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Effect of Insulation on the Surface Temperature of Roof Membranes

Walter J. Rossiter, Jr.
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Center for Building Technology
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National Bureau of Standards
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U.S. DEPARTMENT OF COMMERCE, Elliot L. Richardson, ***Secretary***
James A. Baker, III, ***Under Secretary***
Dr. Betsy Ancker-Johnson, ***Assistant Secretary for Science and Technology***
NATIONAL BUREAU OF STANDARDS, Ernest Ambler, ***Acting Director***

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ABSTRACT

The surface temperatures of black, gray and white roofs were calculated for various thicknesses of insulation located between the membrane and roof deck. The calculations were performed using a steady-state heat balance equation to illustrate the increase in roof surface temperatures due to solar radiation.

The calculations indicate that the first increment, about 1 inch (25 mm),[1/] of insulation causes a significant rise in the roof surface temperature due to solar radiation. Increasing the amount of insulation above this first increment to greater thicknesses does not appreciably increase the roof surface temperature.

Keywords: Built-up roofing; insulation; performance; radiative cooling; roofing; solar heating; surface temperature.

1. INTRODUCTION

It has been reported that increased amounts of insulation between the roof deck and the membrane will shorten roof life [1-3][2/]. The concern is that roofs with greater amounts of insulation will be subjected to greater extremes in temperature. The reasons stated for lessening roof life were accelerated aging due to higher roof temperatures in the summer and larger contractive forces caused by thermal shock in the winter. Earlier research at the National Bureau of Standards (NBS)[4] showed that bituminous membranes placed over insulation develop higher temperatures on sunny days than membranes placed directly on the deck. On clear nights membranes over insulation can be considerably colder than those that are not insulated. This may have significance in the winter when ambient temperatures are low.

Increased amounts of insulation (lower U-values) are now specified for roofs in many cases because of the need for energy conservation. Buildings are among the largest energy consumers in the United States and use approximately one-third of the total consumption [5]. Much of this energy can be conserved by decreasing the energy consumption of buildings. One of the important methods of accomplishing this is by increasing the amount of insulation. It is noted that approximately 70% of currently constructed low-sloped roofs are insulated [6].

Research is needed to determine the effect of insulation on roof performance. At present, criteria are not available to evaluate the performance of roofing systems which contain increased amounts of insulation necessary to obtain lower U-values. Many factors regarding insulation should be considered in evaluating roof performance. These factors include mechanical properties such as impact resistance, compressive strength, punching shear resistance, cohesive strength and flexural strength; dimensional stability including warping and length changes; coefficient of thermal expansion; moisture effects including

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1/ Numbers in parentheses are in units of the metric system, formally called the International System of Units (SI).

2/ Numbers in brackets refer to references in Section 6.

absorption and permeability; adhesion between roofing components; durability; installation procedures; flammability; and thermal conductivity.

This paper shows that increasing the amount of insulation over that normally used in an insulated built-up roofing system will not cause a significant increase or decrease in the roof membrane temperature. Calculations and illustrations are presented as examples that give membrane temperatures for thicknesses of insulation ranging from zero to five inches (0 to 127 mm).

2. BACKGROUND

In a 1963 National Bureau of Standards Technical Note, Cullen reported temperature data on some built-up roofing systems which were exposed to solar heating and radiative cooling [4]. Solar heating is the process whereby the temperature of a surface rises above ambient air temperature as the surface absorbs solar radiation. Radiative cooling is the process whereby the temperature of a surface drops below ambient air temperature as the surface exchanges long-wave radiation with the cold night sky. Cullen's data showed that in the summer built-up roofing membranes set on insulation may be as much as 80°F (44°C) hotter than ambient air temperature. He also reported that during a winter night a membrane placed over insulation may be 20°F (11°C) cooler than ambient air. The magnitude of the solar heating or radiative cooling was considered dependent upon a number of factors including mass, density and thermal properties of the substrate under the membrane, the absorptance or emissivity of the membrane surface, and atmospheric conditions. The paper did not discuss the magnitude of solar heating or radiative cooling as a function of the amount of insulation or of the U-value of the test specimen.

The information presented in this NBS Technical Note [4] may be subject to some misinterpretation regarding the magnitude of temperature extremes of membranes placed over greater amounts of insulation. The temperature of the membrane is affected by the thickness of the insulation up to a certain point. Beyond this thickness the effect on surface temperature is insignificant. This is demonstrated herein by examining the physical process which occurs when a roof is exposed to solar radiation. Temperatures of building exterior surfaces exposed to solar radiation have been discussed in the literature [7-9].

