior zone, and building C involved five interior zones. Building A had a suspended ceiling between the roof and the conditioned space, and the return air was directed through the unconditioned space between the ceiling and roof. The roof's inner surface for buildings B and C was directly contiguous to the conditioned space. Internal loads including people, lights, and equipment were 14.95 (47.14), 12.92 (40.75), and 14.22 (44.83) Btu/h·ft^2 (w/m^2) for A, B, and C, respectively. Infiltration rates were 0.083 (0.422), 0.167 (0.848), and 0.058 (0.295) cfm/ft^2 (L/s·m^2) for A, B, and C, respectively. Thermostat setpoints of 72 F (22.2°C) for heating and 78 F (25.5°C) for cooling were used for all cases.

Building A Results. Using TMY weather data for 20 locations, building A was first examined for U' set at 0.2 Btu/h·ft^2·F (1.135 w/m^2·k). U' is based on the combined resistance of the roof materials and the inside convective air-film resistance. For the roof construction considered, a U' of 0.2 Btu/h·ft^2·F (1.135 w/m^2·k) corresponded to an insulation thickness yielding an R value of 3.74 h·ft^2·F/Btu (0.659m^2·k/w). The remainder of the resistance, 1.26 h·ft^2·F/Btu (0.222 m^2·k/w), was due to the aggregate, built-up roof membrane, steel deck, and interior air-film. For other U' values, the contribution due to aggregate, built-up roof membrane, steel deck, and interior air-film remained constant. The quoted U' value was obtained by changing only the thickness of insulation. For two larger thicknesses of insulation, runs were made for 15 of the selected locations. DOE-2.1B was allowed to size the equipment automatically for all Building A runs. Changes in predicted cooling coil load, heating coil load, electrical energy required by the system fan, and the electrical energy required by the cooling system were recorded. For the lowest level of insulation considered [U' = 0.2 Btu/h·ft^2·F (1.135 w/m^2·k)], changes in predicted HVAC coil loads are depicted by the bar graph of Figure 3. Noting values listed in Table 1 of the daily mean global solar radiation, $\overline{G}_{SD}$, on a horizontal surface for each of the locations, it is noted that (ACES + AHEP) generally increases with an increase in $\overline{G}_{SD}$ (see Figure 4). For the building A cases examined, each predicted ACES value, is larger than the corresponding AHEP value indicating that predicted energy savings during cooling exceed the energy-use penalty during heating. Economic savings depend, however, on the type of cooling and heating systems used and on the relative costs of heating and cooling energy, a practical concern discussed later.

The sum (ACES + AHEP) decreases with an increase in the thickness of roof insulation. This is shown in Figure 5 for four of the locations. Figure 5(a) shows that the net reduction in energy gain, as realized at the coils, decreases with an increase in the thermal resistance. Figure 5(b) shows the excess of cooling energy savings over heating energy penalty for the same four locations. Similar behavior occurred for all locations examined.

Building B Results. Building B was examined for several cases, designated as cases B1, B2, B3, and B4. Case B1 involved operating conditions similar to those used for building A. Nighttime and weekend setback of the thermostats was used and DOE-2.1B was allowed to automatically size the HVAC system on the basis of loads computed in the LOADS subprogram. For fifteen locations and three different insulation levels, predicted changes in cooling coil load, heating coil load, electrical energy required by the system fan, and the electrical energy required by the cooling system were recorded. Figure 6 shows predicted changes in HVAC coil loads for case B1 with U' of 0.2 Btu/h·ft^2·F (1.135 w/m^2·k). Results for case B1 exhibit trends similar to those for building A. The computed sum (ACES + AHEP) increased near linearly with the average daily solar radiation, $\overline{G}_{SD}$. The decrease of the sum (ACES + AHEP) with an increase in roof insulation thickness followed the same trend as for building A. The behavior was similar for all 15 locations examined. Since computed results for building A and for case B1 of building B illustrated similar dependence on insulation level, only a U' of 0.2 Btu/h·ft^2·F (1.135 w/m^2·k) was used for subsequent runs (cases B2, B3, B4) where the effect of other parameters was examined.

For case B2 nighttime and weekend setback of thermostats was used, but the HVAC system capacity was forced to be the same for the α = 0.3 run as that generated by DOE-2.1B for the α = 0.8 run. For 15 locations, predicted changes in cooling coil load, heating coil load, electrical energy required by the system fan, and the electrical energy required by the cooling system were recorded. The coil load increments, ACES and AHEP, are depicted in Figure 7, where case B1 results are repeated to accomodate comparison between cases B1 and B2. The comparison shows that forcing the system capacity to be the same for both values of roof absorptance (case B2) changed the predicted ACES and AHEP magnitudes from those computed where the HVAC system capacity was allowed to be sized internally by DOE-2.1B. Changing the system capacity can influence the coil loads in two ways. First, operation with a larger unit would tend to keep the swing in space air temperature lower. Also, since ventilation air was included, changing system capacity will shift the coil load line slightly. While the distinction between results for cases B1 and B2 shown in Figure 7 are not extreme, it is evident that predicted energy savings and penalty (ACES + AHEP) are dependent on HVAC system specification.

Case B3 involved a change in HVAC operating schedule. Internal loads (people, lights, and equipment) were scheduled only during the day for weekdays, but the HVAC system was scheduled to operate continuously. Nighttime and weekend setback were not employed. The HVAC system capacity was again forced to be the same for the α = 0.3 run as that generated by DOE-2.1B for the α = 0.8 run. For 20 locations, predicted changes in cooling coil load, heating coil load, electrical energy required by the system fan, and the electrical energy required by the cooling system were recorded. The predicted coil load increments (ACES and AHEP) are depicted in Figure 8, where B2 results are repeated for comparison. The results show that maintaining the space conditioned continuously causes an increase in both predicted ACES and AHEP values. The increase can probably be explained by the fact that weekend operation is included and that the space was conditioned at night where some time-delayed energy transfer may also be included during a regular work day.

