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The Impact of Surface Reflectance on the Thermal Performance of Roofs: An Experimental Study

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THE IMPACT OF SURFACE REFLECTANCE ON THE THERMAL PERFORMANCE OF ROOFS: AN EXPERIMENTAL STUDY

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FOREWORD

This is one of a series of reports to be published describing research, development, and demonstration activities in support of the National Program for Building Thermal Envelope Systems and Materials. The National Program involves several federal agencies and many other organizations in the public and private sectors who are addressing the national objective of decreasing energy wastes in the heating and cooling of buildings. Results described in this report are part of the National Program through delegation of management responsibilities for the DOE lead

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Nomenclature

A	Flat roof's sunlit surface area
G_i	Long wavelength thermal radiation (energy rate per unit area) incident on the exterior roof's surface
G_s	Solar radiation (energy rate per unit area) incident on sunlit roof's surface
h_c	Outside roof surface air-film heat transfer coefficient
h_i	Inside roof surface air film heat transfer coefficient
h_o	Combined convective and radiative heat transfer coefficient ($h_c + h_r$)
h_r	Effective radiative heat transfer coefficient (see equation [4])
q_{net}	Instantaneous rate of heat transfer into roof's exterior surface
R	Thermal resistance of roof assembly (does not include air-film heat transfer coefficients
R^2	Correlation coefficient for linear regression analysis of data sets
T_a	Outside air temperature
t_m	Mean panel temperature
T_s	Roof's exterior surface temperature
T_{SA}	Sol-air temperature
x_i	Generic representation of variables

Greek Symbol

α_s	Hemispherical surface solar absorptance
ΔR	Difference between the energy emitted by a blackbody at T_a and the longwave radiation incident on a surface
ϵ	Infrared emittance
ρ_i	Hemispherical surface infrared reflectance
ρ_s	Hemispherical surface solar reflectance
σ	Stefan-Boltzmann Constant

BTESM REPORTS

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2. LBL-9821: *Measurement of In-situ Dynamic Thermal Performance of Building Envelopes Using Heat Flow Meter Arrays* (December 1979).

3. NBS/BS Series 123: *The Effect of Moisture on the Thermal Conductance of Roofing Systems* (April 1980).

4. ORNL/Sub-78/97726/I: *A Field Study of Moisture Damage in Walls Insulated Without a Vapor Barrier* (May 1980).

5. ORNL/CON-46: *An Appraisal of the M Factor and the Role of Building Thermal Mass in Energy Conservation* (July 1980).

6. NBSIR 80-2100: *Thermal Resistance Measurements of a Built-Up Roof System* (October 1980).

7. ORNL/TR-4679: *Roofing Felt on Polystyrene* (December 1980).

8. ORNL/TM-7629: *Roofing Research – A Bibliography* (April 1981).

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22. ORNL/Sub-42539/3: *Heat Transfer Characteristics of a Low Density Concrete Wall* (August 1983).

23. ORNL/CON-97: *Thermal Mass Assessment* (September 1983).

24. ORNL/Sub-81-22293/1: *Energy Savings Potential of Roofing Research* (December 1983).

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30. ORNL/Sub-82-22293/2: *Roofing Industry Perspective and Research Capability* (March 1985).

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32. ORNL-6171: *Insulation System Basics for Built-Up Roof* (June 1985)

33. ORNL-6172: *Decision Guide for Roof Insulation R-Value* (June 1985)

34. ORNL/Sub-70376/1: *A Survey of Building Anomalies and Assessment of Thermal Break Materials for Anomaly Correction, Volume I - Survey and Assessment* (July 1985).

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38. K/CSD/TM-56: *Analysis of Calibrated Hot Box Data for Three Concrete Walls* (September 1985).

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40. ORNL/CON-188: *Roof Test Center - A Preliminary Concept Paper* (November 1985).

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42. ORNL/Sub-43122/2: *Thermal and Hygric Roof (THR) Model Program* (January 1986).

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44. K/CSD/TM-59: *Calibration of Heat Flux Through a Wall Containing a Cavity - Comparison of Several Models* (February 1986).

45. NBSIR 86-3328: *The Assessment of Accuracy of In-Situ Methods for Measuring Building Envelope Thermal Resistance* (February 1986).

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69. ORNL/Sub/85-27486/1: *A Capacitance Probe for Measurement of Moisture Content in Open Pore Thermal Insulations* (January 1989).

70. ORNL/TM-10339: *A Study of The Effect of Lowering a Roof's Solar Absorptance in Its Thermal Performance and Associated Building Energy Use* (February 1989).

71. NISTIR 88-4008: *Corrosion of Metallic Fasteners in Low-Sloped Roofs: A Review of Available Information and Identification of Research Needs* (February 1989).

72. ORNL/TM-10675: *Design Description of the Large Scale Climate Simulator* (March 1989).

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EXECUTIVE SUMMARY

Peak surface temperature of a low-slope roof is affected by the roof's solar reflectance. A white roof will be cooler during hours of maximum sunshine than an otherwise comparable black roof. Roof surface temperature in turn affects the heat transfer through the roof assembly. Considering only energy needed to heat and cool a building, a reduced roof surface temperature is undesirable during the winter but desirable during the summer. The net annual impact on building energy use caused by changing the roof's surface reflectance depends on many factors, a principal one being location.

Concurrent experimental and analytical studies were undertaken by the Building Thermal Envelope Systems and Materials (BTESM) group within the Energy Division at Oak Ridge National Laboratory to study the effect of roof solar reflectance on surface temperature and heat transfer through the roof.

One 4 ft by 8 ft test panel on the Roof Thermal Research Apparatus (RTRA) at ORNL was devoted to an experimental study of the distinctions between white and black surfaces. Half of the panel was covered with a black polyisobutylene (PIB) membrane. A white PIB membrane was installed over the other half. The entire panel was insulated with two 15/16-inch thick fiberglass board providing a nominal assembly R-value of 7.5 hr-ft^2-°F/Btu. A heat flux transducer was installed in the center of each half section. This was positioned midway through the assembly and thermocouples were mounted below the membrane, at the midplane and beneath the insulation. Heat fluxes from both transducers, all temperatures and local weather data were recorded hourly.

Data accumulated over an 18-month period were studied. Cumulative and instantaneous heat fluxes through each section and hourly surface temperatures were compared and seasonal distinctions in the measurements were noted. The reflectance of both membranes was measured with a reflectometer and estimated using a surface energy balance with measured data as input. Some changes (≈0.05 to 0.1) were noted. A plausible explanation was that dirt accumulation and environmental factors altered the characteristics.

Conclusions of the study include:

1. With increased interest in use of single-ply membranes in the roofing industry, the fact that a black membrane's temperature may exceed that of a white membrane by 40 to 50°F during peak sunlit hours is useful to manufacturers of membranes and membrane adhesives.

2. Nighttime surface temperatures of the two membranes were nearly identical throughout the year, showing that the infrared emittances are the same despite the distinction in their reflectance of solar radiation.

3. The data show that there can be a difference in the HVAC energy required for a building with a white compared to that for one with a black roof. The net annual effect, however, depends on many factors; for example, climate, roof insulation, and building type. This suggests that modeling may be the most practical means of evaluating the influence of reflectance on building energy use in lieu of an extensive experimental effort.

4. The expression for an energy balance at the surface of a dry roof was examined with measured data as input from several sets of data over the test period. Internal consistency was found but an estimate of uncertainty indicated that, in addition to good confidence in all measurements, validation of the energy balance is noticeably dependent on the heat transfer coefficient. A plausible explanation of the variance in the trends of results when checking the balance with nighttime data was that latent effects may have been present.

5. When considering any additional experiments, the following suggestions are offered based on observations made in this work.

   i. Some means for monitoring the presence of moisture should be included.

   ii. An experiment should be devoted explicitly to determining any changes in reflectance of roof surfaces over long-term exposure to outdoor conditions.

   iii. Some experimental effort should be devoted to determination of the heat transfer coefficient for typical roofs. While this effect may seem small in evaluating total thermal resistance for a well-insulated roof, it is most important for roofs with little or no insulation and in determining transient surface thermal behavior.

   The evaluation of experimental data made in this study has aided in indicating needs for improving studies of reflectance effects and has provided insight needed in interpreting results of modeling a whole building with DOE 2.1B. The ongoing modeling effort is to be used to generate guidelines on how to estimate changes in building energy use at different climates caused by a change in the roof's solar reflectance.

The Impact of Surface Reflectance on the Thermal Performance of Roofs: An Experimental Study

ABSTRACT

The thermal effects of black versus white membranes on an insulated low-slope roof were studied over an 18 month period as one of a series of tests conducted on the Roof Thermal Research Apparatus (RTRA) at the Oak Ridge National Laboratory (ORNL).

Half of the insulated roof test panel's 4 ft x 8 ft surface was covered with a black polyisobutylene (PIB) membrane. A white PIB membrane was installed over the other half. Both sections were identically insulated with two 15/16-inch thick fiberglass boards to provide a nominal thermal resistance of 7.5 hr-ft^2-°F/Btu. A heat flux transducer was installed in the center of each section with thermocouples placed below the membrane, at the midplane and beneath the insulation. Local weather data together with specimen heat flux and temperature data were recorded hourly.

Seasonal differences in measured heat flux and temperature data between the black and white membranes are reported. These data include cumulative and instantaneous heat fluxes and hourly surface temperature variations. Peak membrane temperatures were observed to differ by up to 50°F during the day. Nighttime differences in membrane surface temperatures were negligibly small, typically much less than 1°F.

Changes due ostensibly to dirt accumulation and local environmental factors were observed in surface reflectance values calculated from the energy balance at the roof membrane and from reflectometer measurements. This suggests that long-term studies of the reflective characteristics of white roofs in service are needed to determine if any benefits continue without significant alteration.

The experimental results reported here are currently being used to validate numerical modeling of surface effects upon roof system performance and building energy requirements. The results of the modeling and analysis efforts will be reported in a subsequent paper.

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INTRODUCTION

The thermal performance of low-slope roofs as affected by the choice of a black or white membrane for the exterior layer is the focus of this study. The results of an extensive experimental study conducted at the Oak Ridge National Laboratory (ORNL) are discussed. The data provide useful insight for developing generalized thermal performance predictions for low-slope roofs at various geographical locations and for different surface reflectances.

Elevated roof surface temperatures caused by solar flux can affect the performance of roofing materials. Roof temperatures also impact HVAC system loads. An increase in a sunlit roof's temperature increases summer heat gain but reduces winter heat loss. The energy-conservation impact of black versus white is dependent upon numerous factors related to general conditions, such as climate, and design specific parameters, such as internal loads, envelope R-values, etc. What works well with one design or location may not be appropriate elsewhere. Consequently, the ability to predict the effect of roof reflectance on thermal performance for different locations and HVAC operating conditions is needed by engineers and architects.

The experimental work described herein was undertaken as one step in understanding and quantifying how a roof's solar reflectance affects surface temperature variation and heat transfer through a roof assembly. The experimental investigations are part of an ongoing body of work directed towards predicting the energy-conservation consequences of increasing a roof's solar reflectance for different locations throughout the United States.

A brief review of related studies and an outline of the equation representing the surface energy balance for a sunlit roof precede the description of the experimental program.

RELATED STUDIES

The roof is an important part of the building envelope. Many low-rise industrial and commercial buildings, as well as some residences, have low slope roofs constituting a major portion of the above ground building envelope. It has been estimated that there are about 1100 square miles of low slope roofs within the United States and that almost 40 percent of these have no insulation at all. [1] Increasing roof insulation can make roofs more energy efficient; however, alternate energy-savings schemes, such as use of evaporative roof cooling or highly reflective surfaces, have also received attention and are promoted by some manufacturers.

The use of highly reflective roofs has been discussed widely in the literature [2-11, 17, 18]. Attention to light colored roof membranes is increasing as more systems become available. A key motivating factor is design aesthetics, but the energy-savings potential can also be important. The issue of "white" versus "black" was discussed in an issue of "Roofing Spec". [2] Claims by many "white" roof advocates were noted, but caution was suggested in connection with selection of a roof solely on the basis of color. The unbiased treatment concluded that it was impossible to make a blanket statement about the better choice of black or white since each had points of relative merit and deficiencies.

The ASHRAE Handbook of Fundamentals [3] outlines a simple method for calculating cooling loads. The cooling load temperature difference (CLTD) accounts for surface temperature increase caused by insolation. CLTDs are tabulated for specific cases and a procedure is given for correcting the values for other conditions. One correction factor pertains to color of the exposed surface. The effect is discussed only in connection with cooling. When sizing HVAC equipment, maximum loads are to be determined; solar effects must be included to determine maximum cooling load but should be ignored when determining maximum heating load. When considering the effect of color as an energy conservation measure, the impact on both heating and cooling energy needs to be evaluated.

