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NATIONAL BUREAU OF STANDARDS REPORT

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SOLAR HEATING, EMISSIVE COOLING, AND THERMAL MOVEMENT
AND THEIR EFFECT ON THE PERFORMANCE OF A BUILT-UP ROOF

~~Not for publication or for reference.~~

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by

William C. Cullen

NBS

U. S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS

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NBS PROJECT | **NBS REPORT**

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SOLAR HEATING, EMISSIVE COOLING, AND THERMAL MOVEMENT AND THEIR EFFECT ON THE PERFORMANCE OF A BUILT-UP ROOF

1. INTRODUCTION

In military construction, a large percentage of the roof area is protected with built-up roof systems. The built-up system may be a relatively simple system or it may consist of a number of components as:

1. Roof deck
2. Vapor barrier
3. Insulation
4. Waterproof membrane
5. Protecting surface

Each of these components may involve many materials exhibiting many different properties, the combination of which may result in a complex roof system. It follows that as the complexity of a roof system increases, the problems involving performance and maintenance also increases and to solve these problems, the properties of the system components must be known. Obviously, it is impracticable to list, determine and evaluate the properties of each specific material intended for use in a roof system but, still, criteria are needed to differentiate between a material which will perform as intended and one that will not. In this connection and at the request of agencies of the Defense Department, a program was conducted under Project 10447, Performance of Roofings, Tri-Service Engineering Investigations of Building Construction and Equipment, NBS, to study some fundamental factors involved in the performance of a built-up roof system.

Three factors which we believe to be primary contributing factors in many premature roof failures are:

1. Solar Heating
2. Emissive Cooling
3. Thermal Movement

Our experience in both the laboratory and in the field has established that the high temperatures attained by a roof surface, rapid changes in temperature, and thermal movements resulting from solar heating and emissive cooling are contributing factors in common built-up roof failures as:

1. Blistering
2. Wrinkling and buckling with the resultant cracking
3. Splitting and membrane ruptures
4. Slippages
5. Flashing failures
6. Chemical degradation of bitumen
7. Physical deterioration of bitumen

The purpose of this report is to present typical data on solar heating and emissive cooling which were obtained during summer and winter exposures and to relate this data to the properties of components of a roof system. The properties include the mass, heat capacity and density of the substrate to which the membrane is applied and to the reflective and emissive characteristics of the protecting surface. Another purpose is to furnish data on thermal expansive and contractive characteristics of a composite built-up membrane and to relate these characteristics to built-up roof performance.

2. SOLAR HEATING AND EMISSIVE COOLING

The greatest known source of energy is the sun and this energy is transmitted to the earth in wave form as infrared, ultraviolet and visible radiation. Roofs, per se, are exposed to solar radiation and the energy accompanying it. The law of conservation of energy demands that the radiant energy impinging on a roof surface must be quantitatively accounted for by three factors:

1. Reflection
2. Transmission
3. Absorption

For the purpose of this report, we shall deal primarily with the absorbed, infrared energy that is converted to heat energy which in turn results in the heating of the components of a roof system. It may be of interest to note that Billington (1)[1/] reported that the solar intensity (amount of energy falling on a plane surface perpendicular to the rays) outside the earth's atmosphere is about 420 BTU/sq. ft./hr. A good deal of this energy is absorbed by the atmosphere and the maximum recorded at the earth's surface is about 320 BTU/sq.ft./hr. The effect of solar radiation on building components was recognized by Beckett (2) as early as 1935 when he warned that there is a very real danger of structural failure due to expansive movements resulting from heating of the slab by sunshine.

1/ Numbers in parenthesis refer to literature references at the end of this report.

The effect of solar heating also contributes to the degradation of the waterproofing bitumen since this process is essentially a photo-oxidative reaction which is accelerated by heat.

Another concept, not as well known as solar heating, but equally as important to roof temperatures is emissive cooling which, in effect, is the reradiation of energy from the roof surface to the sky. The emission of radiation is not confined to luminous bodies as generally believed. The radiation from a material at moderate temperatures is entirely in the form of long-wave radiation which cannot be seen but can be detected by its cooling effect on the material. Consequently the outgoing radiation has a significant influence on roof surface temperature.

The emissivity of a perfectly black body is unity and it has been reported (1) that most building materials have an emissivity of approximately 0.9 which is independent of the color or texture of the surface. Metallic bodies, however, have low emissivities at ordinary temperatures, and, therefore, will tend to remain at somewhat higher temperatures than their non-metallic counterparts.

It becomes readily apparent that solar heating and emissive cooling contribute substantially to the magnitude of the thermal cycle of a built-up roof system. Assuming a clear day, the roof surface temperature begins to rise under exposure to the morning sun and it reaches its maximum about noon and then declines as the sun declines until night falls. If the night is clear and still, the heat loss from the roof surface to the sky will result in a sub-cooling of the roof surface.

The magnitude and rate of the temperature increase or decrease will depend on the following factors:

1. Intensity of solar radiation
2. Ambient air temperature
3. Clearity of the atmosphere
4. Wind velocity
5. Reflectance of the roof surface
6. Emissivity of the roof surface
7. Thermal properties of the roof system

The effects of wind velocity has been discussed by Hendry and Page (3). Their computations indicated that the maximum roof temperature on a still day was 30°F higher than on a day with a 12mph wind and 16°F higher than on a day with a 4mph wind.

Data which were reported by Cullen and Appleton (4) showed that roof membranes insulated from the roof deck attained higher and lower temperatures than non-insulated membranes and underwent greater temperature fluctuations when exposed to varying weather conditions.

In order to study, the influence of other factors, such as the substrate and surface treatments on solar heating and emissive cooling, a program of experimental work was planned and carried out.

2.1 Experimental Design

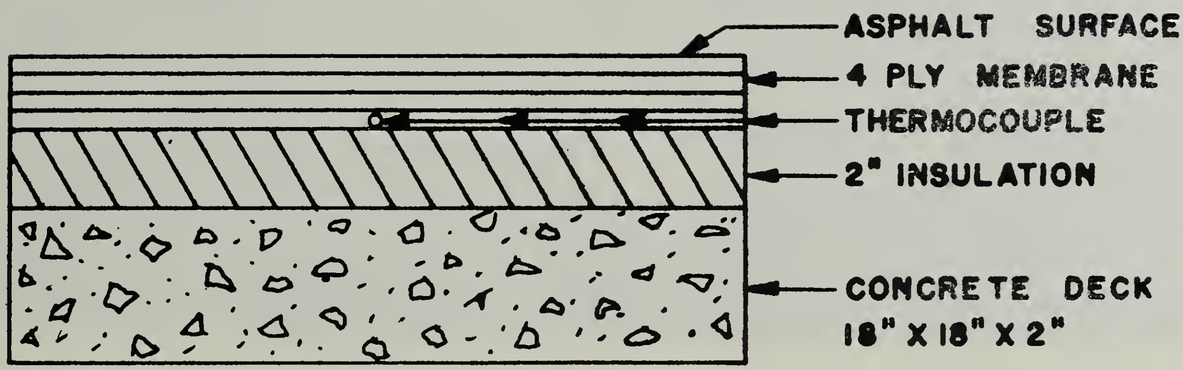
The laboratory experiments were designed to determine the effect of both the thermal properties of the membrane substrate and the color and character of the membrane surface on temperature and temperature fluctuations of a built-up roof subjected to solar heating and emissive cooling.

Twenty, 18 in. x 18 in., built-up roof system specimens were constructed in the laboratory employing three different substrates and five different protective surfaces. Conventional 4 ply asphalt-saturated organic felt built-up membranes were applied to ten 1/2" plywood decks and ten 2" dense concrete decks. Two inches of expanded polyurethane insulation was placed between the deck and the membrane on ten of the specimens. One of five protective surfaces was then applied to each specimen. Each specimen was instrumented with copper-constantan thermocouples at selected locations and temperatures recorded simultaneously 24 hours a day. Figure 1 is a schematic diagram of two smooth surfaced specimens on concrete decks.