The effect of solar loading on a roof's surface temperature is influenced by the exterior heat transfer coefficient. All of the previously discussed computations were made using correlation of h_o with wind speed that corresponds to a rough surface. Case B4 runs were made with conditions being the same as for case B3 except for the h_o correlation. The h_o correlation for a very smooth surface was used. For 20 locations, predicted changes in cooling coil load, heating coil load, electrical energy required by the system fan, and the electrical energy required by the cooling system were recorded. The coil load changes, ACES and AHEP, are shown in Figure 9 where B3 results are repeated for comparison. The comparison shows that using lower h_o values increased both ACES and AHEP. The increase was as much as 60% in some cases. This contrast indicates the important role that the surface heat transfer coefficient plays in the surface energy balance. This also indicates how the energy balance on a sunlit roof is significantly affected by wind speed

Building C Results. Calculations for the multizone office building, building C, were made for five locations. Continuous space conditioning, involving the same scheduling as that used for case B3, and system capacity matching were used. Predicted ACES and AHEP values for building C are shown in Figure 10 together with those for building A and cases B1, B2, and B3 for building B. All cases shown in Figure 10 are for the common U' value of 0.2 $Btu/h \cdot ft^2 \cdot F$ ($1.135\ w/m^2 \cdot k$) and the same h_o correlation, that being the one for a rough surface. ACES and AHEP values of Figure 10 are listed in Table 2 together with estimates based on the report of Chang and Busching (1983). For the buildings examined in this study, the ACES and AHEP values computed by DOE-2.1B are generally lower than values estimated by the data given by Chang and Busching (1983). Second, computed ACES and AHEP magnitudes for a particular location and for buildings having identical roofs are affected by other parameters such as HVAC system operation

Comparisons of Building Predictions to Steady-State Estimates

An interesting comparison can be made between steady-state estimates of (ACES + AHEP) by Equation 9 and DOE-2.1B predictions for the examined buildings. The DOE-2.1B correlation of h_o with wind speed for a rough surface was used with the mean wind speeds listed in Table 1 to determine h_o for the 20 locations. This h_o was used with a U' value of 0.2 $Btu/h \cdot ft^2 \cdot F$ ($1.135\ w/m^2 \cdot k$) to calculate U_o. Values for $\bar{G}_{SD}$ given in Table 1 were used. The results of calculating the steady-state estimate of (ACES + AHEP) by Equation 9 are tabulated in Table 3. DOE-2.1B results for building A and cases B1, B2, and B3 for building B are listed also. The percentage difference, based on the steady-state estimate, is also given. For the range of cases considered, all steady-state estimates were higher than the corresponding results obtained with DOE-2.1B. The steady state predictions for the cases shown were higher by percentages that ranged from 39% to 74%.

Economic Considerations

For investment considerations, coil load changes must be considered with respect to their ultimate impact on purchasing energy. The ACES and AHEP values computed in this study represent changes in annual cooling and heating coil requirements. Utilization efficiency from source to coil must be used to determine the resultant change in energy demand at the source. The change in cooling energy at the source is given by ACES/β, where β denotes the effective annual coefficient of performance for the cooling system. Likewise, the change in heating energy at the source is given by (AHEP)/η, where η denotes the effective annual heating system efficiency. For example, if $\beta = 2.5$ and $\eta = 0.7$, ACES/AHEP would have to exceed 3.57 for a resultant savings in energy at the source. The distinction in energy cost for heating and cooling must be used to determine the economic impact. For economic considerations, savings associated with an investment that occur over an extended time and involve the time-value of money can be cast into present worth, which indicates what the predicted savings represent in today's money. The present worth of an investment represents the maximum expenditure today that can be made without the investment representing a loss. The present worth of a particular ACES and AHEP combination is given by

$$PW = \frac{(ACES)(CEC)(PWF)_c}{\beta} - \frac{(AHEP)(HEC)(PWF)_h}{\eta} \qquad (12)$$

where CEC and HEC represent current cooling energy cost and current heating energy cost, respectively. Also, $(PWF)_c$ and $(PWF)_h$ represent present-worth factors for cooling and heating, respectively. These present-worth factors depend on the life of the energy-saving modification (reduction of α here), the applicable discount rate, and the escalation rate for the respective energy cost.

Determination of the present worth of an investment by Equation 12 requires good insight or good speculation as to the life of the investment, the discount rate, and fuel escalation rates. Estimations can be made with the aid of published estimates for some of these. For example, uniform present-worth factors for ten DOE regions and averages for the United States are tabulated in a DOE life-cycle cost manual (DOE 1984). Also included are mid-1983 energy costs.

Without taking the full step of estimating present-worth factors, an interesting comparison of estimated savings can be made by casting the computed results into current cost savings. For this comparison, natural gas was considered to be the heating fuel and the cooling system was considered to be electrically driven. Use was made of mid-1983 national average costs of electrical energy and natural gas for the commercial sector (DOE 1984). Electrical savings were taken as the computed savings in electrical cooling energy plus the savings in HVAC fan energy. In doing this, the DOE-2.1B-generated HVAC system coefficient of performance was automatically taken into account. An electrical energy cost of 18.24 $\$/10^6 \cdot Btu$ (0.06226 \$/kW·h) was used. Heating by natural gas was assumed with an efficiency of 70% and a fuel cost of 5.58 $\$/10^6 \cdot Btu$ (0.01904 \$/kW·h). Results of this cost evaluation are tabulated in Table 4. Largest savings occur for locations with large average daily solar radiation and characterized by large cooling requirements. All cases presented for comparison in Table 4 correspond to a roof U' value of 0.2 $Btu/h \cdot ft^2 \cdot F$ (1.135 $w/m^2 \cdot k$). Use of larger U' values will result in smaller savings and vice versa. For the range of cases compared here, it is noted that the upper bound on calculated current savings per square foot of roof area is of the order of the cost of one kW·hour of electrical energy. This observation, however, is based on a heating system efficiency of 70% and a ratio of electrical energy cost to heating energy cost of 3.27 to 1.