Dubin's [4] treatise on energy conservation included nomographs that facilitate estimation of roof heat gain and roof heat loss for different magnitudes of solar intensity and roof insulation using two values of surface solar absorptance. Chang and Busching [5] used Dubin's nomographs in assessing the effect of color in a study of the energy-saving potential of roofing research within the United States. Within the scope of those estimates, they stated that the annual wintertime heat loss through a roof having a solar reflectance of 20 percent is about 12 to 25 percent less than the annual heat loss through an otherwise similar roof having a solar reflectance of 70 percent. Conversely, the summertime heat gain was noted to be about two to four times larger for the 20 percent reflective roof compared to the 70 percent reflective one. The estimates showed, for a roof having a thermal resistance of about 5 hr-ft^2-°F/Btu, a maximum annual cooling savings of about 13,000 Btu/ft^2 in the Southwest and a maximum annual heating penalty of about 16,000 Btu/ft^2 in the North.

Reagan and Acklam [6] made heating and cooling calculations for several residences in Tucson, Arizona. Daily heat gains for one residence were calculated for roof reflectance values of 25 and 65 percent. Noting that the calculations gave a much lower roof heat gain for the case of reduced roof reflectance, the effect on overall energy savings is still small when the roof's contribution to the total house load is small.

Griffin [7] contrasted use of heat-reflective, aluminum asbestos-fibrated coating on a roof to use of conventional black asbestos-fibrated coating using ASHRAE's CLTD method for the estimates. He concluded that a savings of 0.25 \$/ft^2 in present worth could be realized over 20 years in climates characterized by long cooling seasons and noted that other climatic factors complicated estimates of the impact on heating energy needs.

Talbert [8] made estimates of the expected energy savings due to use of a roof surface having a solar reflectance of 70 percent. The location used was Phoenix, Arizona and two estimation methods were employed. One followed the ASHRAE CLTD method and the other utilized the equivalent sol-air temperature difference. Correlating his estimates with those of Griffin, he predicted an annual cooling savings of about \$1600. However, it was acknowledged that a detailed computer model should be used to more accurately determine energy savings for highly reflective roofs.

Interest in the use of reflective roofs prevails as evidenced by both commercial advertisements and articles in trade magazines related to roofing. One such article [9] reported a 5 to 30 percent annual reduction in air-conditioning costs at 130 establishments of a commercial firm who installed white roofs on their places of business.

Another article [10] described an on-going research project in a Southern state focusing on energy-efficient building methods. Three 14- by 22-ft structures were being tested simultaneously. The control structure was described as being built according to traditional technology of 10 to 15 years ago. Its roof was a conventional built-up roof (BUR). The second building had a highly reflective white roof mastic applied over the BUR. The third building incorporated a variety of energy-efficient techniques. Preliminary results for one day's operation in October 1985 indicated a 43 percent reduction in power consumption by the second building, a reduction attributable solely to the use of the reflective white mastic on the roof.

The "white" versus "black" issue was mentioned in a newspaper article [11] discussing work at the University of Florida on the use of aluminum foil in attics as an energy-conservation measure. The article implied that the researcher wished to dispel the notion that roof color makes a difference in the energy it absorbs by quoting him as saying, "White may be a little bit cooler for the first year or so, but it will turn gray within a few years and not do the job. The texture of the roof plays a more important role than color in many cases."

ENERGY BALANCE AT EXTERIOR ROOF SURFACE

A mathematical expression for the instantaneous energy balance at the outer surface of a roof is important in evaluating experimental data and for modeling heat flux through the building thermal envelope. Boundary conditions at a sunlit roof surface are complex and transient. Typically, a low-slope roof assembly is composed of a metal deck, vapor retarder, one or more layers of insulation, a waterproof membrane and usually some form of ballast. The assembly is, therefore, nonhomogeneous and multi-layered. Detailed thermal analysis is amenable to numerical techniques. As shown in Figure 1, the instantaneous energy balance at a sunlit roof's surface can be expressed as:

$$q_{net}/A = (1-\rho_s)G_s+(1-\rho_i)G_i-h_c(T_s-T_a)-\epsilon\sigma T_s^4 \qquad (1)$$

Each term on the right-hand side involves a transient quantity, the instantaneous relationship of which can result in large temperature gradients just inside the roof layer. For modeling work, equation (1) must be solved simultaneously with the conduction equation for the roof assembly. The results are highly sensitive to the accuracy with which the convection and radiation terms are supplied, as shall be shown later in the discussion of the experimental results.

Equation (1) describes an idealized case when the heat transfer mechanisms

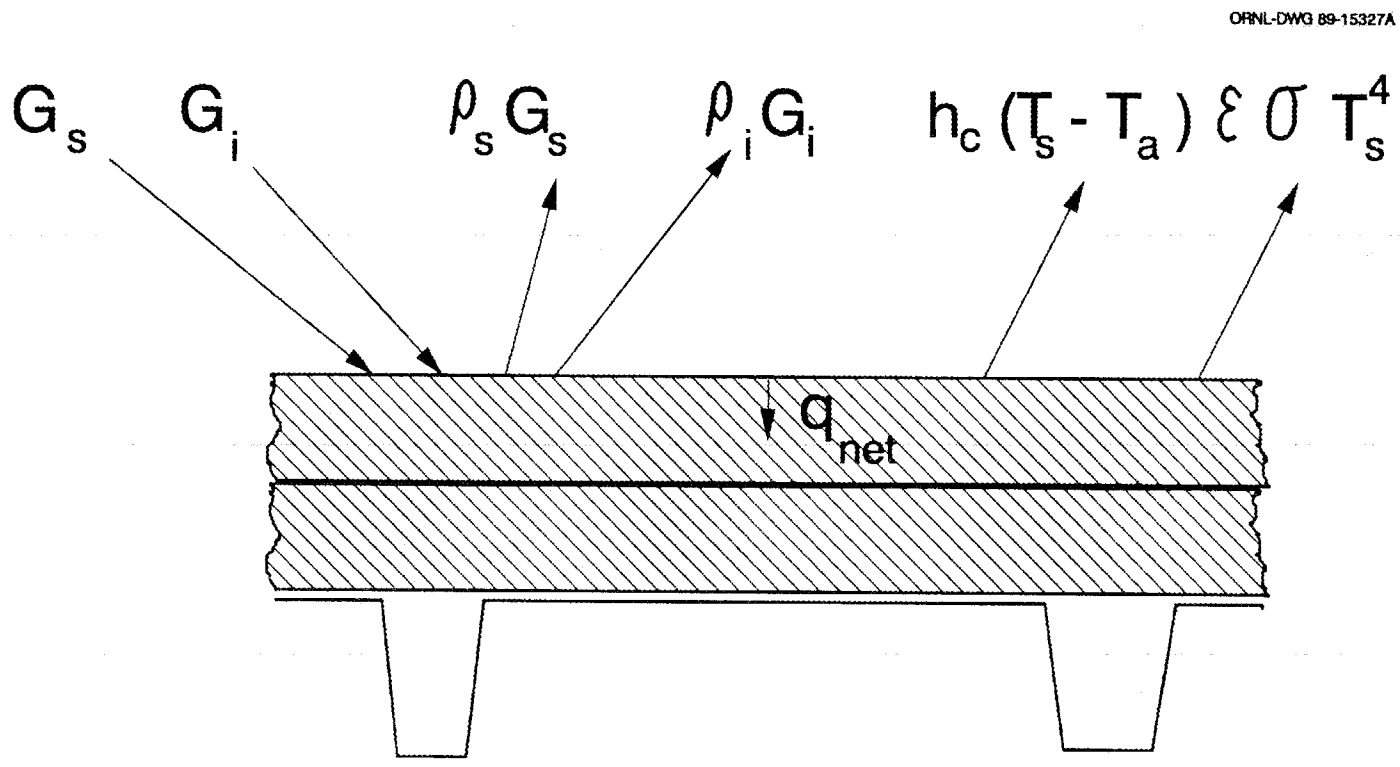


FIG. 1: Energy balance at the exterior surface of the roof assembly in the absence of moisture loading.

are restricted to conduction through the roof, radiation, and convection. In practice, roofs can be covered during certain periods by water in the form of rain, snow, dew or frost. When water is condensing or evaporating on the surface, or a layer of frost is subliming, equation (1) should be modified to include the latent energy associated with the phase change taking place. Likewise, rain or snow require additional modifications to properly describe their impact.

Equation (1) is the basis for defining the sol-air temperature, a hypothetical air temperature which would cause the same net rate of heat transfer to the surface using a combined convective-radiative film coefficient. By rearranging equation (1), the sol-air temperature is given by:

$$T_{SA} = T_a + \frac{\alpha_s G_s}{h_o} - \frac{\epsilon \Delta R}{h_o} \tag{2}$$

The combined convective-radiative external heat transfer coefficient h_o is defined by:

$$h_o = h_c + h_r \tag{3}$$

where

$$h_r = \epsilon\sigma(T_s^2 + T_a^2)\ (T_s + T_a) \tag{4}$$

While both h_c and h_r are temperature dependent, h_c also depends on the exterior boundary layer or, more specifically, on the flow field adjacent to the roof's surface. Uncertainty in the external film coefficient is a critical difficulty in accurately modeling roof heat transfer along with the difficulty in obtaining the surface radiative characteristics, α_s and ϵ.

SOLAR REFLECTANCE VALUES FOR ROOFING

While the reflective character of a roof is often associated with its color, color alone is not an adequate technical indicator. Solar energy principally lies within the wavelength band of 0.1 to 2.5 microns. Color specifically relates to the visible band of 0.35 to 0.7 microns. Strictly speaking then, the roof's reflectance for the solar band is needed.

Equation (1) illustrates the importance of roof solar reflectance in the energy balance at the roof's surface. A critical issue is to identify realistic solar reflectances for actual roofs. Reagan and Acklam [6] listed reflectances for a variety of building materials, including built-up roof (BUR) materials. These ranged from 12 percent for dark pea gravel to 75 percent for a white coated smooth surface. The DOE-2 manual [13] contains a table of suggested reflectance values which are listed in Table 1 for reference. Published solar reflectance values for typical building materials can range from five to 95 percent [3, 6, 8, 13].

A complicating factor for reliably modeling highly reflective sunlit surfaces is that the reflectance will change during the roof's service life. Many factors can influence the aging characteristics of a reflective membrane. Very little has been reported for changes in roof solar reflectance over an extended service period.