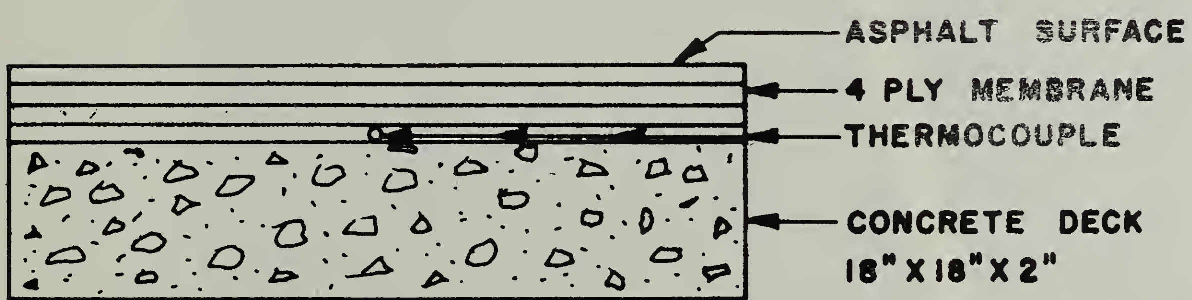
The specimens were exposed on the roof of the Industrial Building, National Bureau of Standards, Washington, D. C., in a horizontal position on a platform about 3 feet above the roof surface. Each specimen was supported on face bricks about 3 inches above the platform. This arrangement provided for the free circulation of air beneath a large portion of each experimental slab. Figure 2 shows a general view of the exposures while Figure 3 is a close up of a typical specimen.

2.1.1 Properties of Substrate

Three different materials were selected and employed as substrates for the experimental specimens. It is believed that these materials represent the extremes of built-up roof substrates used in service. Table 1 lists the selected materials together with their approximate densities and specific heats.



INSULATED SPECIMEN



NON-INSULATED SPECIMEN

FIG. 1

FIGURE 2. ROOF EXPOSURES OF BUILT-UP ROOF SPECIMENS.

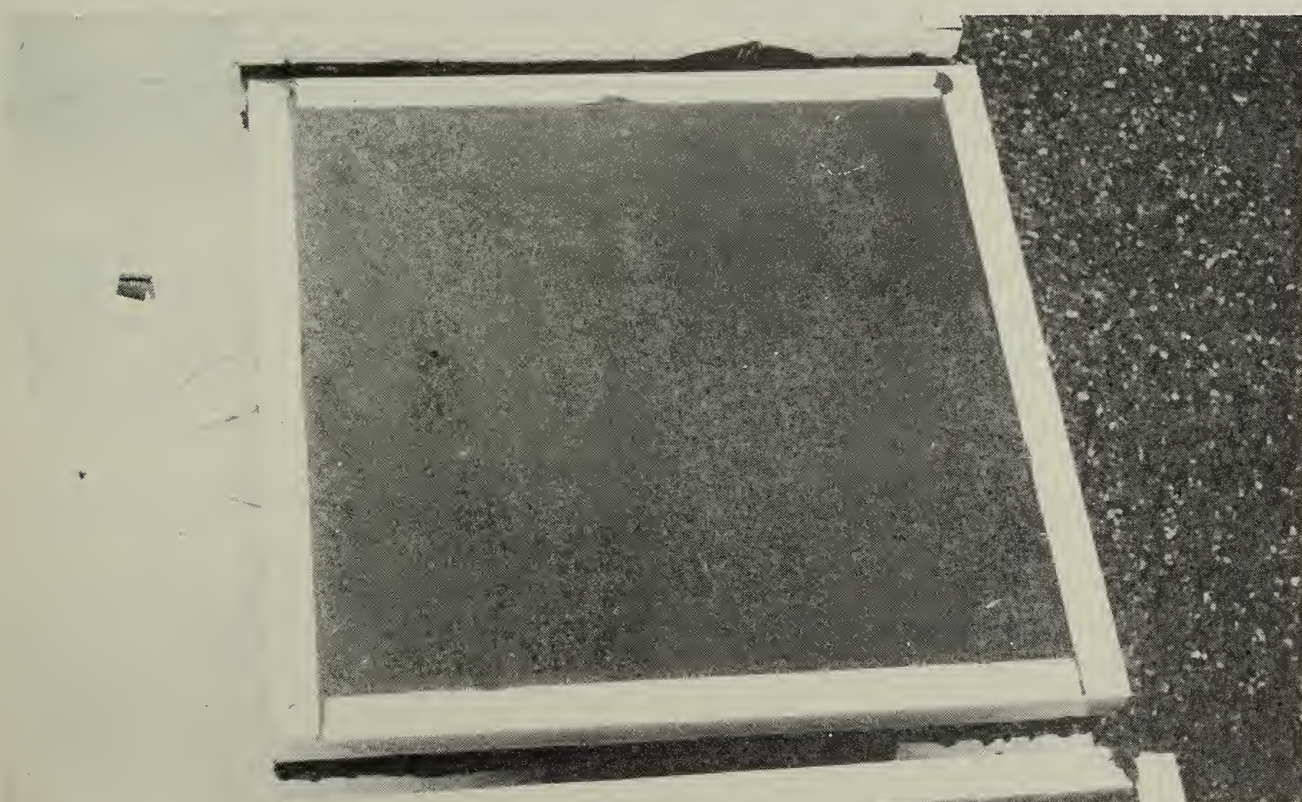


FIGURE 3. TYPICAL SPECIMEN.

TABLE 1.

PROPERTIES OF SUBSTRATE

Material	Density	Specific Heat
	lbs/ft^3	g cal/gram
Concrete	140	.21 to .25
Plywood	40	.42
Expanded Polyurethane	2	.40

2.1.2 Properties of Protecting Surfaces

Five commonly used surfaces were selected for use in the experimental work. It is our opinion that these surfaces represent the extremes of those used in service. Table 2 lists the materials used together with their significant properties.

TABLE 2.

PROPERTIES OF SURFACINGS

Material	Color	Weight Used	Solar Reflectance
		$lbs/100\ ft^2$	
Asphalt	Black	25	.5 to .10
Crushed Stone	Dark Grey	400	.20 to .30
Scoria	Maroon	150	.20 to .30
Marble Chips	White	200	.50 to .60
Polyvinyl Fluoride	White	Thin film (002")	.85 to .95