3. HEAT TRANSFER THROUGH FLAT ROOFING SYSTEMS

Heat transfer concepts, as defined by the ASHRAE Handbook of Fundamentals [10], are given in table 1. These concepts are also defined and discussed in a roofing trade publication [11]. The important term to be considered in this discussion is the U-value or overall coefficient of heat transmission (thermal transmittance).

There are two ways of increasing the thermal efficiency (lowering the U-value) of a roofing system. One method is to use a more efficient insulation (lower k-factor), and the other is to increase the thickness of the insulation. Using presently available roof insulation the k-factor is limited and therefore a roof with a low U-value, for example 0.05 to 0.10 Btu/h ft^2 °F (0.28 to 0.57 W/m^2K), cannot be achieved with the thickness of insulation normally used. This leads to the only remaining option for lowering the U-value; namely, increasing the thickness of the insulation. A list of k-factors for the most common roofing insulations is given in table 2.

Figure 1 shows schematically the physical processes which occur when a roof is exposed to sunlight (radiant energy). A portion of the sunlight incident on the roof is absorbed, part is reflected. As some of the sunlight or radiant energy is absorbed, the temperature of the roof surface rises. This energy is dissipated by three processes, conduction, convection and re-radiation. The better the roof is able to dissipate the energy through these three processes, the less the temperature of the roof surface will rise. Adding insulation to the roof reduces the amount of heat dissipated by conduction. Consequently, a roof membrane over insulation will be hotter than if it were placed directly on a deck. As the amount of heat dissipated through conduction is reduced, the heat dissipated through convection is increased. Therefore, the temperature of the membrane will not continue to increase significantly as more insulation is added to the roof.

Table 1. Heat Transfer Concepts

Symbol	Concept	Definition	Units
k	thermal conductivity	Time rate of heat flow through a homogeneous material under steady-state conditions through unit area, per unit temperature gradiant.	Btu/h ft^2 °F/in (W/mK)1/
C	thermal conductance	Time rate of heat flow through a material for any thickness. C = k/n where n = thickness expressed in inches or meters.	Btu/h ft^2 °F (W/m^2K)
R	thermal resistance	The reciprocal of the thermal conductance, R = 1/C.	°F h ft^2/Btu (m^2K/W)
U	overall coefficient of heat transmission (thermal transmittance)	The reciprocal of the summation of the resistance of each material in a wall, roof, floor or ceiling plus the surface conductance on both sides. $U = 1/R_{total}$	Btu/h ft^2 °F (W/m^2K)

1/ SI units in parenthesis

Table 2. Thermal Conductivities of Roof Insulations

Insulation	Density	Thermal Conductivity, k[1/]
	lb/ft^3 (kg/m^3) [2/]	Btu/h ft^2 °F/in (W/mK) [2/]
Foamed urethane[3/]	1.5-2.5 (24-40)	0.16 (0.9)
Glass fiberboard[3/]	4-9 (64-144)	0.25 (1.4)
Extruded polystyrene[3/]	1.8 (29)	0.25 (1.4)
Cork board[4/]	6.5-8 (104-128)	0.28 (1.6)
Mineral fiberboard[3/]	16-17 (256-272)	0.34 (1.9)
Wood fiberboard[5/]	15-22 (240-352)	0.36 (2.0)
Perlite aggregate board[5/]	11 (176)	0.38 (2.2)
Cellular glass[3/]	9 (144)	0.40 (2.3)
Lightweight concrete, Perlite aggregate[4/]	20-40 (320-641)	0.70-1.15 (4.0-6.5)
Lightweight concrete, Vermiculite aggregate[3/]	20-40 (320-641)	0.70-1.15 (4.0-6.5)

1/ Tabulated values are for a mean temperature of 75°F (24°C).

2/ SI units in parenthesis.

3/ Values from the ASHRAE Handbook of Fundamentals, 1972 edition [12].

4/ Values from the ASHRAE Handbook of Fundamentals, 1967 edition [13].

5/ Values from the Manual of Built-Up Roof Systems [14].