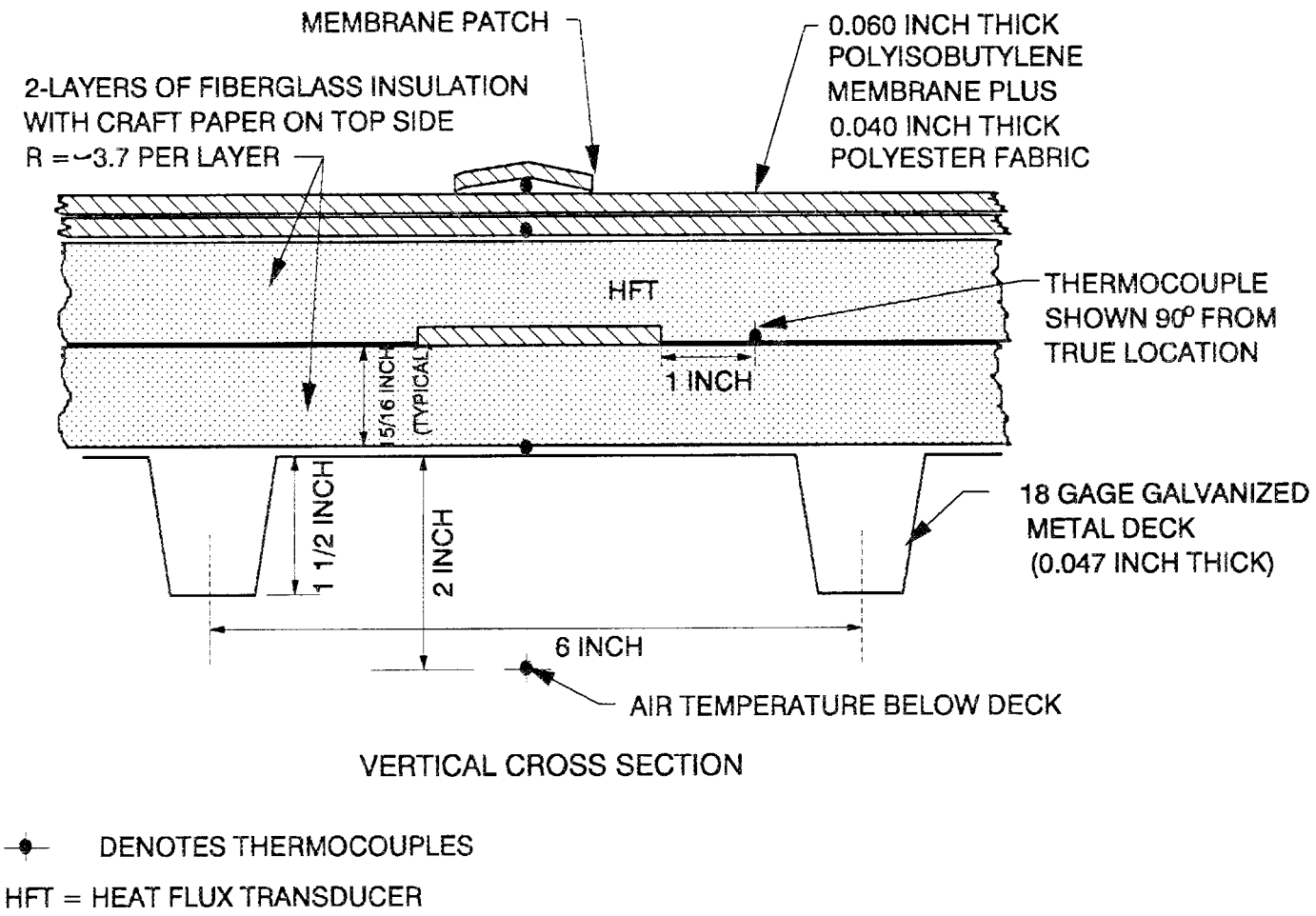
EXPERIMENT DESIGN

The Roof Thermal Research Apparatus (RTRA) at the Oak Ridge National Laboratory (ORNL) is an outdoor facility designed to test assemblies of low-sloped roof systems. Constructed of masonry block with a concrete slab floor, the interior dimensions are approximately 8 ft by 27 ft. Both the air temperature and relative humidity inside the building are controlled. The roof is designed for the insertion and removal of four test panels, each measuring 4 ft by 8 ft. Four experiments can therefore be conducted simultaneously with the bottom surfaces of the panels exposed to controlled indoor conditions while their top surfaces are exposed to the outdoor weather of East Tennessee.

The test panels are instrumented with temperature sensors and heat flux transducers. Weather measurements include solar flux, infrared flux, wind velocity, barometric pressure, precipitation, relative humidity and ambient air temperature. An automatic data acquisition system collects hourly data and transfers it to computer files for long-term storage and subsequent analysis.

A panel was installed in March 1986 for comparing the thermal performance of black and white roof membranes. A cross section of the test panel is shown in Figure 2 and a plan view is given by Figure 3. One half of the test panel was covered with a white polyisobutylene (PIB) roof membrane while a black PIB layer was applied to the other half. Both membranes were supplied by the same manufacturer. Underneath the PIB membranes were two layers of 0.9375 inch thick fiberglass roof insulation board, providing a nominal thermal resistance of 7.5 hr-ft^2-°F/Btu. The bottom of the assembly was a typical corrugated sheet metal deck. Two heat flux transducers were installed. These were calibrated at ORNL with a screen tester whose accuracy has been demonstrated within one percent using National Bureau of Standards standard reference materials [19]. Each heat flux transducer was placed between two layers of insulation and centered in its respective half of the assembly. Several thermocouples were installed to monitor temperatures for each half of the specimen. Sensor locations are indicated in Figures 2 and 3.

Data acquisition began in March 1986. Except for occasional gaps caused by power outages or temporary equipment failure, over 18 months of hourly data have been recorded continuously since initiation of the test. Over most of the test period, data logged at each hour was obtained by averaging readings taken every minute over the interval from five minutes before the hour until five minutes after the hour. The procedure was modified in April 1987 to continuously record data every five minutes with hourly averages calculated from 30 minutes before to 30 minutes after the hour.



VERTICAL CROSS SECTION

DENOTES THERMOCOUPLES

HFT = HEAT FLUX TRANSDUCER

FIG. 2: Cross section of roof test panel.

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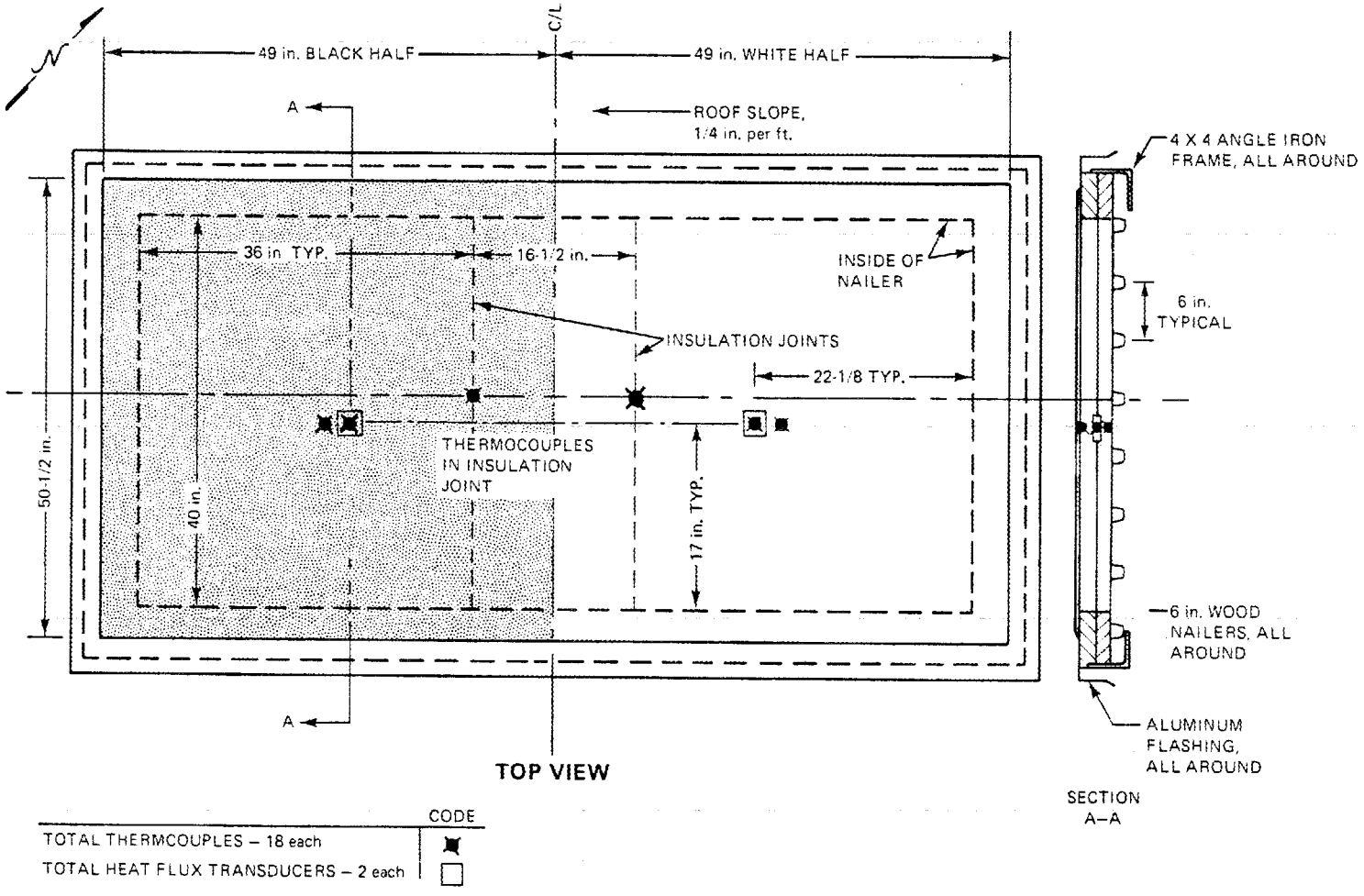
PLAN VIEW AND SECTION OF BLACK AND WHITE MEMBRANE TEST



	CODE
TOTAL THERMCOUPLES – 18 each	■
TOTAL HEAT FLUX TRANSDUCERS – 2 each	□

FIG. 3: Plan view of roof test panel.

EXPERIMENTAL RESULTS

Typical experimental results comparing black and white behavior are discussed below. The comparisons are very sensitive to daytime versus nighttime conditions. To avoid bias, only those days with a complete 24-hour record were used. Discarding days with missing data resulted in the elimination of 39 days during the first year of testing: 4 in March, 3 in April, 6 in May, 1 in June, 4 in July, 8 in October, 8 in November, 2 in January 1987, and 3 in February 1987. Consequently, 7,824 hours of data are examined for the first year's operation. For certain considerations, data obtained after the end of the first year are also included.

Variation of Surface Temperatures

As shown in Figure 2, PIB surface temperatures were measured by thermocouples positioned on top of the membrane but underneath a small patch of membrane material glued to the surface. Another thermocouple was located between the membrane layer and the top of the insulation. These two agreed very closely throughout the tests. Temperature data for a summer week and for a winter week, both having clear skies and good weekly insolation, are shown in Figures 4 and 5, repectively. Temperature data for a winter week during which several cloudy days occurred are shown in Figure 6. Data for a week in September 1986, Figure 7, illustrate a variety of weather conditions. The first five days were cloudy with heavy rain occuring twice. The last two days were clear and sunny.

Several observations can be made from the temperature variations shown in Figures 4 through 7. Daytime behavior is characterized by large peaks in surface temperature, particularly during clear days. During the summer, peak black surface temperatures reached 180°F, exceeding ambient air temperatures by 80 to 90°F. The white membrane was 50°F cooler than the black membrane at these times, never exceeding 135°F. Similar behavior occurred for clear weather during the winter, although temperature peaks were moderated to 121°F and 89°F for the black and white membranes, respectively. The effect of clouds in attenuating these differences can be seen in Figures 6 and 7. The effect of rain is also shown for two days in Figure 7.

Equally as noteworthy as the differences that occurred during the daytime is the similarity of the nighttime behavior of the two membranes. The black and white surface temperatures agree almost exactly during the night hours. This can be seen by the coincidence of surface temperatures during night hours for all cases shown in Figures 4 through 7.

The agreement between nighttime black and white surface temperatues was quantified by analyzing all of the data obtained when insolation was not present. Due to file size limitations for the computer program, two sets of data were assembled for the analysis. The first set covers the period from March 7 through August 22, 1986. The second set extends from October 10, 1986 through April 14, 1987. Linear regressions of nighttime black surface temperature on nighttime white surface temperature were

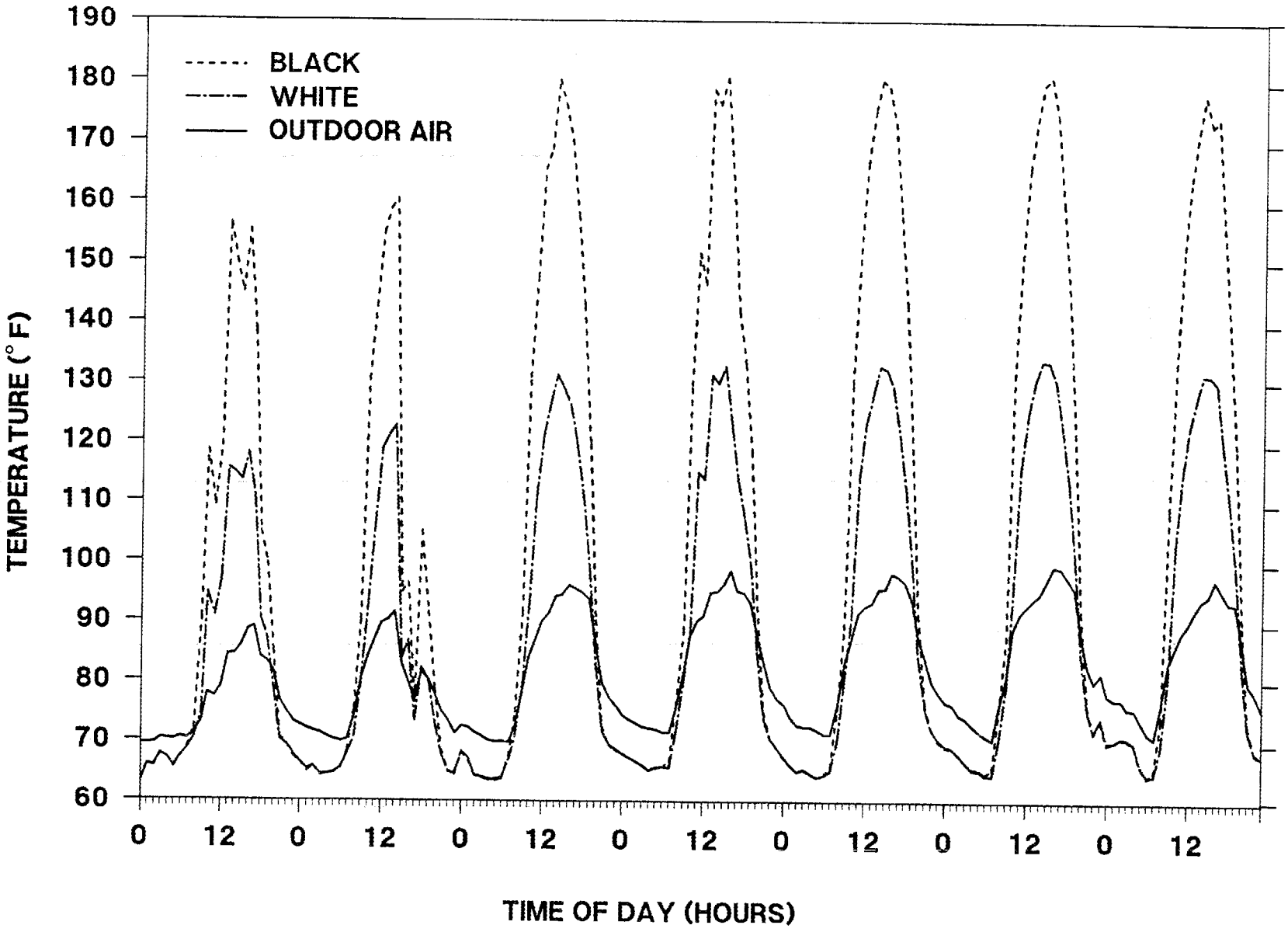


FIG. 4: Diurnal temperature cycling of black and white roof membranes and outdoor air during clear weather, July 15-21, 1986.