2.2 Experimental Results

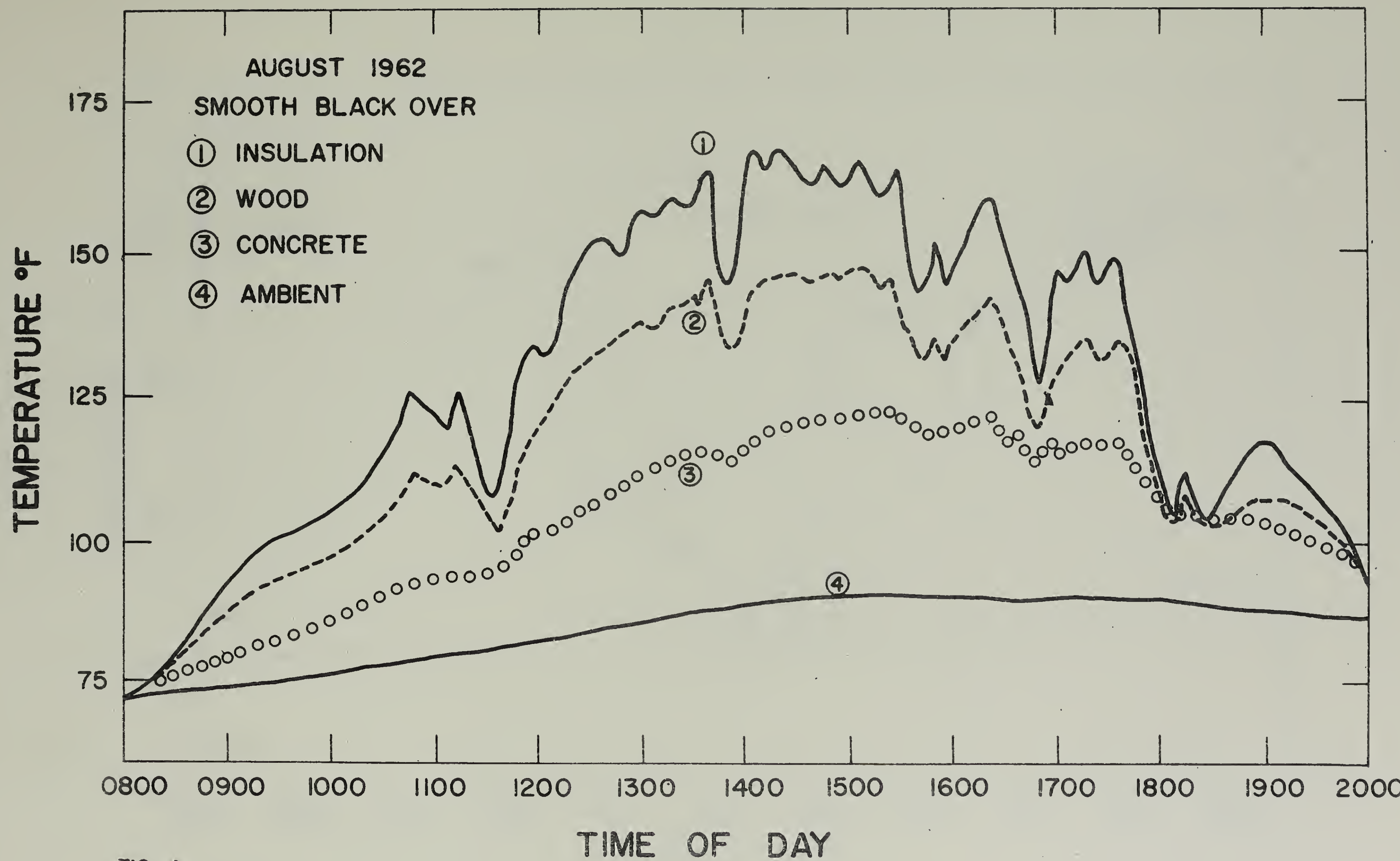
2.2.1 Solar Heating

The influence of the membrane base on the temperature and temperature changes produced by the solar heating of a black, smooth-surfaced roof membrane is shown in the time-temperature curves in Figure 4. The maximum temperatures attained by the membranes over concrete, wood and insulation on a summer day in August 1962 were 120°F, 145°F, and 165°F, repectively. In respect to temperature fluctuations it is interesting to note that between the hours of 5:30 pm (1730) and 6:00 pm (1800), the temperatures of the membranes over concrete, wood and insulation declined 15°F, 30°F, and 45°F, respectively. The degree of temperature change between a membrane placed over insulation and a similar one placed over concrete is vividly illustrated in Figure 5. The temperatures were measured on a day which included sunshine, clouds, and heavy rains.

One might infer from this information that all insulated roof membranes are subjected to greater extremes in both temperatures and temperature variations. This is true if other factors are similar, however, other variables come into play which limit these extremes to a lesser or greater extent. For example, Figure 6 shows the effect of surface color on the thermal cycle of a black and a white smooth-surfaced built-up roof membrane placed over insulation. A comparison of curve 1 with curve 2 indicates a decline of 40°F for the black and only 15°F for the white between noon (1200) and 1:00 pm (1300) and then as the surfaces were again exposed to sunshine, the black surfaced membrane registered a gain of 90°F while the white surfaced membrane was limited to a 25°F rise between the 1:00 pm (1300) and 3:00 pm (1500).

The influence of other surfaces as crushed stone and marble chips on the thermal cycles of membranes placed over insulation and over concrete are illustrated in Figure 7. These results again confirm our theory that the higher the coefficient of solar reflectance of the roof surface the smaller the temperature difference between the insulated and non-insulated membranes.

Figure 8 illustrates the effect of the protecting surface on the temperature and temperature changes of membranes placed over insulation. Although these curves represent specimens placed over insulated concrete decks similar curves were obtained on the specimens placed over insulated wood decks. These observations indicate that the type or kind of deck is not related to roof temperature when an efficient insulation is used. For convenience, the maximum temperatures which were recorded at 1:30 pm (1330) by membranes protected with the selected surfaces are listed in Table 3.



AUGUST 1962
SMOOTH BLACK OVER
① INSULATION
② WOOD
③ CONCRETE
④ AMBIENT
TEMPERATURE °F
175
150
125
100
75
0800
0900
1000
1100
1200
1300
1400
1500
1600
1700
1800
1900
2000
TIME OF DAY

FIG. 4

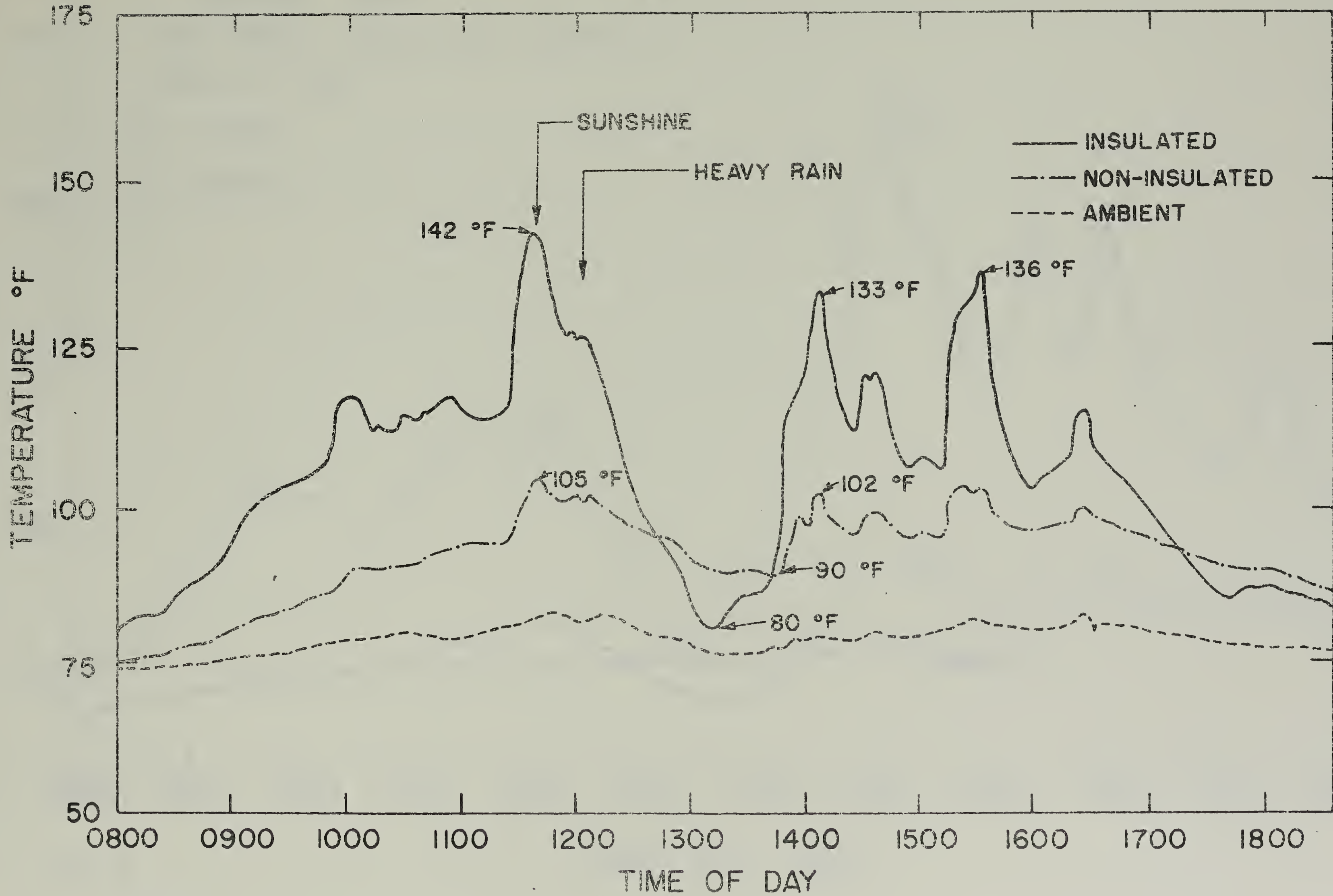

SUNSHINE
HEAVY RAIN
INSULATED
NON-INSULATED
AMBIENT
142 °F
105 °F
133 °F
136 °F
102 °F
90 °F
80 °F
175
150
125
100
75
50
TEMPERATURE °F
0800
0900
1000
1100
1200
1300
1400
1500
1600
1700
1800
TIME OF DAY