CONCLUSIONS AND RECOMMENDATIONS

Observations and Limitations

Exact magnitudes of changes in heating and cooling energy that occur when a roof's solar absorptance is lowered are affected by building construction, HVAC system scheduling and operation, thermal resistance of the roof, and local climatic conditions. The majority of ACES and AHEP comparisons depicted in this work correspond to a roof U' value of 0.2 $Btu/h \cdot ft^2 \cdot F$ (1.135 $w/m^2 \cdot k$). Sufficient runs were made, however, to show that energy savings are reduced as the thermal resistance of the roof increases. The savings follow the general trend of varying inversely with thermal resistance.

The sunlit-surface energy balance algorithm incorporated within DOE-2.1B accomodates user modification of the surface's solar absorptance, but the option for simultaneously altering the infrared emittance is not available. When a roof's solar absorptance is lowered, it is likely that its infrared emittance will also be lowered. A reduced infrared emittance will affect longwavelength radiative transfer to the sky. This effect has not been quantified in this study.

Calculations were made for a specific reduction in α of 0.5. This seems to represent a practical upper limit on the change; however, little information is available on the life of reflective materials and coatings. Dirt and other environmental influences can cause a reduction in the reflective properties. Also, the influence of such factors as water ponding, snow, and roof-mounted equipment has not been reckoned with.

The calculated results were shown to be strongly dependent on the value used for the surface convective heat transfer coefficient. The rather simplistic models that are used in the computational algorithms need to be evaluated for real building situations. While the external heat transfer coefficient does not affect the total energy transfer significantly for a well-insulated roof, the need for an accurate heat transfer coefficient is much more essential for accurate prediction of surface temperature and accurate quantifying of the changes in heat transfer due to changing surface properties.

CONCLUSION

Within the scope of this study which involved calculations based on decreasing a flat roof's solar absorptance from 0.8 to 0.3, the following conclusions are offered:

1. Energy savings can be realized, particularly for locations characterized by large mean daily global solar radiation and large building cooling requirements.

2. Energy savings are distinctly less than steady-state estimates.

3. For a roof having a thermal resistance of about 5 $ft^2 \cdot h \cdot F/Btu$ (0.881 $m^2 \cdot k/w$), the saving is of the order-of-magnitude of one kilowatt-hour of electrical energy per square foot of exposed roof area.

4. Energy savings vary inversely with the magnitude of the roof's thermal resistance.

5. Energy savings may be almost twice as large for a roof where the exterior heat transfer coefficient is governed by smooth-surface correlations as for one governed by the roof-surface correlation.

6. Exact magnitudes of savings for the same building vary with HVAC sizing and operational schedule.

7. Exact magnitudes of savings vary between buildings having identical roofs.

RECOMMENDATIONS

Based on conclusions and the noted limitations of this study, the following specific recommendations are given for further work:

1. Examine the effect of a reduced infrared emittance simultaneously with a reduced solar absorptance on calculated ACES and AHEP values.

2. Study how the radiative properties of a roof's surface change with environmental exposure.

3. Investigate in more detail how the convective heat transfer coefficient on roofs varies with environmental parameters.

4. Study the reduction in surface temperature swing associated with reflective roofs.

NOMENCLATURE

ACES = Reduction in cooling energy per unit roof area following a discrete change in α

AHEP = Increase in heating energy per unit roof area following a discrete change in α

CDD = Designates cooling degree-days

CEC = Cooling energy cost

G = Incident solar radiation per unit roof area

$\overline{G}_{SD}$ = Mean daily solar radiation on a horizontal surface

HDD = Designates heating degree-days

h_e = External film heat transfer coefficient due solely to convection

HEC = Heating energy costs

h_o = h_e plus radiative coefficient

PW = Present worth of an investment

PWF = Present worth factor

T_i = Conditioned space temperature

T_{sa} = Sol-air temperature

T_∞ = Outside air temperature

U = Overall heat transfer coefficient (outside air to inside air)

U' = Heat transfer coefficient (outside surface to inside air)

U_o = Overall heat transfer coefficient (sol-air to inside air)

$\overline{V}$ = Annual mean wind speed

α = Hemispherical surface absorptance

β = Cooling system coefficient of performance

ΔR = Difference between the energy emitted by a blackbody at T_∞ and the longwave radiation incident on a surface

ε = Infrared emittance

η = Heating system efficiency

ρ = Hemispherical surface reflectance

τ = Hemispherical transmittance

Subscripts

1, 2 = High α, low α

c, h = Cooling, heating

λ = Monochromatic value

REFERENCES

ASHRAE. 1985. ASHRAE Handbook-1985 Fundamentals, Atlanta: American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc.

Baker, M.C. 1980. Roofs--Design, Application and Maintenance. Sponsored by the National Council of Canada, Multiscience Publications, Limited, 1980.

Chang, T., and Busching, H.W. 1983. "Energy savings potential of roofing research." ORNL/Sub/82-22293/1, report prepared under Purchase Order No. 19X22293V for ORNL by Clemson University, December 1983.

DOE. 1980. DOE-2 Reference Manual--Parts 1 & 2. prepared for the U.S. Department of Energy under Contract W-7405-ENG-8, Lawrence Berkely Laboratory and Los Alamos National Laboratory LA-7689-M, Ver.2.1, LBL-8706, Rev. 1, May 1980.

DOE. 1984. Federal Energy Management Program Life Cycle Cost Manual. (NBS 135) Update, DOE/CE-0076, Washington, D.C.: U.S. Department of Energy, March 1984.

Dubin, F.S., and Long Jr., C.G. 1978. Energy Conservation Standards for Building Design Construction and Operation. McGraw-Hill Book Company.