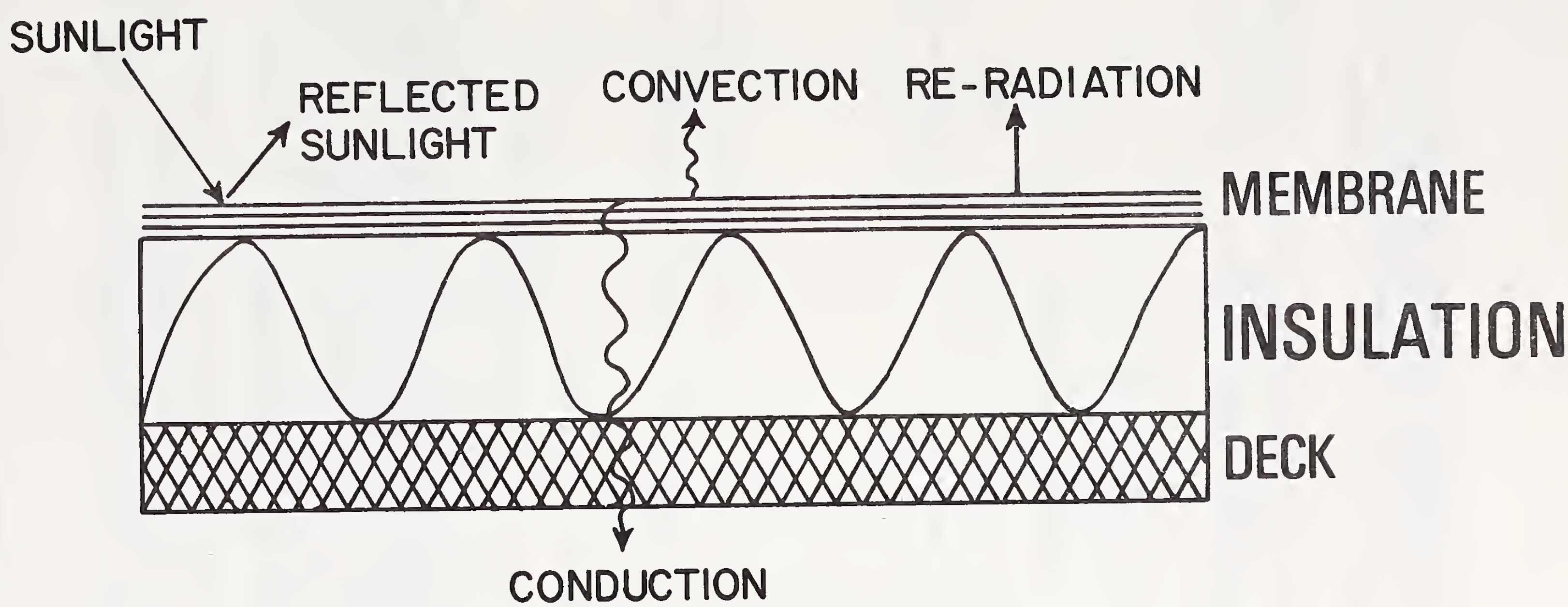


FIGURE 1. THE PHYSICAL PROCESSES WHICH OCCUR WHEN A ROOF IS EXPOSED TO SOLAR RADIATION.

The absorptance of radiant energy and dissipation of heat energy can be expressed mathematically. The law of conservation of energy states that energy can neither be created nor destroyed. Thus, for a steady-state condition all the sunlight energy absorbed by the roof must be dissipated by conduction, convection and re-radiation, as given in the following equation.

Absorbed Energy = Heat Losses (Conduction + Convection + Re-radiation)

This is called a heat balance equation. For a steady-state condition, it is mathematically expressed as follows [15]:

$$\alpha I = U\ (t_s - t_i) + h_o\ (t_s - t_o) + \varepsilon \Delta R \qquad (1)$$

where

α = absorptance of the roof for solar radiation

I = total solar radiation incident on the roof, Btu/h ft^2 (W/m^2)

U = coefficient of heat transmission of the roof, not including outside surface conductance, Btu/h ft^2 °F (W/m^2K)

t_s = surface temperature, °F (°C)

t_i = inside air temperature, °F (°C)

h_o = coefficient of heat transfer by convection and long-wave length radiation to the surroundings (not including the sky) at the outer surface,1/ Btu/h ft^2 °F (W/m^2K)

t_o = outside air temperature, °F (°C)

ε = hemispherical emittance of the surface

ΔR = the net long-wave radiation to the sky,1/ Btu/h ft^2 (W/m^2)

The above equation includes the two terms which are of interest to this discussion, namely, the U-value and the surface temperature. After selecting values for the other parameters, the surface temperature of the roof was calculated as a function of the U-value. Table 3 lists three sets of values for the parameters in equation (1) which were used in the calculations. These values represent environmental conditions on a hot, sunny, summer day where the outside air temperature is 95°F (35°C), the inside air temperature is 72°F (22°C) and the wind is 5-10 miles per hour (2-4 m/s) at the roof level. Each set differs from the others only in the value of the absorptance of the roof surface. Values of absorptance correspond to black, gray and white surfaces.