FIG. 5

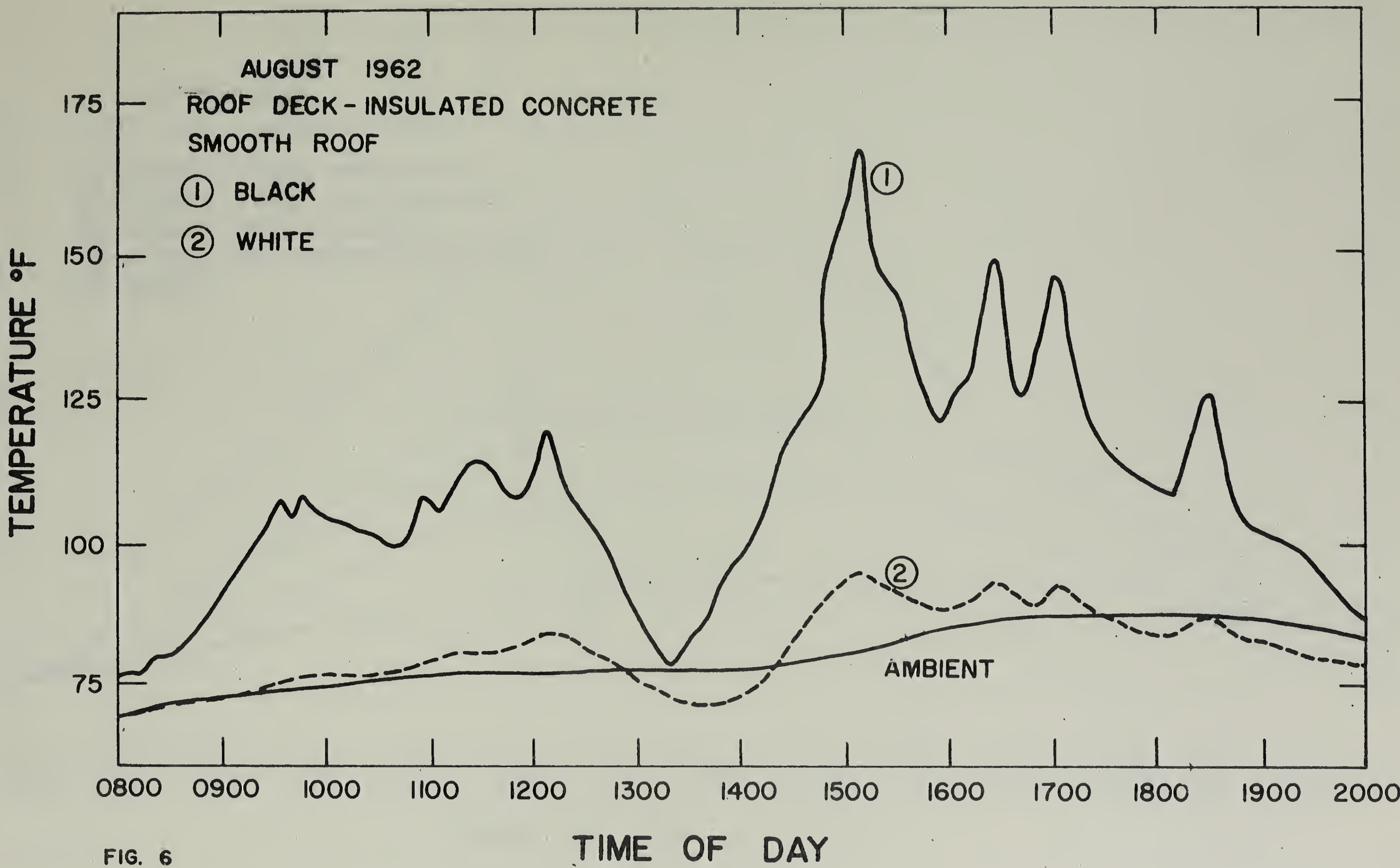
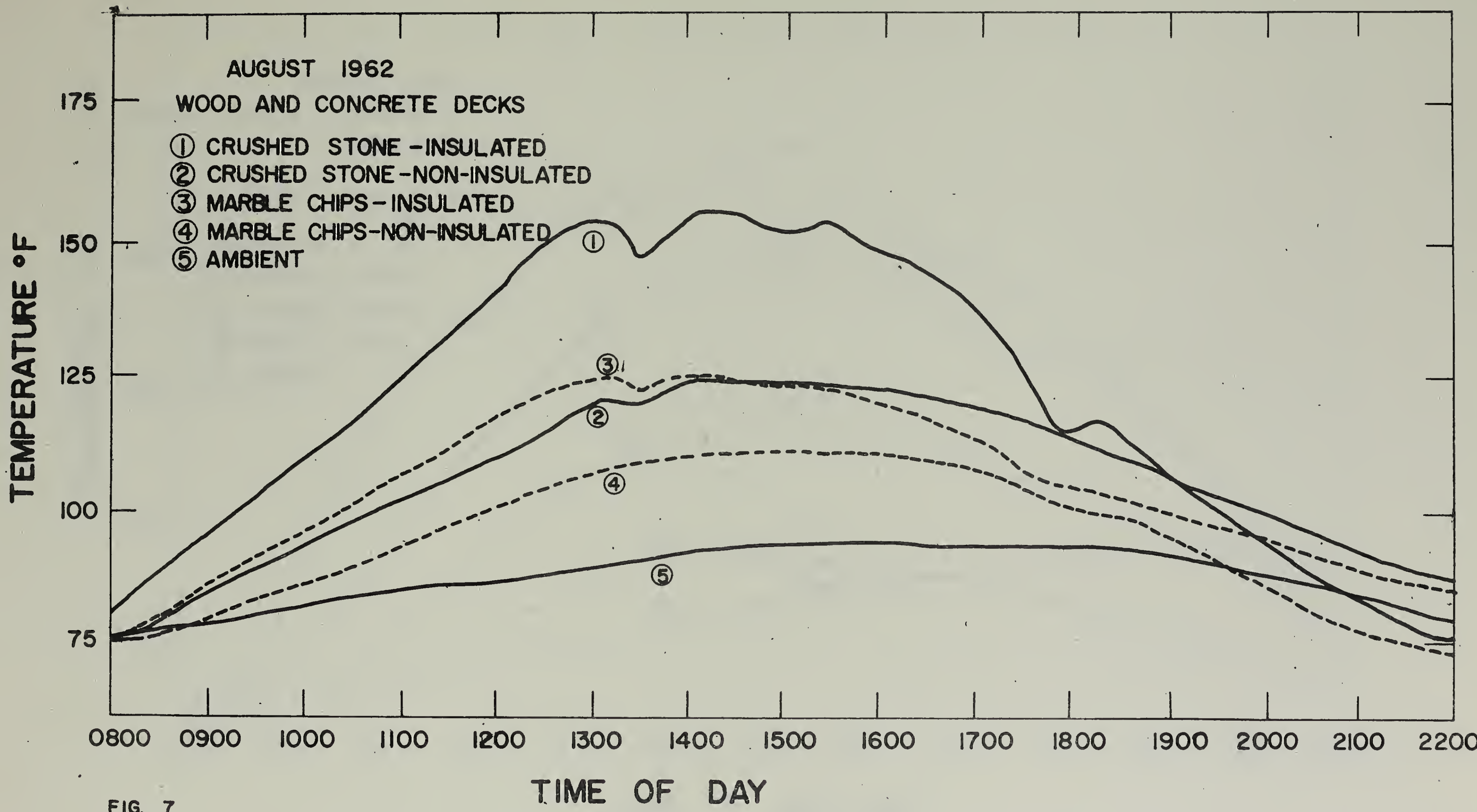

AUGUST 1962
ROOF DECK - INSULATED CONCRETE
SMOOTH ROOF
① BLACK
② WHITE
175
150
125
100
75
TEMPERATURE °F
①
②
AMBIENT
0800
0900
1000
1100
1200
1300
1400
1500
1600
1700
1800
1900
2000
TIME OF DAY

FIG. 6



AUGUST 1962
WOOD AND CONCRETE DECKS
① CRUSHED STONE - INSULATED
② CRUSHED STONE - NON-INSULATED
③ MARBLE CHIPS - INSULATED
④ MARBLE CHIPS - NON-INSULATED
⑤ AMBIENT
TEMPERATURE °F
175
150
125
100
75
0800
0900
1000
1100
1200
1300
1400
1500
1600
1700
1800
1900
2000
2100
2200
TIME OF DAY