Griffin, C.W. 1980. "Cost savings with heat-reflective roof coatings." Plant Engineering, July 1980, pp. 98-102.

Keeton, J.R., and Alumbaugh, R.L. 1981. "Energy factors and temperature distribution in insulated built-up roofs." TN N-1600, Port Hvenenee: Civil Engineering Laboratory, Naval Construction Battalion Center, February 1981.

Knapp, C.L., Stoffel, T.L., and Whitaker, S.D. 1980. "Insulated data manual." SERI/SP-755-789, October 1980.

Probert, S.D., and Thirst, T.J. 1980. "Design and performance of roofs." Applied Engineering 6, pp. 79-97.

Reagan, J.A., and Acklam, D.M. 1979. "Solar reflectivity of common building materials and its influence on the roof heat gain of typical southwestern U.S.A. residences." Energy and Buildings, 2, pp. 237-248.

Robinson, J.N. 1981. "The assessment of roofing research--an interim report." ORNL/TM-7640, Oak Ridge National Laboratory, July 1981.

Rossiter, W.J., Jr., and Mathey, R.G. 1976. "Effect of insulation on the surface temperature of roof membranes." National Bureau of Standards, NBSIR 76-987, February 1976.

Shuman, E.C. 1980. "Field measurements of heat flow through a roof with saturated thermal insulation and covered with black and white granules." Thermal Insulation Performance, ASTM STP 718, D.L. McCleroy and R.P. Tye, eds., American Society for Testing and Materials, pp. 519-539.

Talbert, S.G. "Energy savings of buildings using aluminum roof flakes." Energy Savings Report. Columbus: prepared by Battelle Columbus Laboratories, Columbus, Ohio, for Transmet Corporation.

WERA. 1980-83. "Wind energy resource atlas." PNL-3195-WERA 1 through 9, Vols. 1 through 9, 1980-83.

TABLE 1
Climate-Related Data for 20 Locations Used in This Study

Location	CDD F (°C)	HDD F (°C)	$\overline{G}_{SD}$ Btu/day·ft² (MJ/day·m²)	$\overline{V}$ mph (m/s)
Phoenix, AZ	3506 (1948)	1552 (862)	1869.4 (21.2)	5.1 (2.3)
Bakersfield, CA	2178 (1210)	2183 (1213)	1749.2 (19.9)	6.9 (3.1)
El Paso, TX	2097 (1165)	2677 (1487)	1899.7 (21.6)	8.1 (3.6)
Albuquerque, NM	1316 (731)	4291 (2384)	1827.5 (20.8)	9.4 (4.2)
Miami, FL	4037 (2243)	205 (114)	1472.9 (16.7)	9.4 (4.2)
San Antonio, TX	2993 (1663)	1570 (872)	1499.0 (17.0)	9.4 (4.2)
Tampa, FL	3366 (1870)	716 (398)	1492.1 (16.9)	8.3 (3.7)
Augusta, GA	1994 (1108)	2547 (1415)	1361.6 (15.5)	6.7 (3.0)
Lake Charles, LA	2738 (1521)	1498 (832)	1364.6 (15.5)	8.7 (3.9)
Memphis, TN	2029 (1127)	3226 (1792)	1365.9 (15.5)	8.9 (4.0)
Denver, CO	625 (347)	6016 (3342)	1568.4 (17.8)	11.2 (5.0)
St. Louis, MO	1474 (819)	4748 (2638)	1326.6 (15.1)	9.6 (4.3)
Washington, DC	940 (522)	5009 (2783)	1208.4 (13.7)	7.8 (3.5)
Chicago, IL	923 (513)	6125 (3403)	1215.1 (13.8)	10.7 (4.8)
Indianapolis, IN	974 (541)	5576 (3098)	1165.0 (13.2)	8.9 (4.0)
Minneapolis, MN	585 (325)	8158 (4532)	1170.2 (13.3)	10.1 (4.5)
Minot, ND	369 (205)	9407 (5226)	1178.3 (13.4)	10.3 (4.6)
Syracuse, NY	551 (306)	6678 (3710)	1034.5 (11.7)	10.1 (4.5)
Portland, OR	299 (166)	4792 (2662)	1066.8 (12.1)	8.3 (3.7)
Seattle, WA	128 (71)	5184 (2880)	1052.7 (12.0)	8.7 (3.9)

Sources: Knapp et al. 1980; WERA 1980-83)

CDD = Cooling Degree-Days
HDD = Heating Degree-Days
$\overline{G}_{SD}$ = Mean Daily Solar Radiation
$\overline{V}$ = Mean Wind Speed

TABLE 2
ACES and AHEP (Btu/ft²)* Predicted for a Flat Roof with U' of 0.2 Btu/h·ft²·F (1.135 w/m²·k) When Its Solar Absorptance Is Reduced from 0.8 to 0.3

Location	Energy Change	Chang and Busching (1983)	A	B1	B2	B3	C
Phoenix, Arizona	AHEP	1312	117	417	331	497	487
	ACES	10681	6520	5581	5181	6078	7000
Albuquerque, New Mexico	AHEP	1918	783	1903	1645	2271	1834
	ACES	8245	3977	3116	2992	3544	4834
San Antonio, Texas	AHEP	931	157	426	348	594	283
	ACES	9885	3581	3692	3260	3869	3956
Indianapolis, Indiana	AHEP	2745	607	1176	864	1152	656
	ACES	5437	1778	1681	1557	2401	2315
Minot, North Dakota	AHEP	3636	916	1212	1217	1617	1001
	ACES	5112	1232	800	852	1170	1676

*Multiplication of tabular entries by (11.354) yields values in kJ/m².