A simple roof structure, chosen as a basis for the calculation of roof surface temperatures in this paper, is shown in figure 2. The roof consists of a metal deck, insulation and a built-up roofing membrane. The thickness and k-factor of the roof insulation were varied. The total thermal resistance of this roof, R_{total}, as shown in figure 2, is 1.25 h ft^2 °F/Btu (0.22 m^2 K/W) plus the thermal resistance of the insulation, R_i.

$$R_{total} = 1.25 + R_i \qquad (2)$$

Using equation (2) and the relationship $U = 1/R_{total}$, the U-value of this roof was calculated as a function of the thickness of the insulation. Tables 4, 5 and 6 give U-values of the roof for k-factors of the insulations of 0.17, 0.24 and 0.36 Btu/h ft^2 °F/in (0.024, 0.035 and 0.052 W/m K) respectively.

1/ The definitions of h_o and ΔR differ from those given in the ASHRAE Handbook of Fundamentals [15]. These definitions were changed in this paper for editorial clarification.

Table 3. Parameters Used in the Heat Balance Equation for Calculating the Surface Temperature as a Function of U-value

Parameter	Units	Case I Black Surface	Case II Gray Surface	Case III White Surface
α 1/	-	0.9	0.7	0.5
I 2/	Btu/h ft^2	300	300	300
	(W/m^2)	(945)	(945)	(945)
t_i	°F	72	72	72
	(°C)	(22)	(22)	(22)
h_o 3/	Btu/h ft^2 °F	4	4	4
	(W/m^2 K)	(23)	(23)	(23)
t_o	°F	95	95	95
	(°C)	(35)	(35)	(35)
ε 4/	-	0.9	0.9	0.9
ΔR 5/	Btu/h ft^2	20	20	20
	(W/m^2)	(63)	(63)	(63)

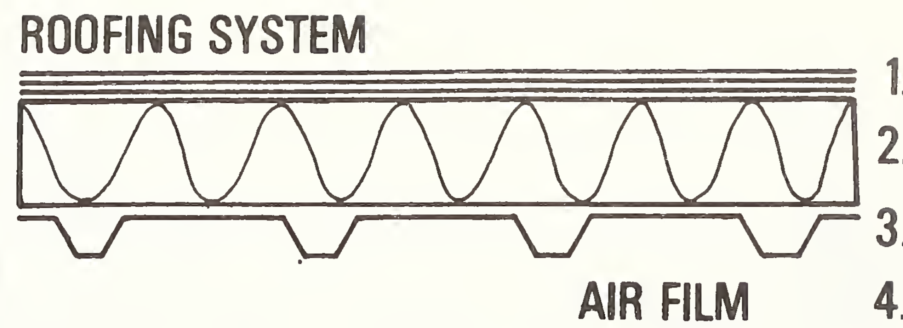
1/ Values from reference [4], page 7.

2/ This value is typical for a horizontal surface on a sunny summer day at noontime at 40° northern latitude.

3/ Value from the ASHRAE Handbook of Fundamentals [16]. This value represents a wind velocity of 5-10 miles per hour (2-4 m/s) across the surface.

4/ Value from the CRC Handbook of Materials Science [17]. Value is for a non-metallic surface.

5/ Value from ASHRAE Handbook of Fundamentals [15]. Value is for a horizontal surface.



COMPONENT	RESISTANCE, R
1. BUR Membrane	0.33
2. Insulation	R_i
3. Metal Deck	0.00
4. Air Film, Heat Flow Downward	0.92

TOTAL THERMAL RESISTANCE: $R_{TOTAL} = 1.25 + R_i$

FIGURE 2. THE TOTAL THERMAL RESISTANCE OF THE ROOF STRUCTURE USED IN THE SURFACE TEMPERATURE CALCULATIONS.

Table 4. Calculated Surface Temperature of the Roof as a Function of the Thickness of the Insulation, k = 0.17 (0.024)

Thickness of Insulation in (mm)	U-value[1/] Btu/h ft^2 °F (W/m^{2}K)	Surface Temperature of the Roof, °F (°C)		
		Case I, Black	Case II, Gray	Case III, White
0	0.80 (4.5)	143.7 (62.1)	131.2 (55.1)	118.7 (48.2)
0.5 (13)	0.24 (1.4)	153.1 (67.3)	139.0 (59.4)	124.8 (51.6)
1.0 (25)	0.14 (0.80)	155.1 (68.4)	140.6 (60.3)	126.1 (52.3)
1.5 (38)	0.10 (0.57)	155.9 (68.8)	141.3 (60.7)	126.6 (52.6)
2.0 (51)	0.077 (0.44)	156.4 (69.1)	141.7 (60.9)	126.9 (52.7)
2.5 (64)	0.063 (0.36)	156.7 (69.3)	141.9 (61.1)	127.1 (52.8)
3.0 (76)	0.053 (0.30)	156.9 (69.4)	142.1 (61.2)	127.3 (52.9)
3.5 (89)	0.046 (0.26)	157.0 (69.4)	142.2 (61.2)	127.4 (53.0)
4.0 (102)	0.041 (0.23)	157.1 (69.5)	142.2 (61.2)	127.4 (53.0)
5.0 (127)	0.032 (0.18)	157.2 (69.6)	142.4 (61.3)	127.6 (53.1)
∞	0.0	158.0 (70.0)	143.0 (61.7)	128.0 (53.3)

1/ U-value of the hypothetical roof system shown in Figure 2. The U-value does not include the thermal resistance of the air at the outside surface of the roof.