FIG. 7

④

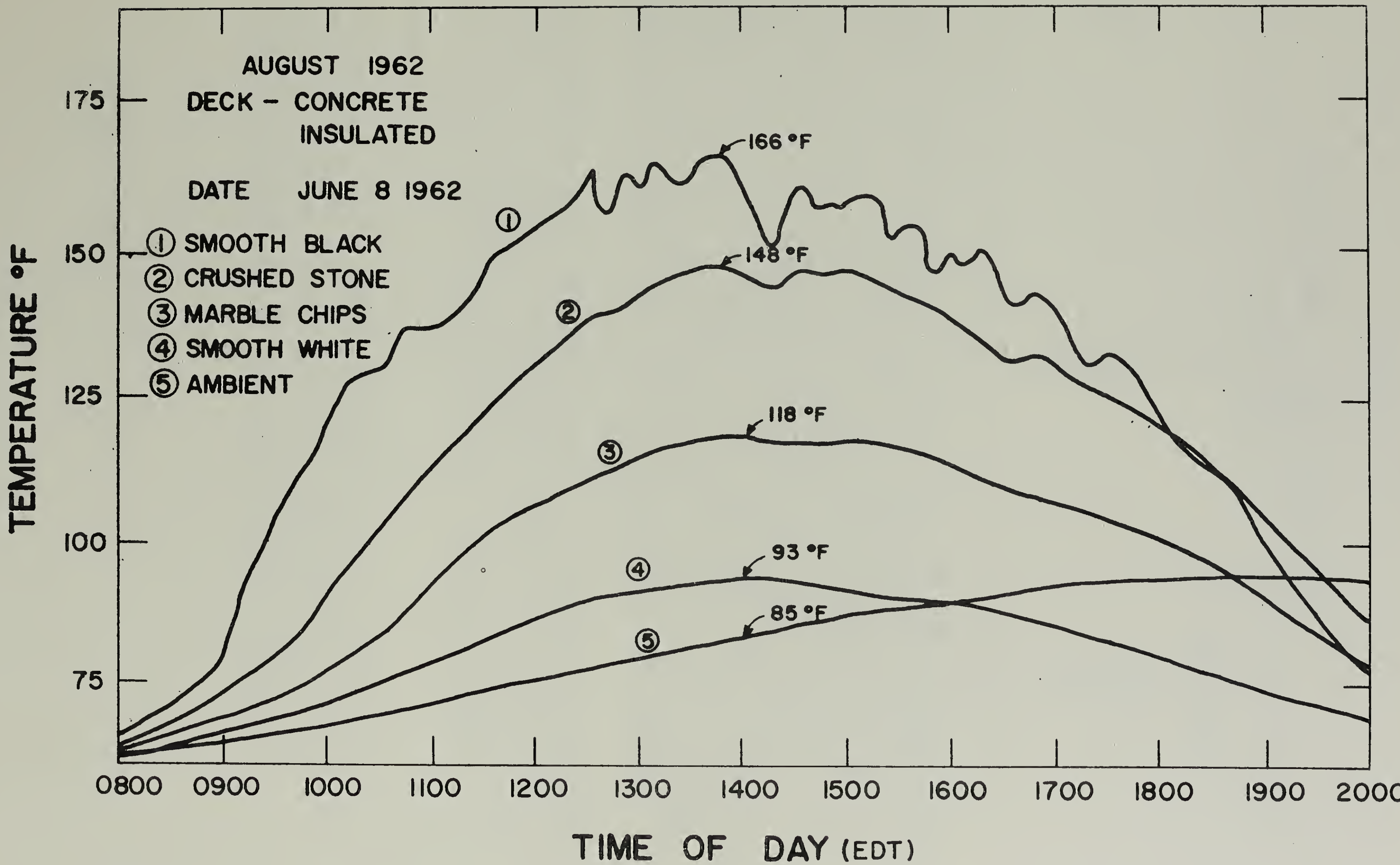

AUGUST 1962
DECK - CONCRETE
INSULATED
DATE JUNE 8 1962
① SMOOTH BLACK
② CRUSHED STONE
③ MARBLE CHIPS
④ SMOOTH WHITE
⑤ AMBIENT
166 °F
148 °F
118 °F
93 °F
85 °F
TEMPERATURE °F
175
150
125
100
75
0800
0900
1000
1100
1200
1300
1400
1500
1600
1700
1800
1900
2000
TIME OF DAY (EDT)

FIG. 8

TABLE 3.

SURFACE EFFECT ON ROOF TEMPERATURE

Surface	Max. temp.	Δt
	°F	From ambient
Black	166	81°F
Crushed stone	148	63°F
Marble chip	118	33°F
White	93	8°F
Ambient	85	----

It has been established by this and other studies that insulation placed between the deck and the membrane may lead to the accelerated deterioration of the built-up roof. On the other hand, if insulation is omitted or placed beneath the deck, it follows that the thermal movement in the slab may be considerable due to solar heating and emissive cooling. The question, therefore, arises as to the magnitude of the temperature changes which occur in the insulated and uninsulated slab. Figure 9 indicates the extent of these changes by the time-temperature curves for the membrane and roof slab temperatures as recorded in both insulated and uninsulated specimens on a summer day in August 1962. Incidently, Curve 2 coincides with the ambient temperature. It can only be concluded that the temperature changes in an uninsulated slab were considerably less than those which occur in an insulated membrane.

A snow cover appears to be an important factor in stabilizing temperatures of a roof membrane. We observed during winter exposures in December and January 1963 when the specimens were covered with snow that no variation was recorded in the temperatures of the ambient and roof membranes regardless of the type of substrate and surface treatment employed.

2.2.2 Emissive Cooling

We have seen that the reradiation of energy from a roof surface often results in a sub-cooling of the roof surface. The degree of sub-cooling is dependent on a number of factors including the properties of the substrate, the wind velocity and atmospheric conditions. Figure 10 serves to illustrate these points. The ambient temperature (Curve 1)

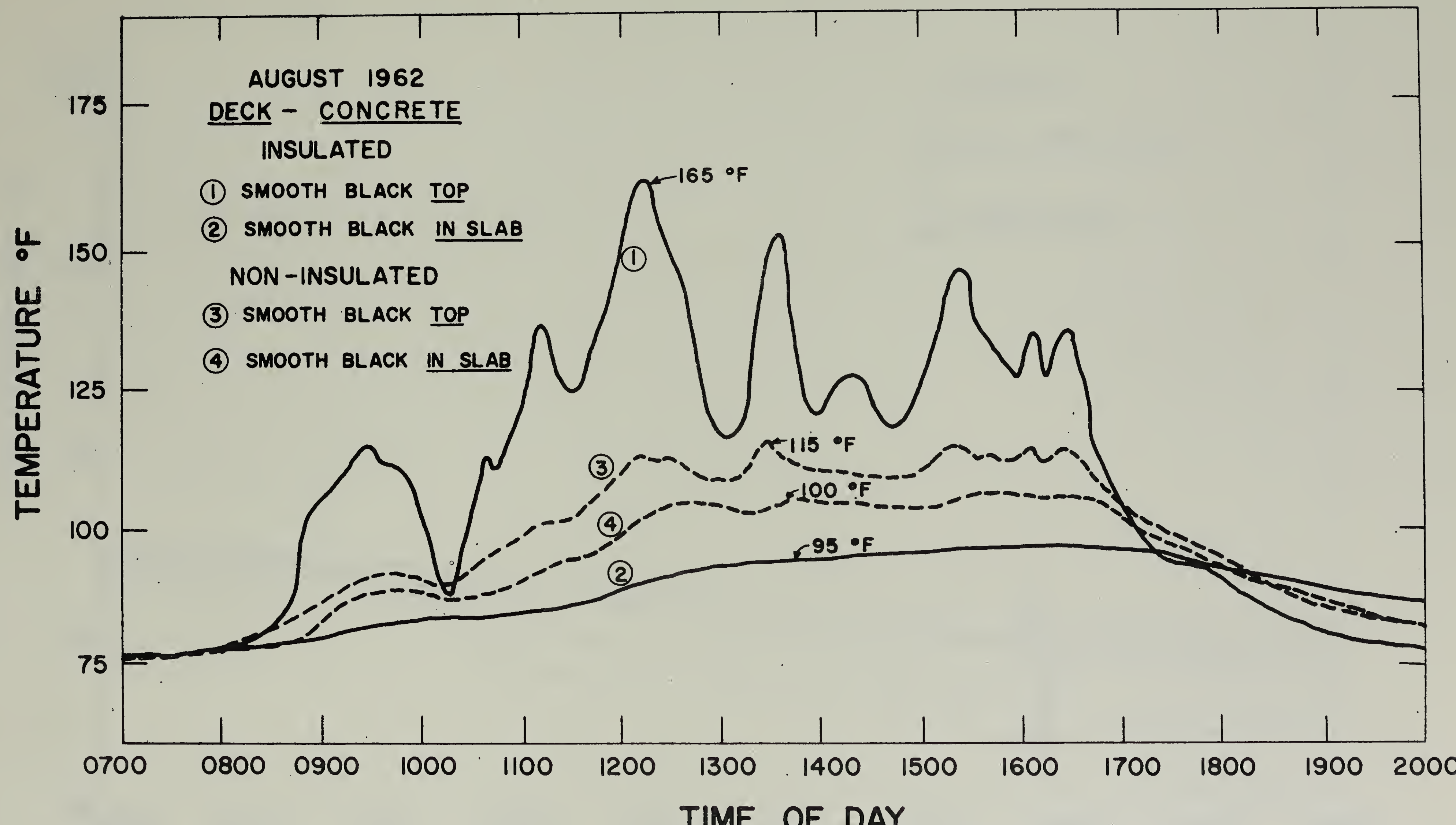

AUGUST 1962
DECK - CONCRETE
INSULATED
① SMOOTH BLACK TOP
② SMOOTH BLACK IN SLAB
NON-INSULATED
③ SMOOTH BLACK TOP
④ SMOOTH BLACK IN SLAB
165 °F
115 °F
100 °F
95 °F
TEMPERATURE °F
175
150
125
100
75
0700
0800
0900
1000
1100
1200
1300
1400
1500
1600
1700
1800
1900
2000
TIME OF DAY