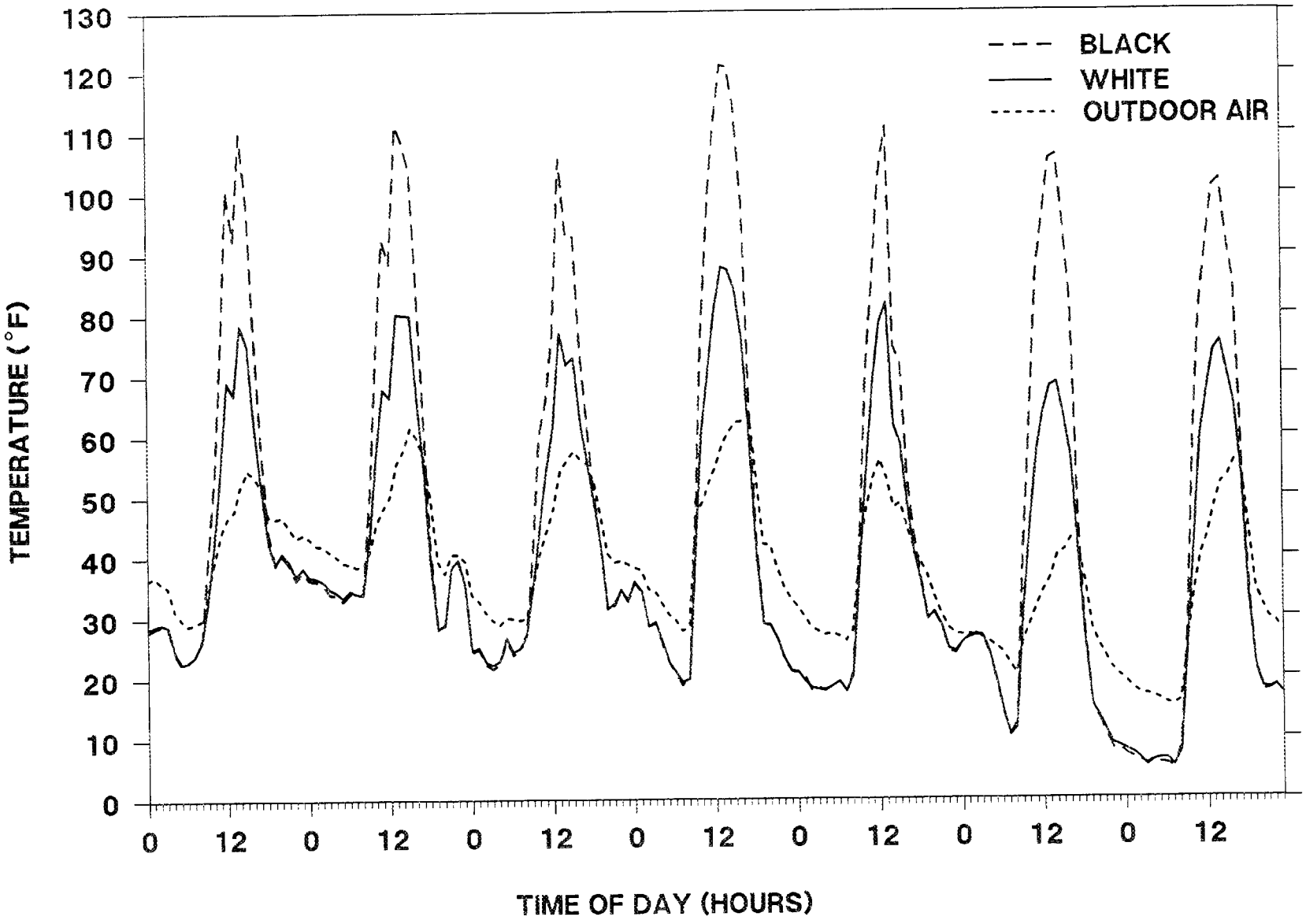


FIG. 5: Diurnal temperature cycling of the black and white roof membranes and outdoor air during clear weather for a winter week, February 4-10, 1987.

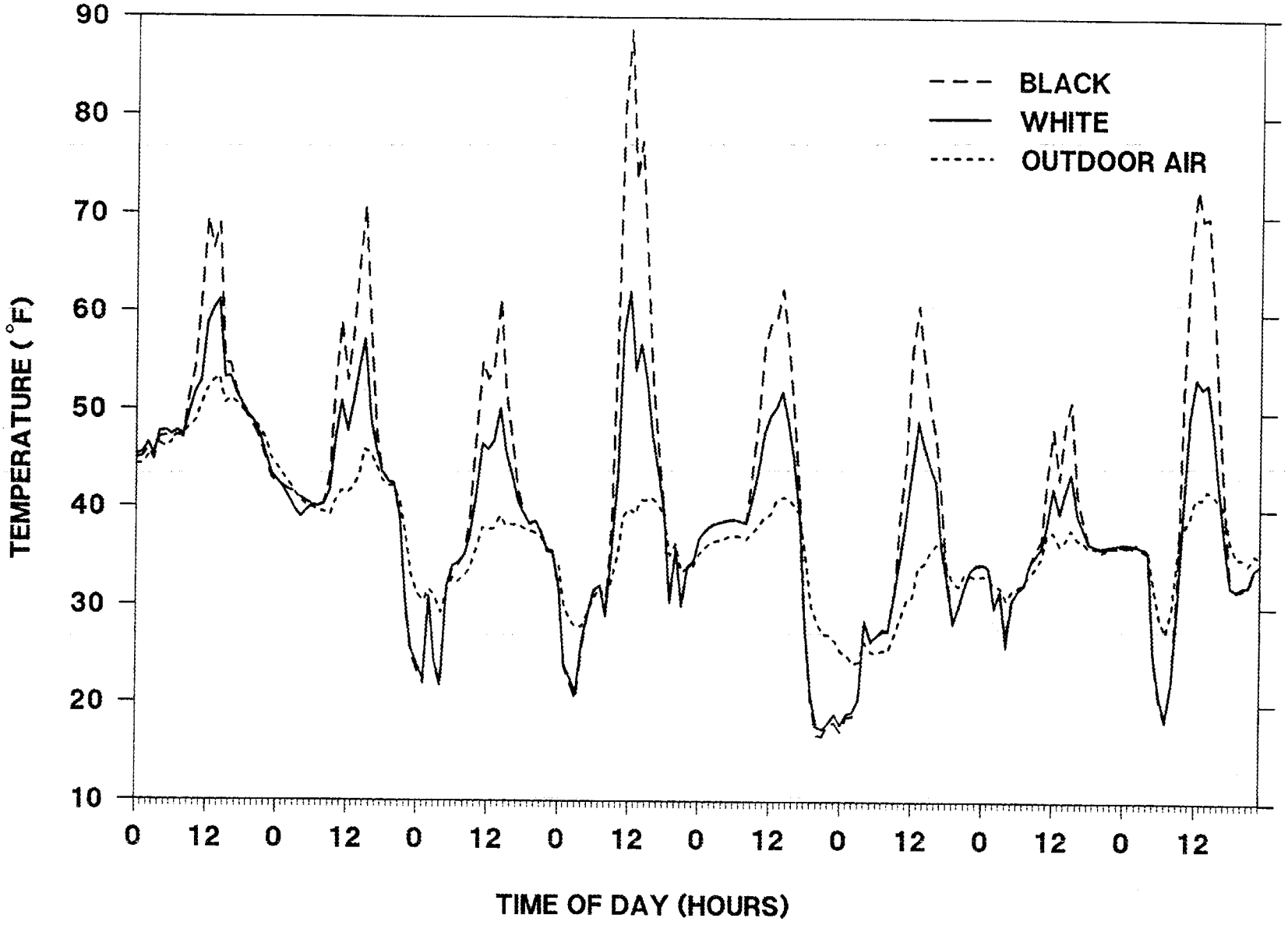


FIG. 6: Diurnal temperature cycling of black and white roof membranes and outdoor air during winter week with cloudy days, December 24-31, 1986.

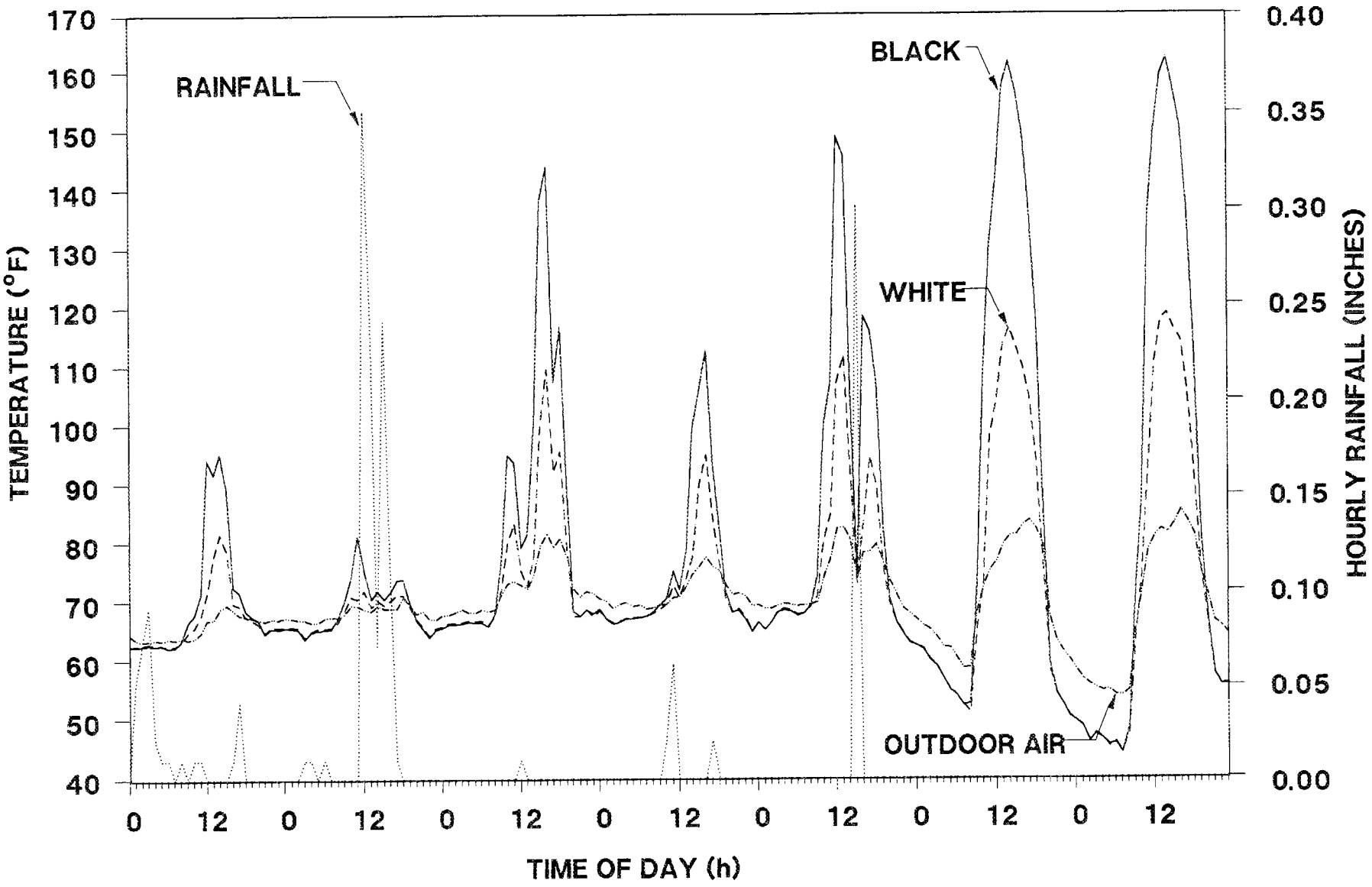


FIG. 7: Diurnal temperature cycling of black and white roof membranes and outdoor air during a five day period of cloudy weather with rain followed by two clear days, September 1-7, 1986.

performed and the results are shown in Table 2. The slopes of the resulting straight lines were within 0.35 percent of 1.00. The data are highly linearly correlated with multiple correlation coefficients, R^2, of 0.9996 for each regression. The standard error in estimated temperatures for the two regressions are 0.55 and 0.42°F, less than the experimental uncertainty of comparing the two measurements (+/- 0.71°F). This comparison emphasizes the nearly identical variation of white and black surface temperatures during non-sunlit hours and indicates that the two surfaces have similar infrared radiative characteristics.