Table 5. Calculated Surface Temperature of the Roof as a Function of the Thickness of the Insulation, k = 0.24 (0.035)

Thickness of Insulation in (mm)	U-value[1/] Btu/h ft^2 °F (W/m^{2}K)	Surface Temperature of the Roof, °F (°C)		
		Case I, black	Case II, Gray	Case III, White
0	0.80 (4.5)	143.7 (62.1)	131.2 (55.1)	118.7 (48.2)
0.5 (13)	0.30 (1.7)	152.0 (66.7)	138.0 (58.9)	124.1 (51.2)
1.0 (25)	0.18 (1.0)	154.3 (67.9)	139.9 (59.9)	125.6 (52.0)
1.5 (38)	0.13 (0.74)	155.3 (68.5)	140.8 (60.4)	126.2 (52.3)
2.0 (51)	0.10 (0.57)	155.9 (68.8)	141.3 (60.7)	126.6 (52.6)
2.5 (64)	0.086 (0.49)	156.2 (69.0)	141.5 (60.8)	126.8 (52.7)
3.0 (76)	0.072 (0.41)	156.5 (69.2)	141.7 (60.9)	127.0 (52.8)
3.5 (89)	0.064 (0.36)	156.7 (69.3)	141.9 (61.1)	127.1 (52.8)
4.0 (102)	0.055 (0.31)	156.8 (69.3)	142.0 (61.1)	127.2 (52.9)
4.5 (114)	0.049 (0.28)	157.0 (69.4)	142.1 (61.2)	127.3 (52.9)
5.0 (127)	0.045 (0.26)	157.0 (69.4)	142.2 (61.2)	127.4 (53.0)
∞	0.0	158.0 (70.0)	143.0 (61.7)	128.0 (53.3)

1/ U-value of the hypothetical roof system shown in Figure 2. The U-value does not include the thermal resistance of the air at the outside surface of the roof.

Table 6. Calculated Surface Temperature of the Roof as a Function of the Thickness of the Insulation, k = 0.36 (0.052)

Thickness of Insulation in (mm)	U-value 1/ Btu/h ft² °F (W/m²K)	Surface Temperature of the Roof, °F (°C) Case I, Black	Case II, Gray	Case III, White
0	0.80 (4.5)	143.7 (62.1)	131.2 (55.1)	118.7 (48.2)
0.5 (13)	0.38 (2.2)	150.5 (65.8)	136.8 (58.2)	123.1 (50.6)
1.0 (25)	0.25 (1.4)	152.9 (67.2)	138.8 (59.3)	124.7 (51.5)
1.5 (38)	0.18 (1.0)	154.3 (67.9)	139.9 (59.9)	125.6 (52.0)
2.0 (51)	0.15 (0.85)	154.9 (68.3)	140.4 (60.2)	126.0 (52.2)
2.5 (64)	0.12 (0.68)	155.5 (68.6)	140.9 (60.5)	126.4 (52.4)
3.0 (76)	0.10 (0.57)	155.9 (68.8)	141.3 (60.7)	126.6 (52.6)
3.5 (89)	0.091 (0.52)	156.1 (68.9)	141.4 (60.8)	126.8 (52.7)
4.0 (102)	0.081 (0.46)	156.3 (69.1)	141.6 (60.9)	126.9 (52.7)
4.5 (114)	0.073 (0.41)	156.5 (69.2)	141.7 (60.9)	127.0 (52.8)
5.0 (127)	0.066 (0.37)	156.6 (69.2)	141.8 (61.0)	127.1 (52.8)
∞	0.0	158.0 (70.0)	143.0 (61.7)	128.0 (53.3)

1/ U-value of the hypothetical roof system shown in Figure 2. The U-value does not include the thermal resistance of the air at the outside surface of the roof.

Substituting these U-values and the values of the parameters given in table 3 in the heat balance equation (equation 1), the surface temperatures of the roof were calculated as a function of the thickness of the insulation. Tables 4, 5 and 6 show the results of these calculations for black, gray and white roofs having insulation with various k-factors. The results of these calculations are illustrated graphically in figure 3.