TABLE 3
(ACES + AHEP) Comparisons between DOE-2.1B Predictions and Steady-State Estimates by Equation 9. Tabular entries for (ACES + AHEP) are in Btu/ft.*

Location	Eq. 9	Building A	Case B1	Case B2	Case B3
Phoenix, AZ	14796	6637 (55.1)**	5998 (59.5)**	5512 (62.8)**	6575 (55.6)**
Bakersfield, CA	11718	5668 (51.6)	5231 (55.4)	4763 (59.4)	5656 (51.7)
El Paso, TX	11544	5361 (53.6)	5800 (49.8)	5017 (56.5)	6429 (44.3)
Albuquerque, NM	10090	4760 (52.8)	5019 (50.3)	4637 (54.0)	5815 (42.4)
Miami, FL	8132	3918 (51.8)	4885 (39.9)	4165 (48.8)	6474 (20.4)
San Antonio, TX	8276	3738 (54.8)	4118 (50.2)	3608 (56.4)	4463 (46.1)
Tampa, FL	8929	3858 (56.8)	4268 (52.2)	3767 (57.8)	5496 (38.4)
Augusta, GA	9280	3503 (62.3)	3492 (62.4)	3775 (59.3)	4936 (46.8)
Lake Charles, LA	7924	3396 (57.1)	4426 (44.2)	3680 (53.6)	5991 (24.4)
Memphis, TN	7816	3472 (55.6)	5253 (32.8)	3961 (49.3)	5603 (28.3)
Denver, CO	7686	3604 (53.1)	-- --	-- --	4838 (37.1)
St. Louis, MO	7223	3186 (55.9)	-- --	-- --	4376 (39.4)
Washington, DC	7518	2958 (60.7)	3415 (54.6)	2996 (60.2)	4426 (41.1)
Chicago, IL	6147	2579 (58.0)	2941 (52.2)	2430 (60.5)	3500 (43.1)
Indianapolis, IN	6667	2385 (64.2)	2857 (57.1)	2421 (63.7)	3553 (46.7)
Minneapolis, MN	6158	2312 (62.4)	-- --	-- --	3296 (46.5)
Minot, ND	6118	2148 (64.9)	2012 (67.1)	2069 (66.2)	2787 (54.4)
Syracuse, NY	5444	2015 (63.0)	2226 (59.1)	1877 (62.5)	2913 (46.5)
Portland, OR	6384	1995 (68.8)	-- --	-- --	2842 (55.5)
Seattle, WA	6113	1573 (74.3)	-- --	-- --	2537 (58.5)

*Multiplication of tabular values of (ACES + AHEP) by (11.354) yields values in kJ/m².
**Numbers enclosed in parentheses represent percent differences.

TABLE 4
Comparative Annual Cost Savings Resulting from Lowering a Roof's Solar Absorptance from 0.8 to 0.3. Values Are Based on Electrical Energy Cost of 18.24 $\$/10^6 \cdot$Btu (0.06226 \$/kW·h) and Heating with Natural Gas Costing 5.58 $\$/10^6 \cdot$Btu (0.01904 \$/kW·h) at an Efficiency of 70%.* All Cases Are for a Roof Having a U' of 0.2 Btu/h·ft²·F (1.135 w/m²·k). Entries are in ¢/ft².**

Location	Bldg. A --	Bldg. B Case B1	Bldg. B Case B2	Bldg. B Case B3	Bldg. B Case B4	Bldg. C --
Phoenix, AZ	5.72	6.75	3.79	3.37	5.37	3.96
Bakersfield, CA	4.75	5.16	3.01	2.34	3.75	--
El Paso, TX	4.43	5.56	2.80	2.06	3.32	--
Albuquerque, NM	3.17	1.75	0.64	0.43	0.87	1.59
Miami, FL	3.25	4.16	2.66	3.54	5.48	--
San Antonio, TX	2.86	3.51	2.13	1.99	3.98	2.29
Tampa, FL	3.12	3.50	2.28	2.62	3.95	--
Augusta, GA	3.03	2.28	1.65	1.63	2.99	--
Lake Charles, LA	1.80	3.92	2.11	2.70	4.21	--
Memphis, TN	2.28	3.32	1.63	1.66	2.59	--
Denver, CO	1.80	--	--	-0.51	-0.55	--
St. Louis, MO	1.89	--	--	0.85	1.63	--
Washington, DC	1.25	1.52	0.51	0.74	1.10	--
Chicago, IL	0.71	0.62	0.01	0.27	0.36	--
Indianapolis, IN	0.90	1.17	0.24	0.60	0.93	0.94
Minneapolis, MN	0.38	--	--	-0.11	-0.09	--
Minot, ND	0.39	-0.55	-0.53	-0.52	-0.76	0.31
Syracuse, NY	0.42	0.21	-0.14	0.08	0.13	--
Portland, OR	0.72	--	--	0.76	0.29	--
Seattle, WA	0.34	--	--	-0.79	-1.04	--

*Cost values represent mid-1983 national averages for the commercial sector (DOE 1984).
**Multiplication of entries by (0.1076) yields values in \$/m².

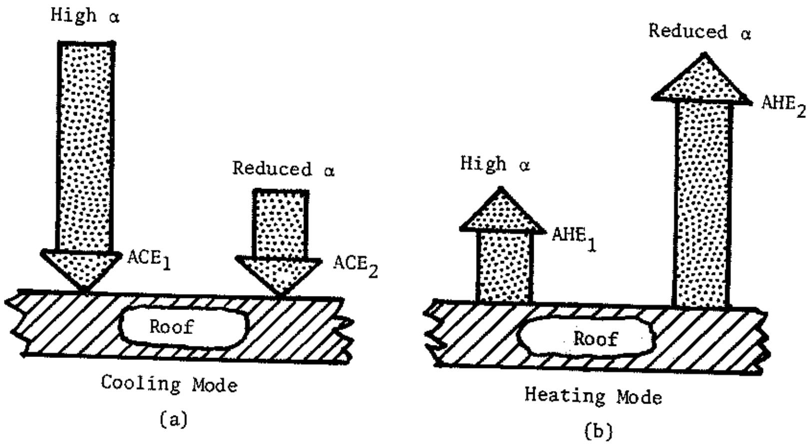

Figure 1. *Change in annual heat transfer through roof due to discrete change in* α