Roof surface temperatures are important not only to building energy performance, but are also of interest to manufacturers and designers working with temperature sensitive adhesive systems, thermoplastic components with softening points below 200°F, temperature dependent strength and permeability properties, and the general problem of controlling thermally induced stresses in roofs which typically contain materials with very different thermal expansion coefficients. Using the 7,824 hours of data from the 326 days with complete diurnal records during the first year, the distribution of surface temperature extremes in 10°F increments are shown in the bar chart of Figure 8 for both the black and white PIB membranes. For the black membrane, surface temperature exceeded 110°F during 1,264 hours, or 16.2 percent of the time. The black surface exceeded 180°F for nine hours. The white membrane's surface temperature exceeded 110°F for only 381 hours, or 4.9 percent of the time, and never exceeded 140°F. It is apparent that materials adjacent to a black roof membrane must be able to withstand substantially higher temperatures and more prolonged exposure periods than those adjacent to a white membrane.

Roof Heat Transfer

Using a highly reflective roof to obtain HVAC energy savings is a controversial subject. Heat gain through the roof can represent an increase in cooling load or a decrease in heating load, depending on the building's instantaneous load requirements. Therefore, changing roof reflectance to reduce heat gain during sunlit hours may have a counteracting cumulative effect overall.

The experimental data included hourly measurements of the instantaneous heat transfer across the midplane of the roof assembly under both the black and white membranes. Both sections experienced positive and negative heat flux readings daily throughout the year due to diurnal transients. Positive fluxes represent heat flow out of the building while negative values indicate heat flow into the building. Weekly cumulative totals, obtained by summing the hourly readings for 168 hours of continuous data, are useful for comparing black and white performance.

Using the same time periods as described in the preceding discussion of surface temperature behavior, variations of cumulative flux throughout each week are shown in Figures 9, 10 and 11. For the summer week in July 1986 (Figure 9), the cumulative heat transfer into the building per unit roof area was approximately 600 Btu/ft² for the black section while the white roof experienced a cumulative gain of about 200 Btu/ft². For the winter week in February 1987 (Figure 10), a reverse trend is noted with

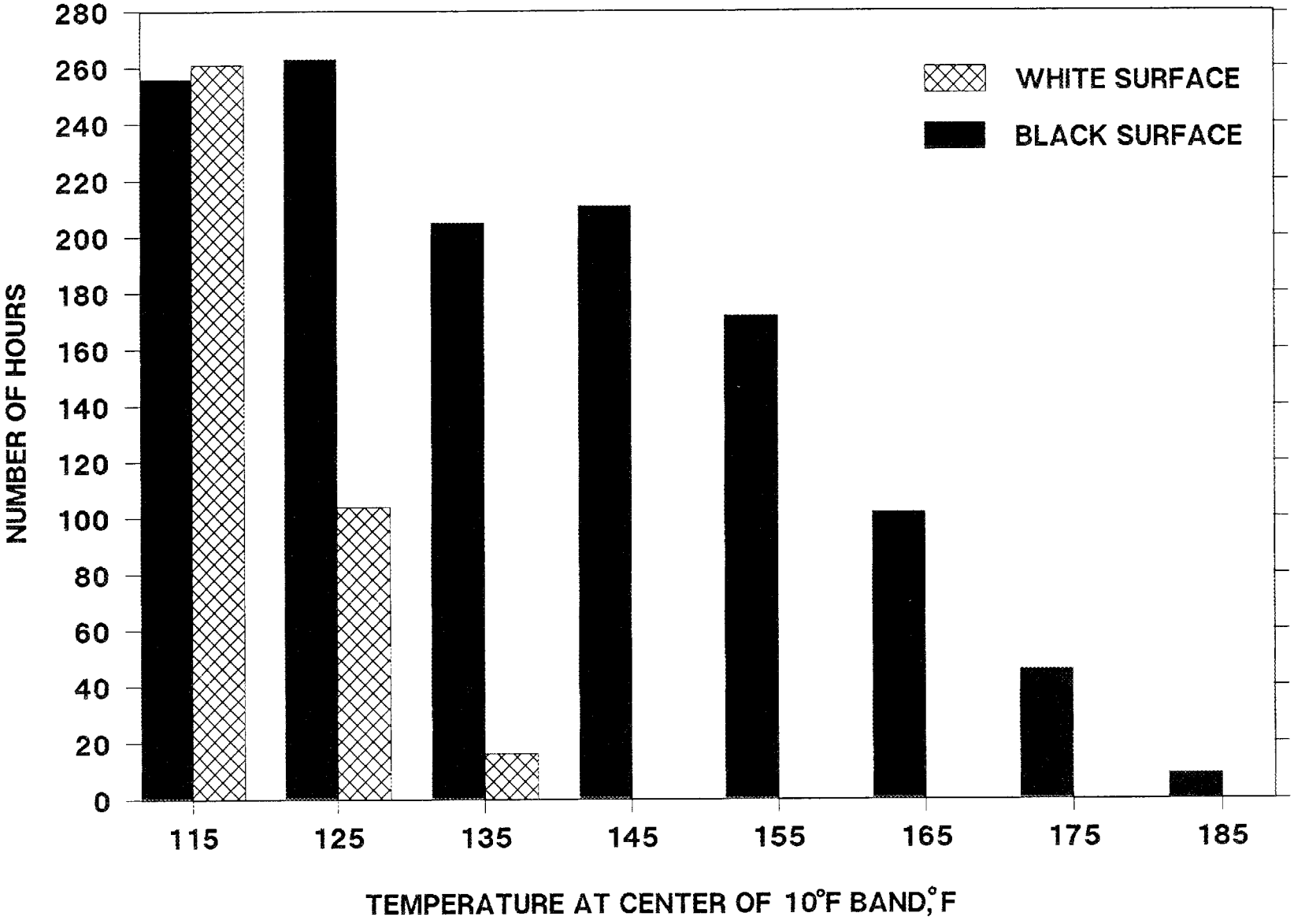


FIG. 8: Number of hours with 326 days of data collected over a year that the black and white roof membranes recorded temperatures at or above 110°F. Data segregated into 10°F bands.

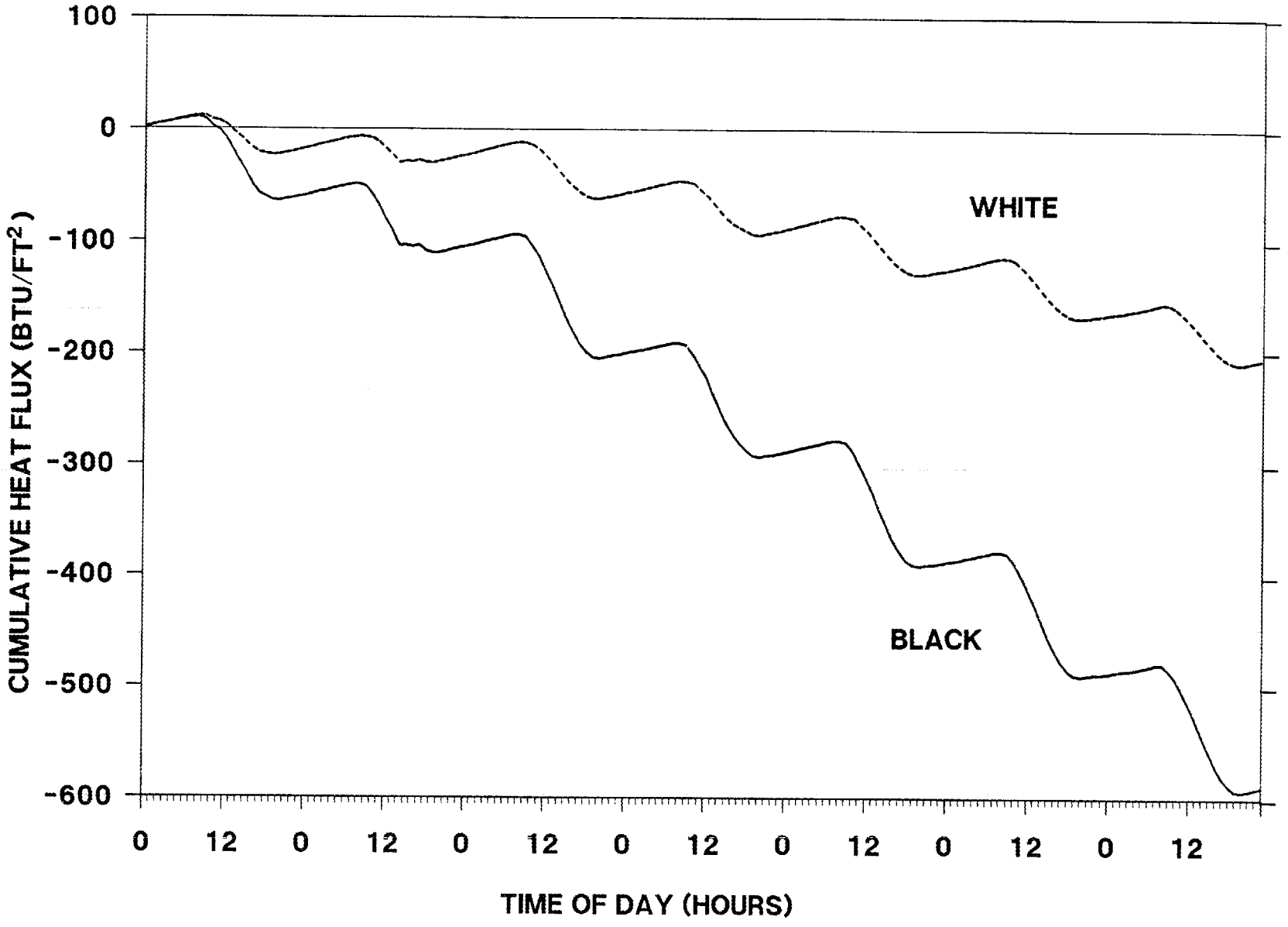


FIG. 9: Cumulative heat fluxes through the black and white roofs during summer weather from hourly heat flux data, July 15-21, 1986. Negative values denote heat flux into the building.