4. DISCUSSION

The surface temperature calculations outlined in the preceding section were based on heat transfer design values and some realistic values of parameters included in the heat balance equation (equation 1). It is emphasized that these values of surface temperature were not determined experimentally. However, the calculated values can be used to illustrate the effect of increasing amounts of insulation on the temperature extremes of the roofing membrane. The theoretical calculations of surface temperatures for steady-state conditions were based on physical principles which are well established [15].

Three different colored roof surfaces were considered in the calculations. As expected, the calculated values shown in figure 3 indicated that a black surface exposed to sunlight becomes hotter than a gray surface and the gray surface is hotter than a white surface. In all three cases, even when there is no insulation in the roof system, the surface temperature is greater than the selected ambient temperature of 95°F (35°C). If the roof is capable of absorbing solar radiation, its surface will in general heat up.

It can also be seen in figure 3 that when insulation is added between the membrane and the deck, the roof surface temperature rises. However, only the first inch (25 mm) or so of insulation causes a significant rise in the surface temperature. As an example, 1 inch (25 mm) of insulation placed under the black surfaced roof causes an increase of about 11°F (6°C). Additional insulation above this amount causes little increase in the surface temperature. For the black surfaced roof, increasing the insulation thickness from 1 to 5 inches (25 to 127 mm) only results in an increase of the surface temperature of about 2 to 4°F (1 to 2°C) depending on the k-factor of the insulation.

The k-factor for a given thickness of the insulation had very little effect upon the surface temperature, as shown in figure 3. As the k-factor decreases, the surface temperature approaches its maximum temperature at a slightly faster rate.

Figure 3 is included to show the effect of the thickness of insulation on surface temperatures because this is an important concern of the roofing industry. A measure of the thermal efficiency of a roofing system is its U-value and not the thickness of insulation. Figure 4 shows the surface temperature of the black, gray and white roofs as a function of the U-value in the range 0.0 to 0.38 Btu/h ft^2 °F (0.0 to 2.2 W/m^2K). This is the range of interest when discussing insulated roofs. Before the energy crisis and the need to conserve energy, most insulated roofs had design U-values of about 0.15 to 0.20 Btu/h ft^2 °F (0.85 to 1.1 W/m^2K). Now, some specifications are requiring U-values as low as 0.05 Btu/h ft^2 °F (0.28 W/m^2K). Of course, a U-value of 0.0 (infinite thickness of insulation) is impossible since it means that the roof transmits no heat. However, a U-value of 0.0 can be used to show theoretically the maximum temperature of the roof surface for a given environmental condition (tables 4, 5 and 6).

Figure 4 shows that decreasing the U-value from 0.20 to 0.05 Btu/h ft^2 °F (1.1 to 0.28 W/m^2K) has a minimum effect on the surface temperatures of the black, gray and white roofs. For the black roof, the increase in surface temperature for this range of U-values is only 3°F (2°C). For the other two roofs, it is even less.

The surface temperature calculations have been performed for a steady-state condition. Under this condition the rate of energy absorbed by the roof is dissipated at an equal rate. Steady-state condition is in general never attained for heat transfer through a roof system. Steady-state condition is approached when a low density insulation having a low heat capacity is located between the membrane and the deck. The surface temperature calculations are more complicated for a non-steady-state condition, and are beyond the scope of this paper. In general, the surface temperature of a membrane will not be as high when it is placed on a high heat capacity material as compared to a low heat capacity material having the same U-value. There is a thermal lag as a high heat capacity material takes time to store thermal energy.