FIG. 9

③

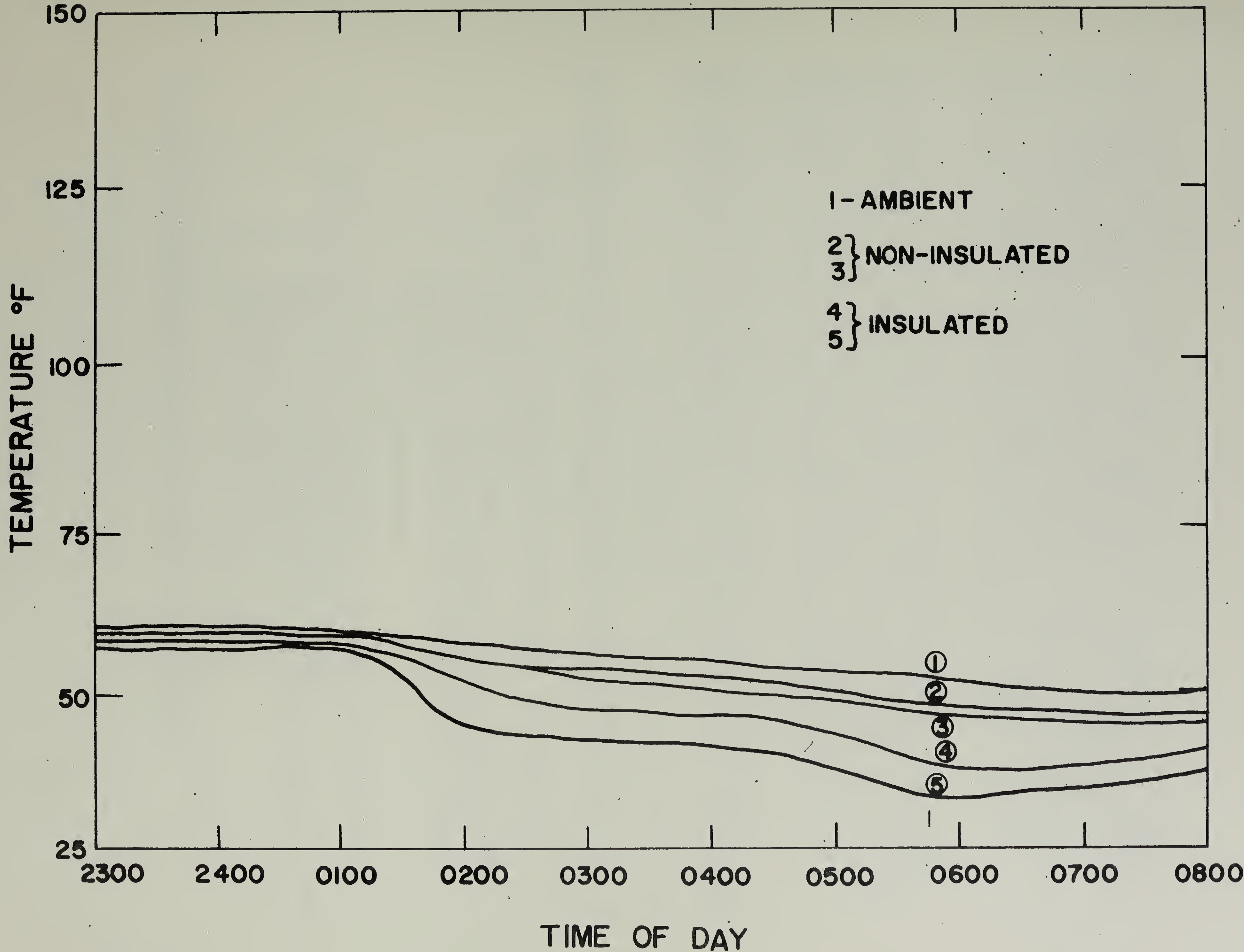

150
125
100
75
50
25
TEMPERATURE °F
2300
2400
0100
0200
0300
0400
0500
0600
0700
0800
TIME OF DAY
1 - AMBIENT
2
3 } NON-INSULATED
4
5 } INSULATED
1
2
3
4
5

FIG. 10

and that of uninsulated specimen (Curve 2 & 3) and insulated specimen (Curves 4 & 5) were obtained coincident with one another on a day when the sky was cloudy until 1:00 am (0100 hours) when the cloud cover lifted. This event was immediately reflected in the apparent temperatures of the ambient and insulated and non-insulated specimens. The temperature of the membrane placed on insulation was about 12°F cooler than those placed over concrete and about 20°F cooler than the ambient. In each case, we observed that the white surfaced membranes (Curves 3 & 5) were slightly cooler than their black counterparts.

The emissive properties of most organic roofing materials, unlike their solar heating characteristics, are for all practical purposed independent of surface color or texture. A case in point is illustrated in Figure 11 where the marked effect of solar heating on the black specimen is clearly indicated in comparison with the slight effect of emissivity on both the black and white surfaced specimens. The time-temperature curves identified as 1, 2 and 3 were recorded on 13 October 1962.

Again during the snow cover in December-January it was observed that the temperatures of the ambient air and all the specimens were essentially the same when the specimens were covered with snow.