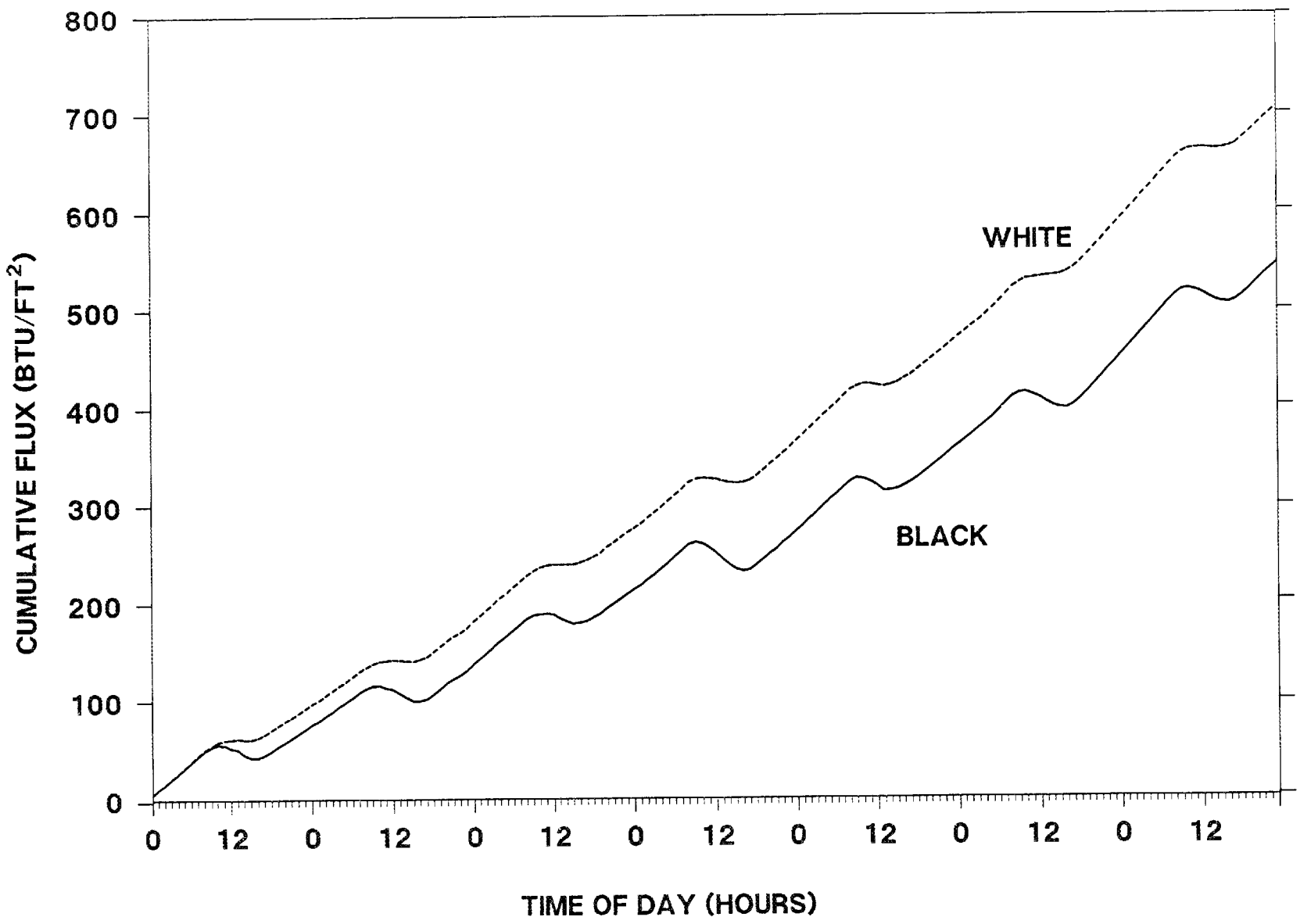


FIG. 10: Cumulative heat fluxes through the black and white roofs during winter weather from hourly heat flux data, February 4-10, 1987. Positive values denote heat flux out of the building.

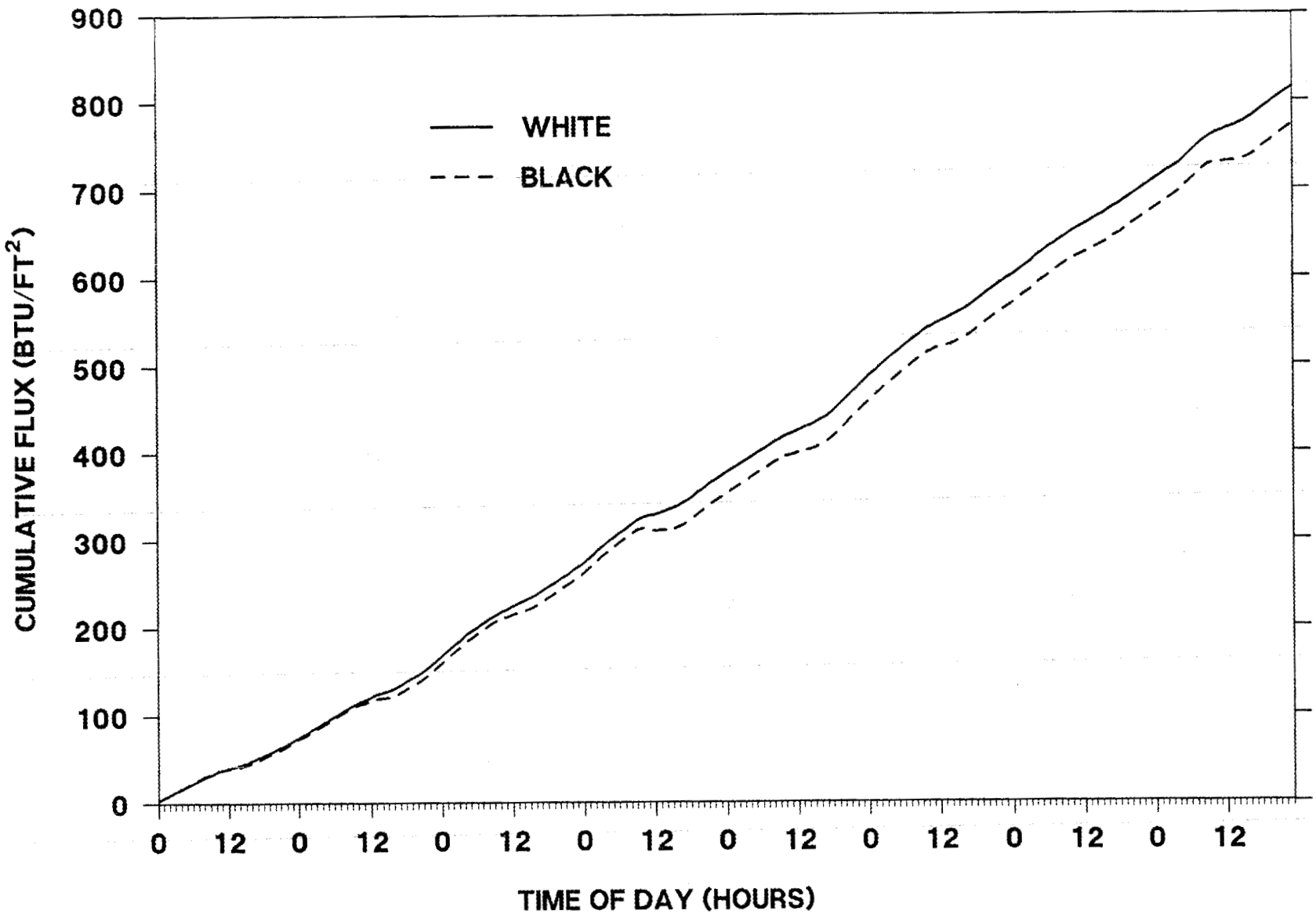


FIG. 11: Cumulative heat fluxes through the black and white roofs during week of winter weather with cloudy days from hourly flux data for December 24-31, 1986. Positive values demote heat flux out of the building.

cumulative weekly heat losses through the white being about 700 Btu/ft² as compared to 550 Btu/ft² for the black roof. During the cloudy week in December 1986 (Figure 11), there is very little difference in the weekly cumulative heat fluxes of the two membranes. These three cases illustrate that weather conditions have an important effect on the distinction between heat transfer through black versus white roofs. This applies not only to the expected counteracting influence for black versus white with changing seasons, but also to changing levels of insolation.

The cumulative heat transfer data were used to quantify the approximate impact on annual energy requirements for the ORNL location, characterized by East Tennessee weather. For the annual period beginning March 7, 1986 and ending March 6, 1987, 47 weekly cumulative sums were obtained. In order to include as much of the data as possible and deal with days for which some data are missing, the weekly sums overlap for a few cases. The resulting weekly fluxes for both the black and white roofs are plotted against the time of year in Figure 12. The white roof exhibits higher heat losses during winter months while, conversely, the black has larger heat gains during the summer months. For this test site, there is little difference in heat transfer through the black and white roofs during the months of November through January.

Using the trapezoidal rule for numerical integration, the area under each curve in Figure 12 was computed to give the integrated heat flux. This resulted in net annual fluxes of 5,381 Btu/ft²-year for the black roof and 15,593 Btu/ft²-year for the white. The ultimate impact on energy costs requires more definitive information to correlate the time series of instantaneous gains with heating and cooling requirements. Although the data in Figure 12 are site dependent, some simple comparisons can be made to illustrate how differences in opinions about energy savings can arise.

Two possible scenarios are considered here for examples. For the white roof advocate, suppose the building is one where heating is never a problem and cooling is required throughout the year. For such a case, any additional gain through the roof represents a penalty in energy use. The area under the curve of Figure 12 for the white roof during only negative weekly fluxes is 1,345 Btu/ft² while that under the curve for the black section is 6,427 Btu/ft². The black roof therefore penalizes annual cooling loads in this case by 5,082 Btu/ft². In the second scenario, suppose the cooling season is defined to be only that period when both curves are negative and the heating season is defined to coincide with the period when both curves are positive. With this scenario, integrated areas for the curves of Figure 12 show that the white section loses 3,701 Btu/ft² more than the black during heating while the black section has a gain of 3,847 Btu/ft² more than the white when cooling is required. Hence, for this second scenario, and considering only roof heat flux, the energy-use distinction between black and white is insignificant. Ultimately, one must examine net energy requirements rather than just roof heat flux. Determination of the savings or penalties associated with switching from a black to white roof, or vice versa, requires full knowledge of location, building type, roof insulation, other loads, HVAC equipment type and HVAC operating schedule.

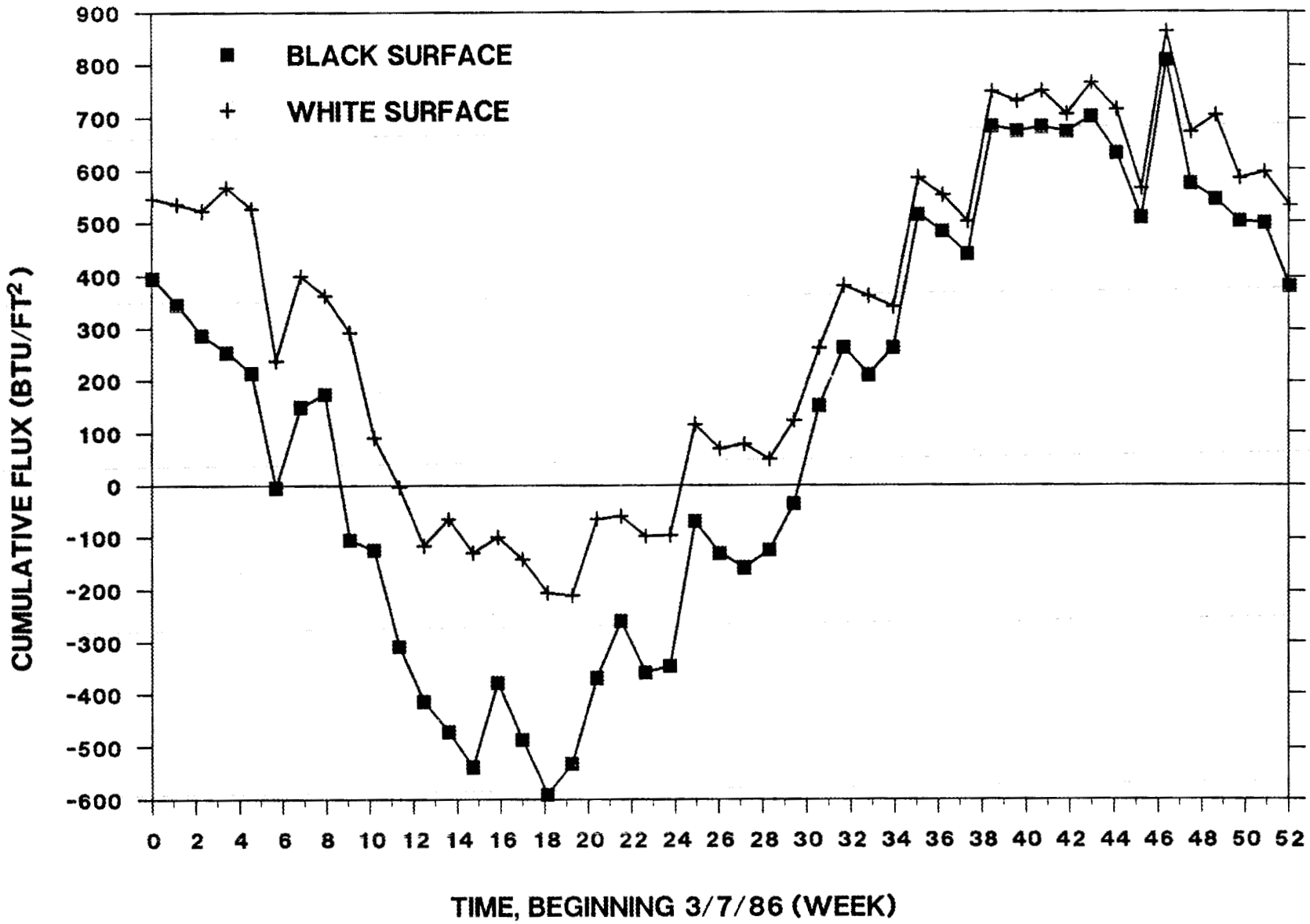


FIG. 12: Weekly cumulative heat fluxes through the black and white roofs over a one-year period, March 7, 1986 through March 6, 1987. Positive values denote heat flux out of the building.