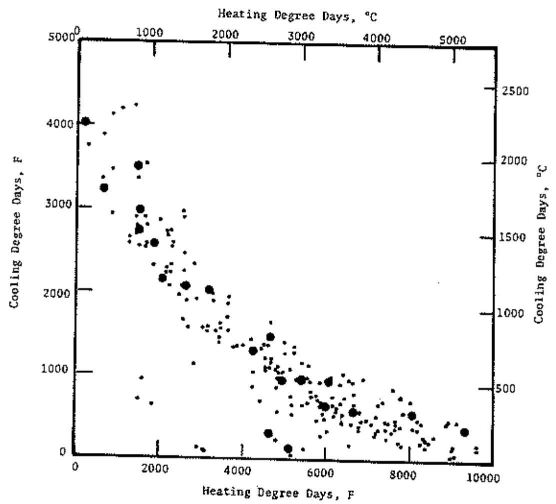

Figure 2. *CDD and HDD data for over 200 weather reporting stations within the U.S.*

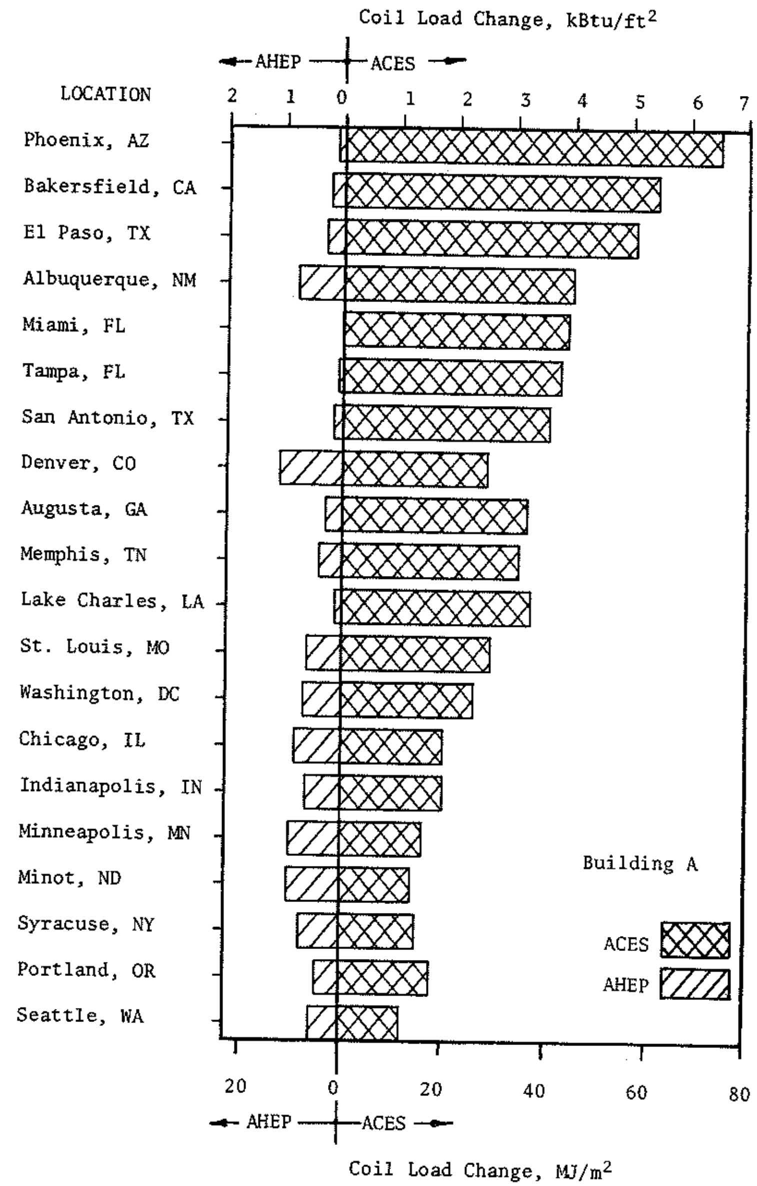

Figure 3. *Predicted ACES and AHEP for building A and* $U' = 0.2$ *Btu/h·ft^2·F (1.135 w/m^2·k)*

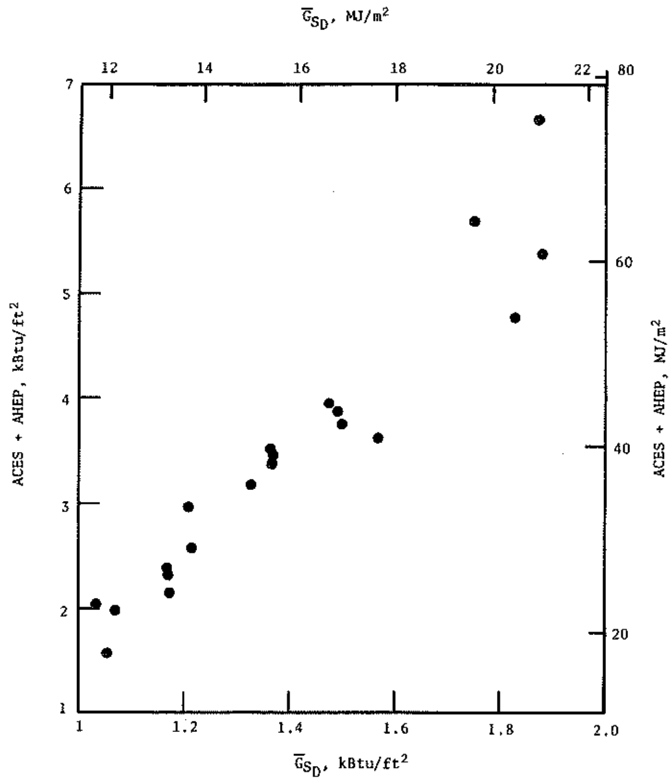

Figure 4. Variation of (ACES + AHEP) with $\overline{G}_{SD}$ for building A and U' = 0.2 Btu/h·ft²·F (1.135 w/m²·k)