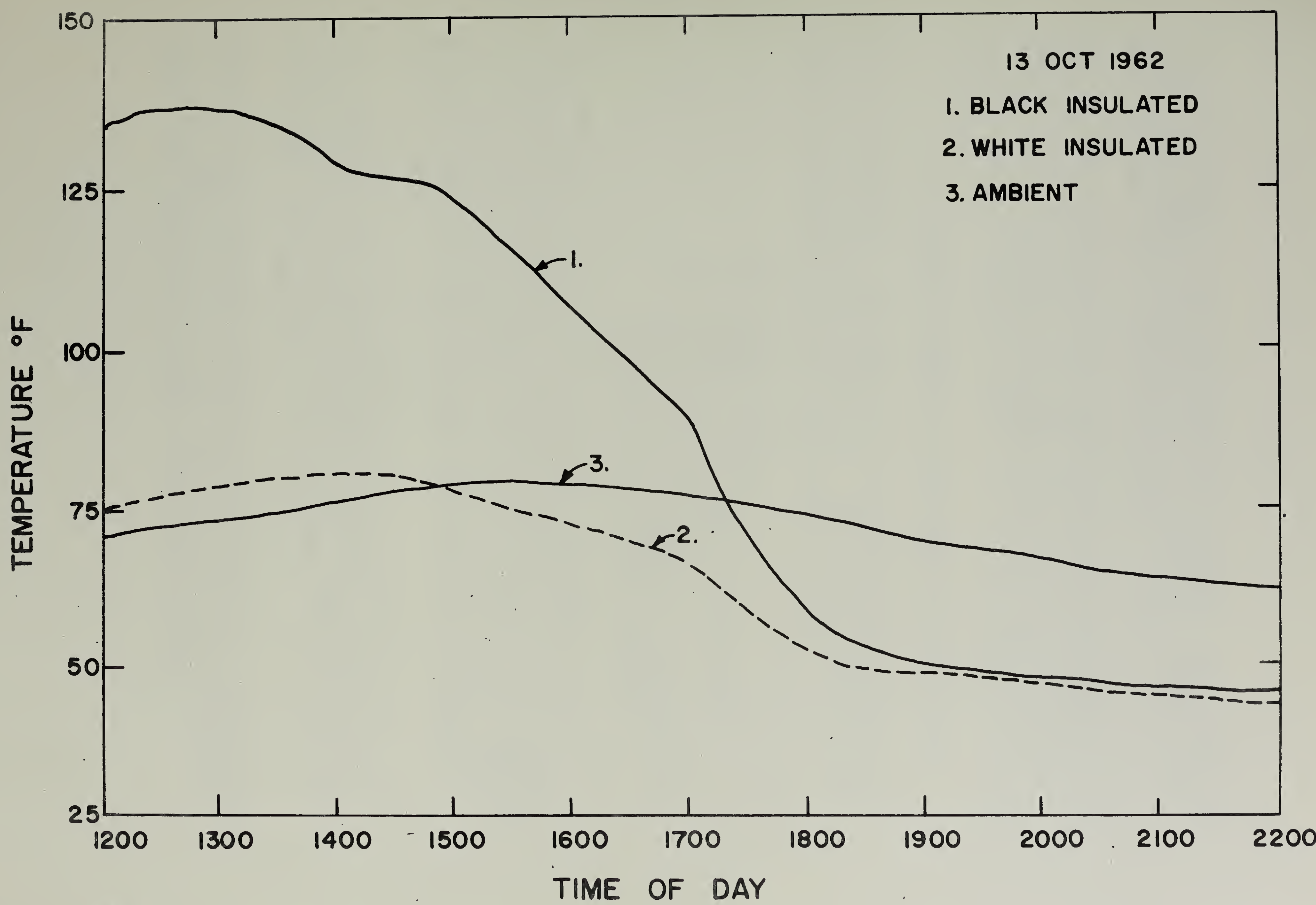
2.3 Summary

In connection with solar heating and emissive cooling of roof surfaces, the findings of this study may be summarized as follows:

1. Roof surfaces are heated by solar radiation. The degree of heating is dependent upon:
    a. Character of substrate (mass, density, specific heat)
    b. Properties of surface protection (color and texture)
    c. Atmospheric conditions (wind velocity, rain, clouds, haze, etc.)
    d. Presence of a snow cover.

2. Roof surfaces may be sub-cooled by their emissive properties. The magnitude of sub-cooling is dependent upon:
    a. Character of substrate (mass, density, and specific heat)
    b. Nature of the exposed material (metallic, organic)
    c. Atmospheric conditions
    d. Presence or absence of snow cover.

For all practical purposes the emissive cooling of organic building materials is independent of color or texture of the surface.



13 OCT 1962
1. BLACK INSULATED
2. WHITE INSULATED
3. AMBIENT
1.
2.
3.
150
125
100
75
50
25
TEMPERATURE °F
1200
1300
1400
1500
1600
1700
1800
1900
2000
2100
2200
TIME OF DAY

FIG. 11

The data obtained in the experimental work indicated that a black, insulated roof membrane was subjected to a temperature change of about 180°F in a period of one year and in excess of 80°F in a period of two hours when exposed in the Washington, D. C. area.

Obviously for other membranes, both insulated and non-insulated, these extremes will be somewhat less depending on the base on which the membrane is applied and on the color and texture of the protecting surface. It is expected that these extremes will also vary to a lesser or greater extent for similar roof systems exposed in different locations.

3. THERMAL MOVEMENT OF COMPONENTS OF A ROOF SYSTEM

It is an established fact that with few exceptions the dimensions of materials increase as the temperature of the material increases and decrease as the temperature decreases. The relation between linear change and temperature has been expressed as follows:

$\Delta L = \alpha L_o \Delta t$ where:
ΔL = change in length
L_o = length at some reference temperature
Δt = temperature change
α = proportionality constant which varies from material to material and is identified as the coefficient of linear expansion.

Our experience in the field has indicated that many of the common built-up roof failures can be directly or indirectly traced to thermal movements within a specific component of the roof system or by the differential movement among the components as the membrane, insulation, deck and flashings. It is our opinion that the expansive and contractive movements resulting from temperature change are of paramount importance and, therefore, the extent of this movement should be known.

The coefficients of linear expansion for many materials used in the roof system has been determined and are reported in the literature. Values for some materials are given in Table 4 where they are reported in the usual term of inches per inch per degree F and in inches per 100 feet per 100 degrees F.

However, little published information is available for the coefficient of linear expansion of a composite membrane consisting of alternate layers of bitumen and felt. Therefore, a program was initiated to measure this property of a number of composite membranes.

TABLE 4

LINEAR EXPANSION OF MATERIALS USED AS COMPONENTS OF A ROOF SYSTEM

Material	Coefficient of Linear Expansion $\frac{\text{in./in.}}{°F}$	$\frac{\text{in./100 ft.}}{100°F}$
Roof Decks		
Steel	6.0×10^{-6}	.7
Concrete	5.0×10^{-6}	.6
Wood	2.0×10^{-6}	.2
Plywood	3.5×10^{-6}	.4
Gypsum	8.0×10^{-6}	1.0
Insulations		
Foam glass	4.6×10^{-6}	.6
Poly Styrene	3.0×10^{-5}	3.6
Polyurethane	3.0×10^{-5}	3.6
Flashing Metals		
Aluminum	1.3×10^{-5}	1.6
Copper	9.5×10^{-6}	1.1
Gal. Iron	6.7×10^{-6}	.8
Lead	1.6×10^{-5}	1.9

3.1 Experimental Design

Two types of samples were used in the experimental work, the first was a sample taken from an actual roof while the remainder consisted of samples prepared in the laboratory. Table 5 identifies the samples.

TABLE 5

Sample No.	No. of Plies	Description
1	5	asphalt-organic felt from actual roof.
2*	4	asphalt - 15 lb. asphalt sat. organic felt.
3*	4	coal tar pitch - 15 lb. coal tar sat. organic felt.
4*	4	asphalt - 6 lb. asphalt impregnated glass mat (felt).
5*	4	asphalt - 15 lb. asphalt saturated asbestos felt.

* Approximately 20 pounds/100 sq.ft. of bitumen were used between the plies and no surfacing was applied to the specimens.

Duplicate specimens, 12 in. x 2 in., were cut from the samples. Two brass reference plugs were inserted into the specimen near each end exactly 10 inches apart when measured at a temperature of 73°F. The specimens were placed unrestrained on a flat surface in the conditioning chamber. A copper-constantan thermocouple was inserted into a control specimen and the temperature of the chamber was reduced to -60°F. The distance between the reference plugs on each specimen was measured to the nearest ten thousandeth of an inch with a Whittemore Strain Guage. The temperature in the chamber was gradually raised in increments of about 10°F and after the specimens reached equilibrium the distance between the reference plugs was measured. This procedure was repeated for each specimen over the temperature range of -60°F to 160°F. The coefficient of linear expansion were calculated by solving the following equasion for α:

$$\alpha = \frac{\Delta L}{L_o} \cdot \frac{1}{\Delta t}$$

3.2 Results

The results of the experiments indicated that the linear change for composite bituminous membranes was apparently not constant over the temperature range to which exposed. The changing nature of this coefficient is illustrated in Figure 12 where the length increase of Sample 1 is plotted against the temperature. The calculated coefficients of linear expansion expressed in./in./°F and in./100ft./100°F for the ranges indicated are also given. The length-temperature curves for other built-up specimens exhibited similar characteristics although their coefficients of linear expansion were somewhat less than those of Sample 1. The calculated coefficients of linear expansion for the various samples over three temperature ranges are given in Table 6.

TABLE 6.

COEFFICIENT OF LINEAR EXPANSION OF BUILT-UP ROOF SPECIMENS

Sample	Description	Coefficient of linear expansion (α) in./in./°F		
		-60°F to 0°F	0°F to 77°F	77°F to 154°F
1	Asphalt-rag	4.1×10^{-5}	1.5×10^{-5}	4.5×10^{-6}
2	Asphalt-rag	1.8×10^{-5}	3.0×10^{-6}	2.5×10^{-6}
3	Coal tar-rag	1.4×10^{-5}	7.5×10^{-6}	3.1×10^{-6}
4	Asphalt-glass	3.2×10^{-5}	5.3×10^{-6}	2.4×10^{-6}
5	Asphalt-asbestos	1.2×10^{-5}	----	----