In addition to being site dependent, specific experimental heat transfer values given herein correspond to roof assemblies of a particular thermal resistance level, a key factor affecting the magnitude of heat transfer through the roof. An estimation of experimental "effective" thermal resistance of the roof insulation layers was found by a technique of dividing the sum of the absolute values of instantaneous temperature difference across the insulation layers by the sum of the absolute values of the instantaneous heat flux. The summation to obtain an R-value was done for data extending over one week. The sum becomes nearly constant near the end of the weekly summation period. Weekly summations were made for selected weeks throughout the data collecting period. While difficult to defend theoretically, this technique has routinely yielded values which agree markedly well with steady-state values obtained in the ORNL screen tester [19]. Although the determination of insulation thermal resistances was not a particular goal of this work, the technique was used to examine data consistency and to see if there was any difference in pattern for the black and white sections. R-values were determined for both roofs from several sets of weekly data. The mean temperature of the stack was also obtained by averaging the mean temperature of each insulation layer, the latter being determined by assuming a linear temperature profile through each board. The variations in R-value with mean temperature are shown in Figure 13. Linear regressions of the R-value data on mean temperature were made for the black and white test specimens. The corresponding straight lines are plotted in Figure 13. The resulting equation for the black section is:

$$R_{black} = 9.20 - 0.028\ t_m \tag{5}$$

and the resulting equation for the white section is:

$$R_{white} = 9.10 - 0.029\ t_m \tag{6}$$

The correlation coefficients, R^2, for the regressions were .937 and .927, respectively, for the black and white. The standard errors in predicted R-value were 0.083 for both cases. The effective R-values for the black section over the range of mean temperatures encountered during the tests are two to three percent higher than those for the white. The consistency of this difference over the entire range suggests this is a good indicator of experimental accuracy.

Solar Reflectance Measurements

Reliable surface reflectance values are critical to modeling calculations. Aging effects must also be known for long-term economic considerations. A commercial reflectometer equipped with a filter for the solar spectrum was used to measure the reflectance of the test panels. The device was used outside with the sun serving as the light source. In addition, an analytical scheme utilizing the heat flux, temperature and radiation data was developed as a second means of determining surface reflectance characteristics.

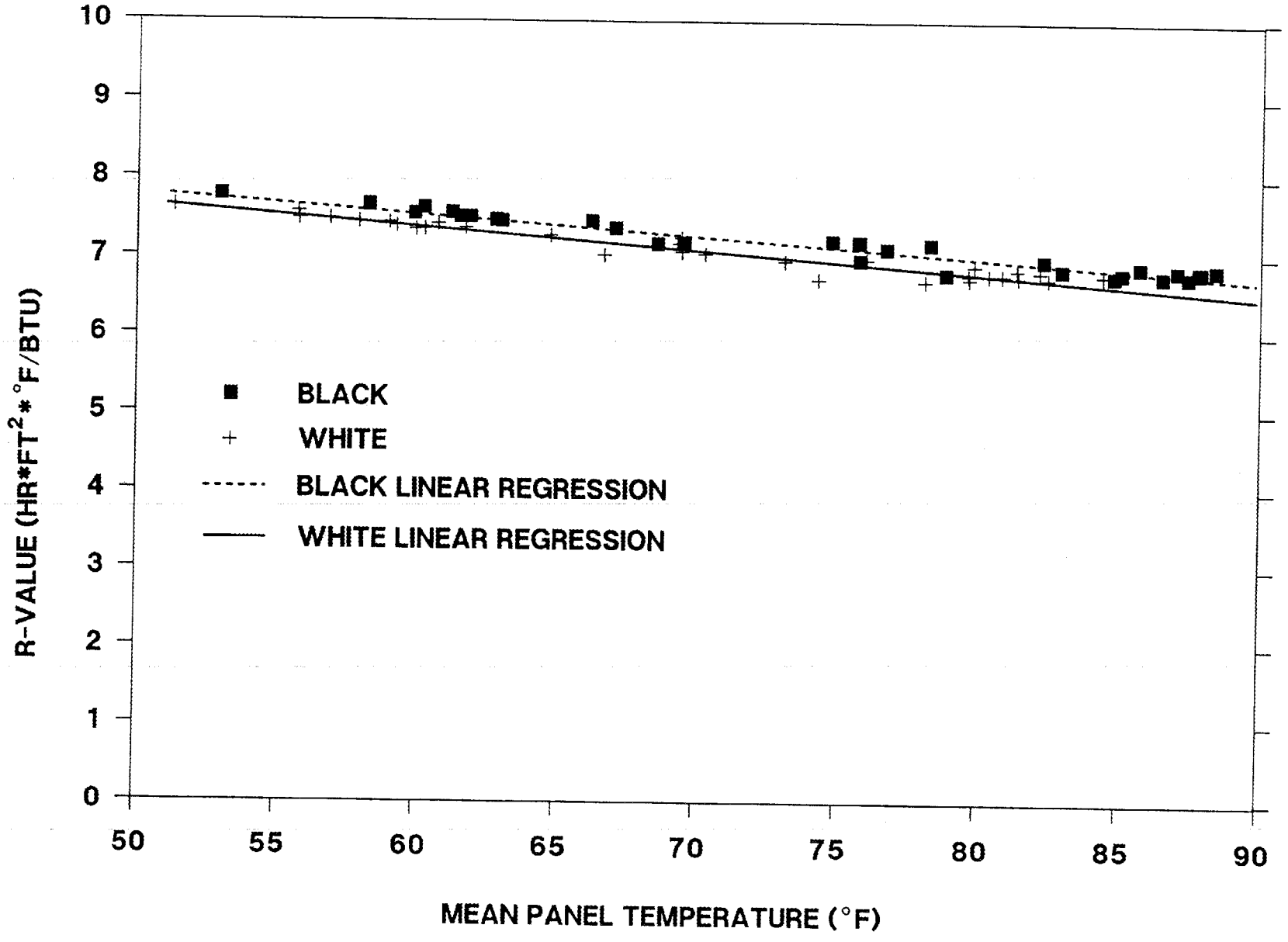


FIG. 13: Variations with temperature of calculated thermal resistances for the black and white roof assemblies.

The basis for the analytical scheme involves integrating equation (1) over an extended time period. The integrated form reduces sensitivity to temporal transients that could produce errors when applying the measured data to the instantaneous equation. Also, the heat flux transducer gives local flux at the midplane of the insulation, but equation (1) involves an energy balance at the surface. It is reasoned, in the absence of large drifts in mean assembly temperature, that integration of measured heat fluxes over an extended time period will more closely agree with integration of the heat flux just inside the surface. An explicit expression for solar reflectance can be obtained from equation (1). The aforementioned integrations were approximated by summing instananeous hourly values. The summations of a quantity are represented by an overbar. The solar reflectance was calculated from

$$\rho_s = 1 - \frac{\overline{q_{net/A}} + \overline{h_c(T_s - T_a)} + \epsilon\sigma\overline{T_s^4} - (1 - \rho_i)\overline{G_i}}{\overline{G}_s} \qquad (7)$$

High relative humidities and nighttime condensation on horizontal surfaces are common in East Tennessee where these experiments were conducted. As noted earlier, evaporation is not considered in the boundary conditions expressed by equation (1). No data are available to indicate when the specimens were dry each morning. Therefore, only those hours for which the solar flux exceeded 30 Btu/hr-ft^2 were included in the summations to reduce the number of hours in the analysis when condensed moisture might still be influencing the surface energy balance. This value of 30 was arbitrarily selected and no detailed study was made to examine sensitivity of results to choice of this cut-off point.

In addition to the measured quantities that had to be used in equation (7), it was also necessary to input a value for surface infrared emittance and the convective heat transfer coefficient had to be estimated. The latter estimates were made using empirical expressions given in Reference [20]. An infrared emittance of 0.92 was used for both the black and white membranes for the calculations. This value of infrared emittance was estimated. Some calculations were made for other values and a subsequent error analysis indicates the sensitivity of the calculated solar reflectance to the choice for infrared emittance. Also, $(1-\rho_i)$ was considered to be the same as the infrared emittance. Excellent nighttime agreement between black and white surface temperatures indicated that both have the same infrared radiative properties. Since no in situ measurements of infrared emittance were attempted, the exact value of this property was not known.

Data from 25 different weeks, distributed throughout the data collection period, were used with equation (7) to determine the effective solar reflectance. The results are shown in Figure 14 along with values obtained using the reflectometer. The reflectometer was extremely sensitive to nearly imperceptible variations in background lighting. The measurements were often erratic and inconsistent. The directly measured data plotted in Figure 14 have been culled from a larger set of observations from which physically unrealistic outliers, based upon accepted theory for the physics of surface radiative heat transfer, were eliminated.

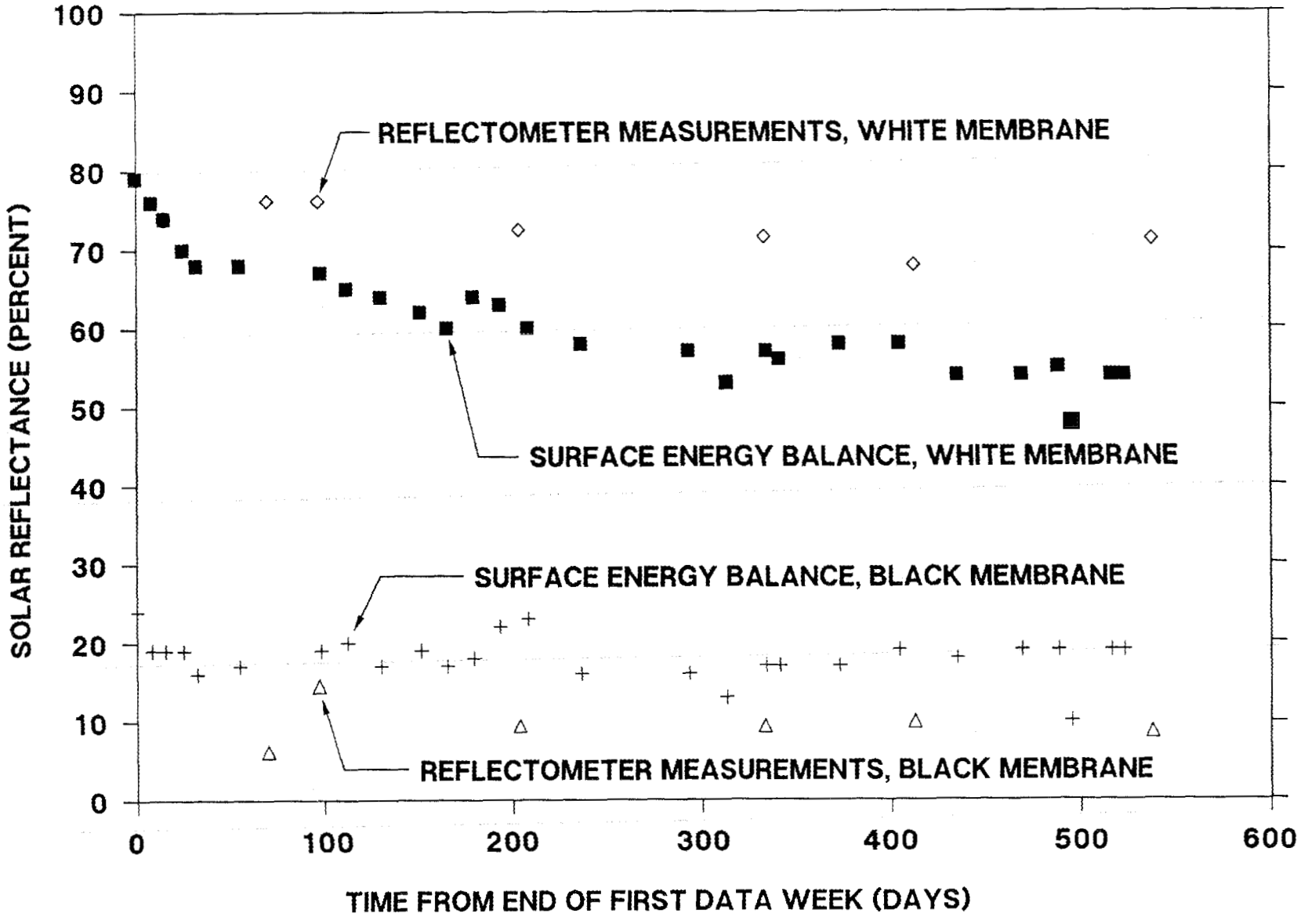


FIG. 14: Variation with time of solar reflectances for black and white membranes over a 75-week period from installation of new material. Two methods for determining reflectance are compared: reflectometer measurements versus values calculated from surface energy balance measurements.