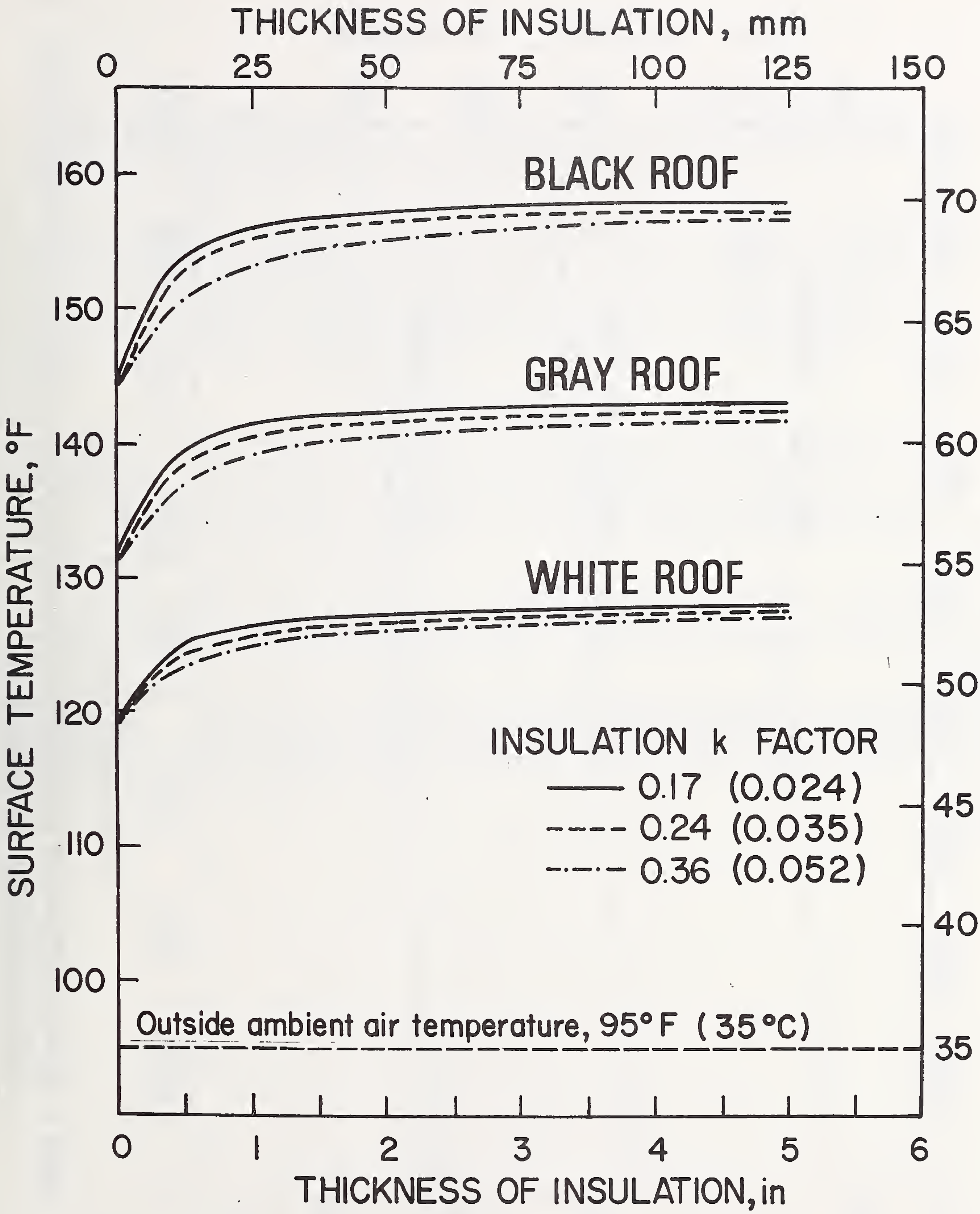


FIGURE 3. SURFACE TEMPERATURE OF THE ROOF MEMBRANE AS A FUNCTION OF THE AMOUNT OF INSULATION FOR THE PARAMETERS GIVEN IN TABLE 3.