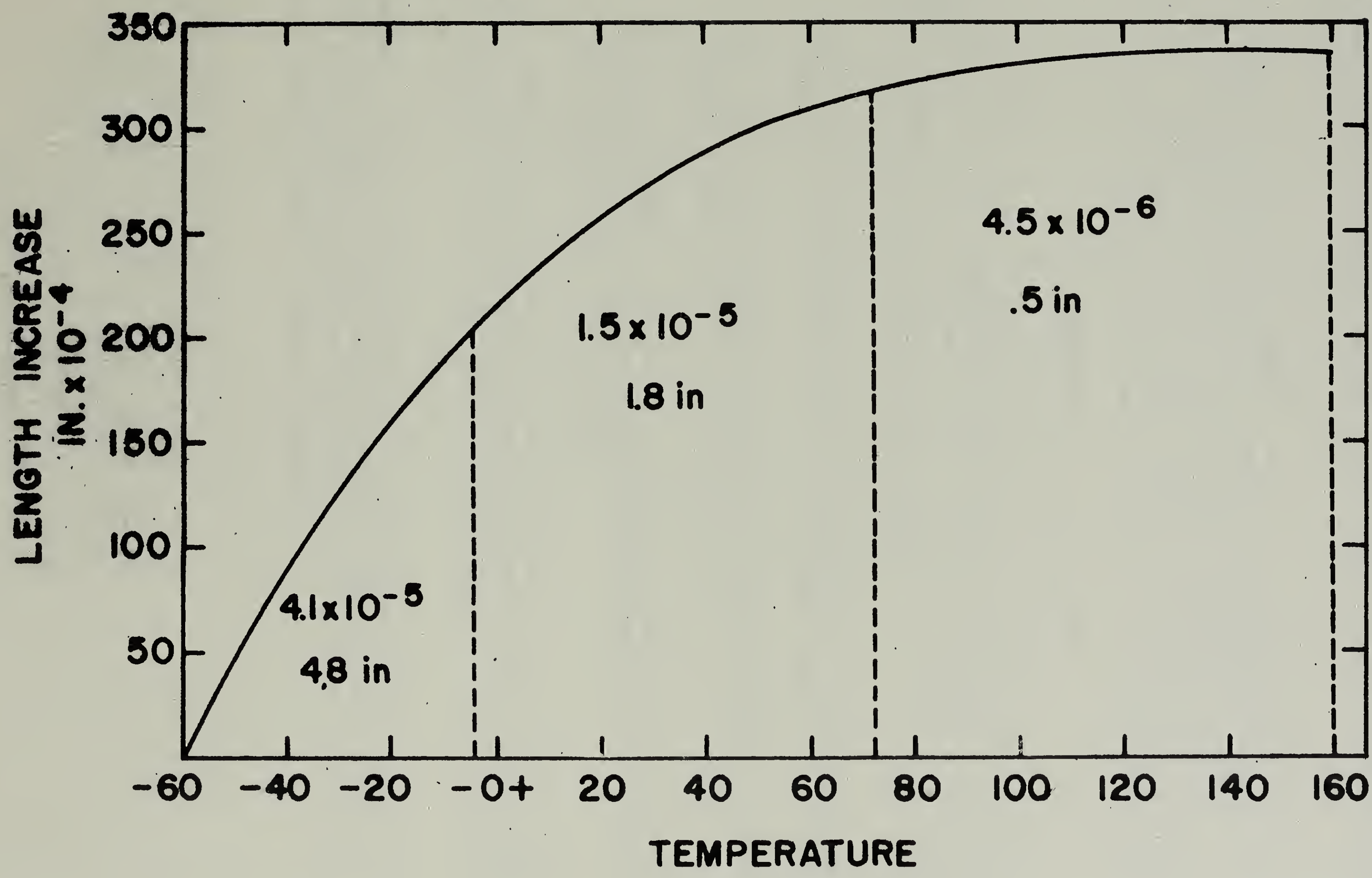

LENGTH INCREASE
IN. x 10^-4
350
300
250
200
150
100
50
-60
-40
-20
-0+
20
40
60
80
100
120
140
160
TEMPERATURE
4.1x10^-5
4.8 in
1.5 x 10^-5
1.8 in
4.5 x 10^-6
.5 in

FIG. 12

The results of the determinations revealed that the expansion and contraction of a built-up membrane due to changing temperatures is apparently greater than for the other components generally used in a built-up roof system. The data also indicated the changing nature of the linear movement of a composite membrane depending on the temperature range to which exposed. This phenomenon appears to hold true for both asphalt and coal-tar pitch materials and for both organic and inorganic reinforcing felts.

The significance of the data appears obvious in that movements due to thermal changes are most critical in the low temperature ranges as opposed to the minimal movement in the high temperature ranges. Although the magnitude of the length change was unexpected, the changing nature of the coefficient of linear expansion can be explained theoretically, at least in part, by the visco-elastic behavior of roofing bitumens.

4. SUMMARY AND CONCLUSIONS

It is an accepted fact that many built-up roof systems are complex systems made up of many components and that the materials comprising the components of a roof system exhibit different movement rates when subjected to temperature changes. As a result of the data obtained in this study, we have established the following:

a. Built-up roof membranes may be subjected to large temperature changes as a result of solar heating and emissive cooling.

b. Built-up roof membranes apparently undergo greater thermal movements than most other components of a roof system.

c. Thermal movement per degree change in temperature of a built-up membrane is not linear with temperature and increases as the temperature is decreased.

When these concepts are considered collectively, it is readily apparent that many of the failures which commonly occur in built-up roof systems result directly or indirectly from solar heating, emissive cooling and thermal movement.

Flashing failures at the junction of a bituminous membrane with metal base flashings, gravel stops and other metal appurtenances may be caused or accelerated by their differences in emissivity and by their different coefficients of linear expansion.

Temperature and temperature changes are certainly factors to be considered in the wrinkle cracking or buckling of roofing felts and in the formation and subsequent growth of blisters beneath or between the plies of the membrane especially if moisture is present in some component of the roof system.

Solar heating is a most important factor when a slippage of roof membrane occurs, assuming other pertinent factors are present.

In connection with the weathering of the roofing bitumen, it is a well-known fact that the chemical degradation of asphalt is accelerated by increased temperatures. In addition, our experience indicates that the physical deterioration of a weathered bitumen may be accelerated by thermal shock due to rapid temperature changes.

Theoretically, solar heating, emissive cooling, and thermal movement may also result in insulation problems such as breakage, cupping or curling, if the following conditions are present: 1) insulation has a high coefficient of linear expansion, 2) adhesion of insulation to roof deck is poor and 3) large thermal gradient exists within the insulation.

Reports from the field regarding splitting failures and membrane ruptures indicated that thermal shock is a primary factor in many such failures. If this is correct, solar heating, emissive cooling, and thermal movement must certainly be considered. Sub-cooling of the membrane due to surface emissivity and the magnitude of linear change exhibited by a bituminous membrane at low temperatures appears significant, especially if the membrane is applied over insulation. This opinion is strengthened by our observations in this study concerning the insulating value of a snow cover which tends to stabilize roof temperatures. This factor accounts for, at least in part, the greater number of complaints involving roof splitting and membrane rupture failures that are received during extended cold spells with no snow cover.

In conclusion, we believe that the data obtained in the present program has shed new light on the pertinent factors involved in many premature failures in a built-up roofing system. Further, the information obtained confirms many of our opinions formally based on field experience alone.

5. PRACTICAL APPLICATION OF THE DATA

It is often quite difficult to convert the data which are obtained in the laboratory directly to practical applications in the field. Nevertheless, due to the critical need of information in roofing practices, we feel that an interpretation of this data for use in the field is not only justified but is necessary. We are aware, of course, that others involved in the various phases of the roofing industry may interpret some of the results differently.

The following statements are based on both the data obtained in this study and on considerable field experience.

1. The use of insulation between the roof deck and membrane should be avoided in extremely cold climates especially those with little snow fall. If the use of insulation above the deck is necessary, and it will be in many cases, the roof should be surfaced with a mineral aggregate and adequate expansion joints should be installed to prevent membrane failures.

2. Roof membranes placed over insulation should always be surfaced with a mineral aggregate or a surface having a high solar reflectance value. Criteria, other than solar reflectance, must also be considered in the selection of a surfacing material as durability, hardness, sieve gradation, and maintenance required.

3. The use of smooth, asphalt surfaced, built-up roofs should be avoided, especially those which are insulated.

4. In connection with the prevention of membrane slippages on roofs having slopes of 1 inch or more per foot, two factors should be considered:
1) the use of reflective surfacing materials to reduce temperature and
2) the placement of insulation beneath the roof deck.

5. The emergency application of a reflective coating to an existing roof showing indications of slippage may prevent a costly failure.

6. Reflective surfaces may be applied to built-up membranes to reduce interior temperature and to reduce air conditioning loads in a conditioned structure.

7. Base flashings constructed of bituminous materials should be used in conjunction with built-up roofings wherever possible.

8. When metallic flashings are tied into the bituminous membrane, a bituminous plastic cement should be employed between the metal and bituminous membrane to compensate for the differential movement of the two materials.

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