The calculated results indicate that the white membrane's solar reflectance initially decreased from 0.8 to 0.7 during the first three months of outdoor exposure. A more gradual decrease to a solar reflectance of 0.55 continued to the end of the 75 week period. It is not apparent that the white membrane's solar reflectance had reached a minimum by the end of the reporting period. The calculated solar reflectance of the black membrane exhibits greater stability about a value of 0.2. The test panels were not cleaned during the reporting period and weathering via dust accumulation and other factors was allowed to proceed undisturbed.

Although the calculated solar reflectance values are reasonable and consistent, there are noticeable differences between them and the directly measured values (see Figure 14). The reflectometer measurements indicate a much more gradual aging effect for the white membrane, decreasing from 0.8 to 0.7 over the entire 75 week period. This aging process may also have been essentially complete after the first 29 weeks of outdoor exposure. The reflectometer measurements also indicate a solar reflectance of 0.1 for the black membrane. Better agreement was found between the reflectometer data and values tabulated in the literature. It remained troublesome, however, that the reflectometer reading seemed to show sensitivity to outdoor conditions.

Since the calculated solar reflectances differed from those measured with the reflectometer, a closer examination was made of the sensitivity of equation (7) to the required measured inputs. The partial derivative of solar reflectance was computed with respect to each variable. This was multiplied by an estimated uncertainty in the measured (or derived) value of the variable to determine the total uncertainty contributed by each parameter to the calculated reflectance. For illustration, the results using data from two representative weeks are shown in Tables 3 and 4. The estimated uncertainty in the calculated solar reflectance is shown for both black and white data, with solar flux, infrared flux, surface emittance, and convective heat transfer coefficient contributing the larger influences. However, the magnitude of the estimate is contingent on the uncertainty assigned to each of the influencing parameters. For each case examined, two different estimates are shown. For the first, a 2 percent uncertainty in both solar flux and infrared flux was assumed. Uncertainties in magnitude of 0.05 and 0.1 were assumed, respectively for surface infrared emittance and the convective heat transfer coefficient. When the values were increased to 5 percent for solar and infrared fluxes and to 0.1 and 0.3 for emittance and convective coefficient, respectively, the estimated uncertainty in solar reflectance increased almost by a factor of 3 being 0.12 for the worst case. The effort reveals that the convective heat transfer coefficient is a most important parameter in making an accurate energy balance at the exterior surface of a sunlit roof. Hence, the accuracy of analytically modeling the complete thermal performance of roofs is contingent on the accuracy with which the heat transfer coefficient can be determined for the situation under study.

The nighttime counterpart of equation (7), with solar flux eliminated, was used to calculate an effective infrared emittance for comparison with tabulated values. The reduced number of measured parameters combined with the coincidence of the nighttime temperature data and the success of the daytime calculations suggested that a very satisfactory result would be obtained. For each weekly period, the calculated infrared emittances for the black and white membranes showed good agreement. However, the calculated emittances for the 25 weeks of data seemed to be too low (0.22 to 0.77), and varied from week to week with no deterministic pattern being discernable. It is suspected that the failure of the nighttime estimates to provide consistent results derives from the previously discussed violation of the boundary condition assumptions in equation (7) caused by dew and frost formation. It is not difficult to include latent effects in equation (7), but data are not available to permit any corroboration with such modeling at this time.

SUMMARY AND CONCLUSIONS

An outdoor exposure experiment comparing the thermal performance of black and white roofing membranes in Eastern Tennessee was conducted over an 18 month period. Surface temperature measurements revealed a pronounced difference between the daytime behavior of the black and white surfaces. Peak summertime temperatures for the black membrane were typically 40°F warmer than for the white membrane, reaching a maximum of 180°F. In like fashion, the black membrane exceeded 140°F for 539 hours during a one year period while the white roof never reached that temperature. These differences remained consistent with seasonal changes in weather, with insolation being the predominant factor affecting their magnitude.

The nighttime surface temperatures of the two roofs were nearly identical throughout the year, revealing them to have the same infrared emissivities despite their widely different solar reflectance values.

Heat flux data for the two roofs confirmed a significant reduction in summertime cooling loads and a concommitant increase in winter heating loads with the high reflectance roof. Translating this general behavior into energy savings requires information on climate and various internal design details for any specific building.

An evaluation of the roof insulation thermal resistance validated the accuracy of the experimental procedure and agreed with nominal values measured in the ORNL screen tester. The expected temperature dependence of fiberglass insulation thermal conductivity was observed in the field test data.

Some reduction in the reflectance of the white membrane was observed to have occurred throughout the test period. Reflectance was measured with a reflectometer. Also, an effort was made to calculate reflectance using a surface energy balance with measured data as input. Measured reflectance values were 0.1 greater than calculated values for the white membrane and 0.1 less than the calculated values for the black. This difference was not larger than the uncertainty in calculated reflectance with plausible uncertainties assigned to the measured data.

With increased interest in use of single-ply membranes in the roofing industry, the fact that a black membrane's temperature may exceed that of a white membrane by 40 to 50°F during peak sunlit hours is useful to manufacturers of membranes and membrane adhesives.

The data show that there can be a difference in the HVAC energy required for a building with a white compared to that for one with a black roof. The net annual effect, however, depends on many factors such as, for example, climate roof insulation, and building type. This suggests that modeling may be the most practical means of evaluating the influence of reflectance on building energy use in lieu of an extensive experimental effort.

The expression for an energy balance at the surface of a dry roof was examined with measured data as input from several sets of data over the test period. Internal consistency was found but an estimate of uncertainty indicated that, in addition to good confidence in all measurements, validation of the energy balance is noticeably dependent on the heat transfer coefficient. A plausible explanation of the variance in the trends of results when checking the balance with nighttime data was that latent effects may have been present.

When considering any additional experiments, the following suggestions are offered based on observations made in this work.

1. Some means for monitoring the presence of moisture should be included.

2. An experiment should be devoted explicitly to determining any changes in reflectance of roof surfaces over long-term exposure to outdoor conditions.

3. Some experimental effort should be devoted to determination of the heat transfer coefficient for typical roofs. While this effect may seem small in evaluating total thermal resistance for a well-insulated roof, it is most important for roofs with little or no insulation and in determining transient surface thermal behavior.

The evaluation of experimental data made in this study has aided in indicating needs for improving studies of reflectance effects and has provided insight needed in interpreting results of modeling a whole building with DOE 2.1B. The ongoing modeling effort is to be used to generate guidelines on how to estimate changes in building energy use at different climates caused by a change in the roof's solar reflectance.

Table 1. Solar Absorptance Values for Various Exterior Surfaces (From Chapter III of Reference 13)

Material	Absorptance	Paint	Absorptance
Black concrete	0.91	Optical flat black	0.98
Stafford blue brick	0.89	paint	0.95
Red brick	0.88	Flat black paint	0.92
Bituminous felt	0.88	Black lacquer	0.91
Blue gray slate	0.87	Dark gray paint	0.91
Roofing, green	0.86	Dark blue lacquer	0.90
Brown, concrete	0.85	Black oil paint	
Asphalt pavement, weathered	0.82	Dark olive drab	
Wood, smooth	0.78	paint	0 89
Uncolored asbestos cement	0.75	Dark brown paint	0.88
Uncolored concrete	0.65	Dark blue-gray paint	0.88
Asbestos cement, white	0.61	Azure blue or dark	
White marble	0.58	green lacquer	0.88
Light buff brick	0.55	Medium brown paint	0.84
Built-up roof, white	0.50	Medium light brown	
Bituminous felt, aluminized	0.40	paint	0.80
Aluminum paint	0.40	Brown or green	
Gravel	0.29	lacquer	0.79
White on galvanized iron	0.26	Medium rust paint	0.78
White glazed brick	0.25	Light gray oil paint	0.75
Polished aluminum reflector		Red oil paint	0.74
sheet	0.12	Medium dull green	
Aluminized mylar film	0.10	paint	0.59
Tinned surface	0.05	Medium orange paint	0.58
		Medium yellow paint	0.57
		Medium blue paint	0.51
		Medium kelly green	
		paint	0.51
		Light green paint	0.47
		White semi-gloss	
		paint	0.30
		White gloss paint	0.25
		Silver paint	0.25
		White lacquer	0.21
		Laboratory vapor	
		deposited coatings	0.02

Table 2. Linear Regression Analysis of Nighttime Black Surface Temperatures on White Surface Temperatures

Data Period	Slope	R^2	Standard Error in Estimated Temperatures, °F
Mar 7 - Aug 22, 1986	1.000918	0.999633	0.55
Oct 1, 1986 - Apr 14, 1987	0.996505	0.999614	0.42

Table 3: Relative Sensitivity of Calculated Surface Reflectance Values to Input Errors: Based on Data From July 15-21, 1986

Influencing Variable x_i	$\frac{\partial \rho_s}{\partial x_i}$	Estimated Uncertainty in Variable $\pm \Delta x_i$	$\left\lvert \frac{\partial \rho_s}{\partial x_i} \Delta x_i \right\rvert \times 10^3$ Black	White
$\bar{q}_{net}$	$-\frac{1}{\bar{G}_s}$	$0.02\ \bar{q}_{net}$	0.99	0.45
$\bar{G}_s$	$\frac{1-\rho_s}{\bar{G}_s}$	$0.02\ \bar{G}_s$ $(0.05\bar{G}s)$	16.6 (41.5)	7.2 (18)
$\bar{G}_i$	$\frac{\epsilon}{\bar{G}_s}$	$0.02\ \bar{G}_i$ $(0.05\ \bar{G}_i)$	15.2 (38)	15.2 (38)
ϵ	$\frac{\bar{G}_i - \overline{\sigma T_s^4}}{\bar{G}_s}$	0.05 (0.1)	25.6 (51.2)	12.5 (25)
h_c	$\frac{\bar{T}_a - \bar{T}_s}{\bar{G}_s}$	0.1 (0.3)	29.3 (87.9)	11 (33)
T_s	$\frac{\bar{h}_c + 4\epsilon\sigma\overline{T_s^3}}{\bar{G}_s}$	0.25	3.5	3
T_a	$\frac{\bar{h}_c}{\bar{G}_s}$	0.25	1.4	1.3
	$\Delta\rho_s$		.04 (.12)	.02 (0.06)

Table 4: Relative Sensitivity of Calculated Surface Reflectance Values to Input Errors: Based on Data from February 4-10, 1987

Influencing Variable x_i	$\frac{\partial \rho_s}{\partial x_i}$	Uncertainty in Variable $\pm \Delta x_i$	$\left\lvert \frac{\partial \rho_s}{\partial x_i} \Delta x_i \right\rvert \times 10^3$ Black	White
$\bar{q}_{net}$	$-\frac{1}{\bar{G}_s}$	$0.02\ \bar{q}_{net}$	0.18	0.22
$\bar{G}_s$	$\frac{1-\rho_s}{\bar{G}_s}$	$0.02\ \bar{G}_s$ $(0.05\ \bar{G}_s)$	16.6 (41.5)	8.6 (21.5)
$\bar{G}_i$	$\frac{\epsilon}{\bar{G}_s}$	$0.02\ \bar{G}_i$ $(0.05\ \bar{G}_i)$	12.3 (30.8)	12.3 (30.8)
ϵ	$\frac{\bar{G}_i - \overline{\sigma T_s^4}}{\bar{G}_s}$	0.05 (0.1)	24.6 (49.2)	16.1 (32.2)
h_c	$\frac{\bar{T}_a - \bar{T}_s}{\bar{G}_s}$	0.1 (0.3)	26.9 (80.7	11.1 (33.3)
T_s	$-\frac{\bar{h}_c + 4\epsilon\sigma\overline{T_s^3}}{\bar{G}_s}$	0.25	4.5	4.2
T_a	$\frac{\bar{h}_c}{\bar{G}_s}$	0.25	2.5	2.5
	$\Delta\rho_s$		0.04 (0.11)	0.03 (0.06)

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