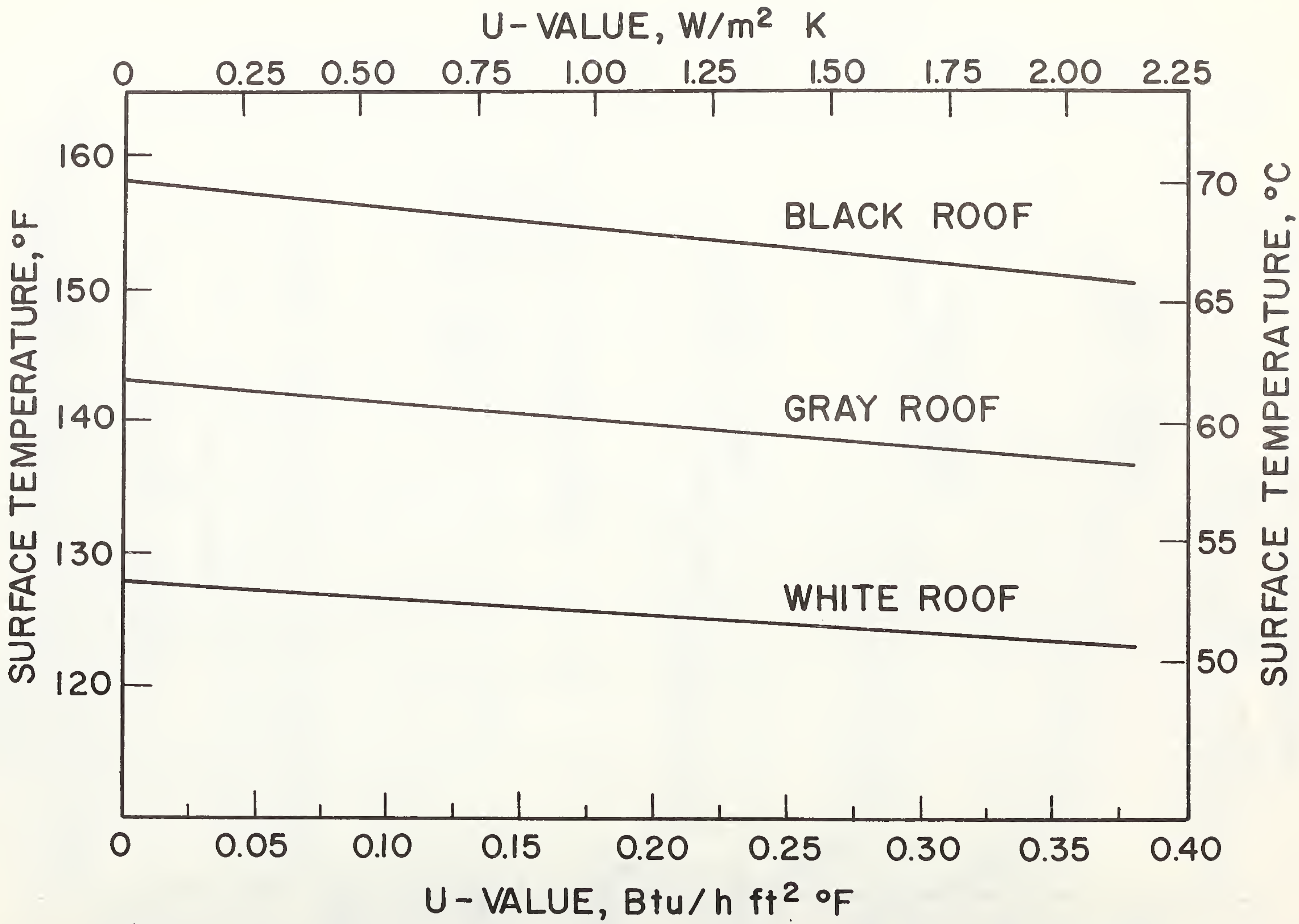


FIGURE 4. SURFACE TEMPERATURE OF THE ROOF AS A FUNCTION OF THE U-VALUE OF THE ROOFING SYSTEM FOR THE PARAMETERS GIVEN IN TABLE 3.

It is interesting to note Cullen [4] reported that roof surface temperatures attained by black surfaced membranes over concrete and wood on a summer day in Washington, DC were 120 and 145°F (49 and 63°C) respectively. This difference in the maximum membrane temperatures of 25°F (14°C) indicates from the experimental results that the heat capacity of uninsulated decks effects the surface temperature of applied membranes.

The heat balance equation (equation 1) can also be used to show the effect of radiative cooling on the surface temperature as a function of the U-value. The magnitude of radiative cooling is greatest on clear still nights when the roof is receiving negligible radiation from the sky. Calculations of surface temperatures are not shown since they are similar to those for solar heating. In general, a membrane placed directly on a deck will not be as cold as one on insulation. However, increasing the thickness of insulation (decreasing the U-value) above the amount normally used causes little decrease in the temperature of the surface of the roof due to radiative cooling.

5. SUMMARY AND CONCLUSIONS

The surface temperatures of black, gray and white roofs were calculated for various thicknesses of insulation located between the membrane and the deck. The calculations were performed using a steady-state heat balance equation to illustrate the increase in roof surface temperature due to solar radiation. The values of the parameters used to solve this equation represented environmental conditions of a hot, sunny, summer day where the outside temperature was 95°F (35°C), the inside temperature was 72°F (22°C) and the wind was 5-10 miles per hour (2-4 m/s) at the roof level.

The calculations indicate that the first increment, about 1 inch (25 mm), of insulation causes a significant rise in the roof surface temperature due to solar radiation. Increasing the amount of insulation above this first increment to greater thicknesses does not appreciably increase the roof surface temperature.

This paper deals only with the surface temperature of roofs containing various amounts of insulation. As pointed out in the paper, the authors believe that research is needed to determine the effect of insulation on roof performance. Criteria are needed to enable the evaluation of the performance of roofing systems which contain increased amounts of insulation necessary to obtain lower U-values.

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The surface temperatures of black, gray and white roofs were calculated for various thicknesses of insulation located between the membrane and roof deck. The calculations were performed using a steady-state heat balance equation to illustrate the increase in roof surface temperatures due to solar radiation.

The calculations indicate that the first increment, about 1 inch (25 mm), of insulation causes a significant rise in the roof surface temperature due to solar radiation. Increasing the amount of insulation above this first increment to greater thicknesses does not appreciably increase the roof surface temperature.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*

Built-up roofing; insulation; performance; radiative cooling; roofing; solar heating; surface temperature.

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