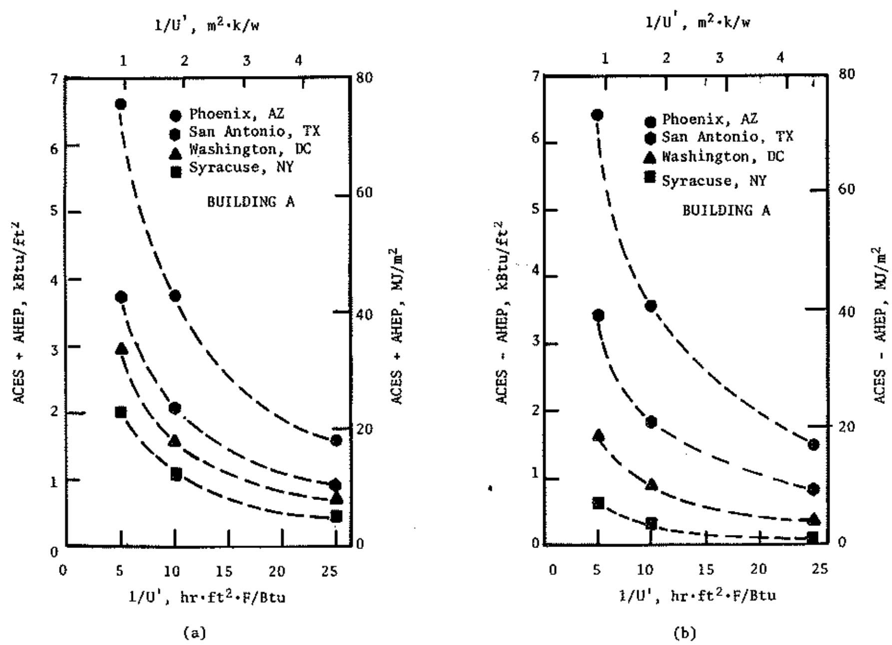

Figure 5. Typical variation of (ACES + AHEP) and (ACES - AHEP) with roof's thermal resistance for building A

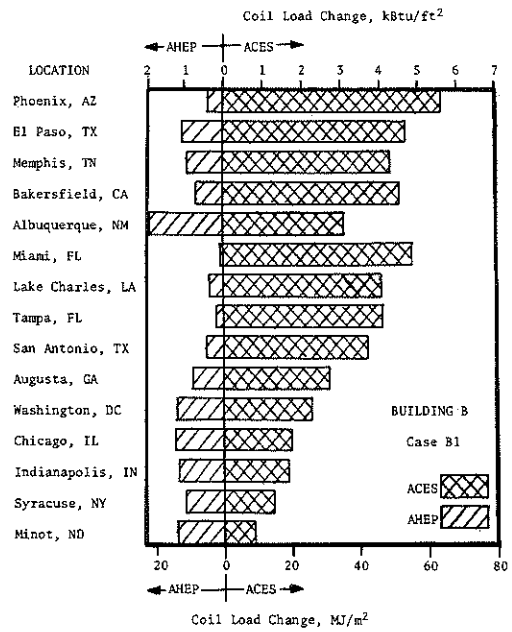

Figure 6. Predicted ACES and AHEP for building B (case B1) and U' = 0.2 Btu/h•ft^2•F (1.135 w/m^2•k)

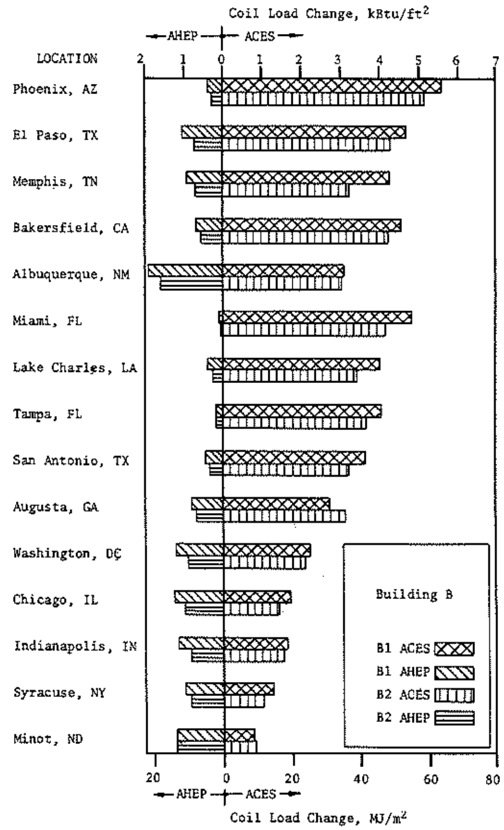

Figure 7. Comparison of predicted ACES and AHEP for cases B1 and B2 of building B with U' = 0.2 Btu/h•ft^2•F (1.135 w/m^2•k)

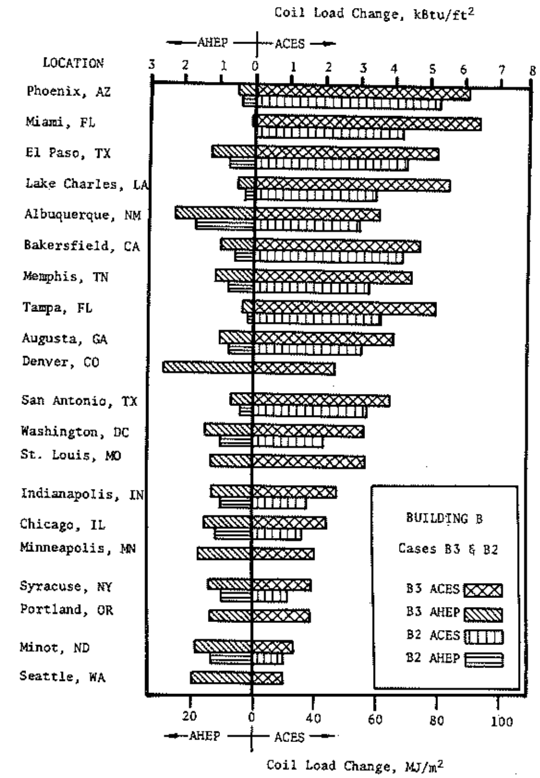

Figure 8. Comparison of predicted ACES and AHEP for cases B2 and B3 of building B with U' = 0.2 Btu/h•ft^2•F (1.135 w/m^2•k)

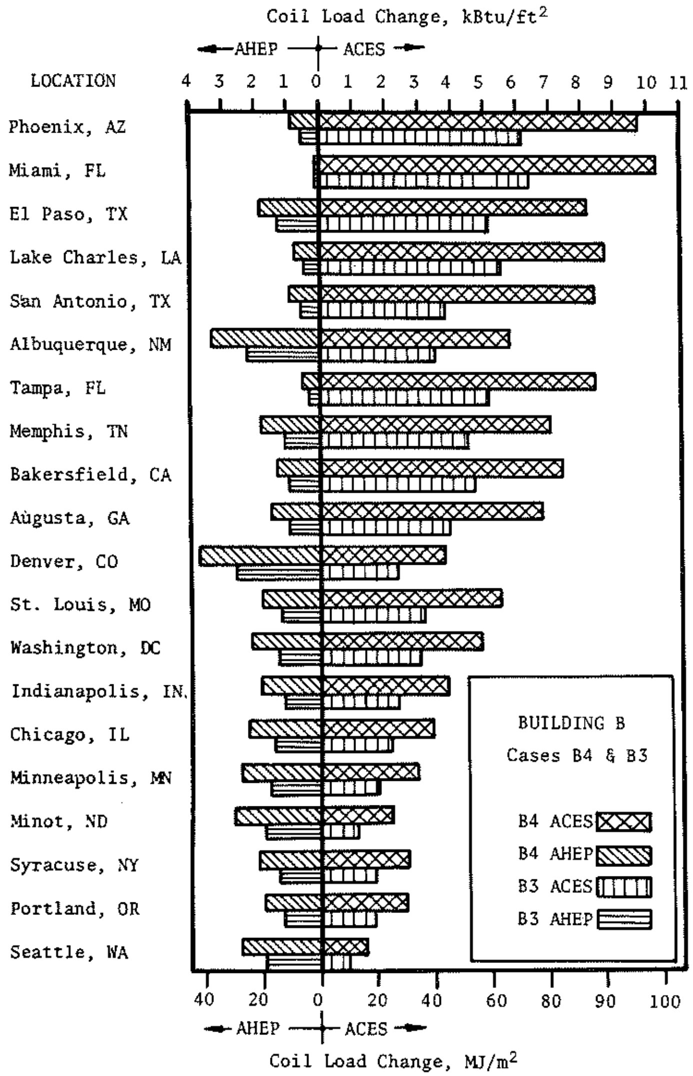

Figure 9. Comparison of predicted ACES and AHEP for cases B3 and B4 of building B with U' = 0.2 Btu/h•ft^2•F (1.135 w/m^2•k)

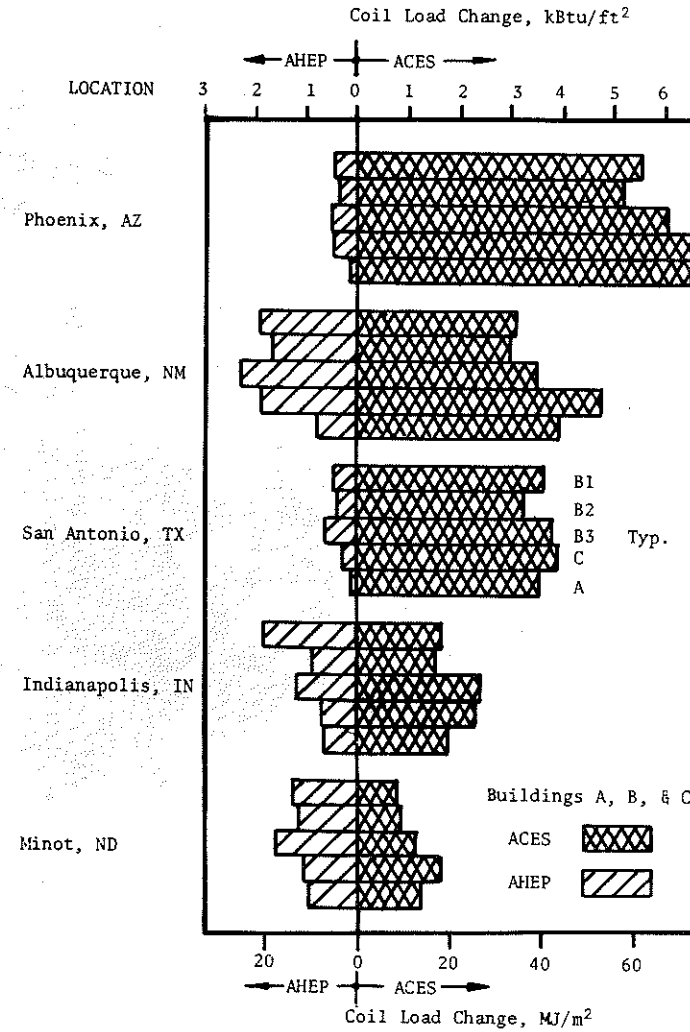

Figure 10. Predicted ACES and AHEP dependence on building model for U' = 0.2 Btu/h•ft^2•F (1.135 w/m^2•k)