NBS

Technical Note 231

SOLAR HEATING, RADIATIVE COOLING, AND THERMAL MOVEMENT – THEIR EFFECTS ON BUILT-UP ROOFING

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U. S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS

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ISSUED DECEMBER 16, 1963

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Reprinted with Errata - April 1964

For sale by the Superintendent of Documents, U.S. Government Printing Office
Washington, D.C., 20402 - Price 25 cents

ERRATA

On page 4; line 11 now reads "purposes, solar radiation is confined to the ratiation spectrum between"

Should read: "purposes, solar radiation is confined to the radiation spectrum between".

On page 7, Table 1, under Weight Used now reads lbs/ft^2.

Should read: lbs/100 ft^2.

On page 7, last line of Table 1 now reads Polyvinyl Fluroide Film.

Should read: Polyvinyl Fluoride Film.

On page 14, 1st line now reads "Duplicate specimens, 12-in. by 12-in., were cut from the samples so"

Should read: "Duplicate specimens, 12-in. by 2-in., were cut from the samples so".

On pages 26 and 27, the legends for Figures 7 and 8 should be transposed.

On pages 30, 31, 32, and 33, for Figures 11 through 14, +40 X 10^{-3} in the scale should read +40 X 10^{-5}.

CONTENTS

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William C. Cullen

Twenty different built-up roof construction specimens, covered with five surfacing materials, were subjected to natural solar heating and nighttime cooling. The temperatures and temperature changes observed during winter and summer exposures are discussed. The data indicate that the temperature attained in a roof membrane is influenced by the absorptance and emissivity of the surface as well as the thermal and physical properties of the substrate to which the roofing is applied. The data show that roofings placed over insulation may be heated to a temperature of 80°F. above ambient due to solar heating and may be subcooled as much as 20°F. below the ambient due to radiative cooling. The thermal movements which occur in the components of a roof system due to temperature change are discussed in relation to built-up roof performance and failures. Thermal expansion data are presented for some composite bituminous membranes. The data show that these membranes undergo greater thermal movements than most other components of a roof system and the rate of expansion is not linear but decreases as the temperature is increased.

1. INTRODUCTION

A major percentage of flat roof construction in the United States consists of built-up roof systems. The built-up system may be a relatively simple system as a deck covered by roofing or it may consist of a number of components such as: a roof deck, a vapor barrier membrane, a thermal insulation, a waterproofing membrane and a protecting surface. These components may involve many materials which exhibit many properties that contribute to the performance of a roof system. As the complexity of a roof system increases, the problems involving performance also increase and the effects of outdoor exposure on the system must be known. For example, in recent years serious splitting and wrinkle cracking failures have occurred in built-up roof membranes. These failures appeared most frequently on membranes applied over insulation and after periods of cold weather. Because of such failures questions have been raised regarding the temperature cycles of roof systems and the expansion and contraction of built-up membranes due to temperature change. Therefore, a program was conducted to study the effects of natural solar heating and radiative cooling on the temperature and thermal movements of built-up roof systems.

Experience in both the laboratory and in the field has indicated that high temperatures attained by a roof surface, rapid changes in temperature, and thermal movements resulting from solar heating and radiative cooling are contributing factors in such other common failures in built-up roof systems as: blistering, buckling, membrane slippages, flashing failures, chemical degradation of bitumen, and physical deterioration of bitumen.

The purpose of this paper is to present temperature data on several built-up roof systems when exposed to natural solar heating and radiative cooling during summer and winter seasons in Washington, D. C., and to discuss these data in terms of roof performance. Another purpose is to furnish data on thermal expansive and contractive characteristics of a composite built-up membrane and to discuss these in relation to the performance of the roof membrane.

2. SOLAR HEATING AND RADIATIVE COOLING

The greatest known source of energy for the earth 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: reflection, transmission, and absorption. For the purpose of this paper, prime consideration will be given to the radiant energy which is absorbed and converted to heat. It may be of interest to note that Billington [1][1/] reported that the intensity of solar radiation (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 and scattered 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 pointed out by Beckett [2] in 1935 when he warned that there is a very real danger of structural failure due to expansive movements resulting from heating by sunshine.

The effect of solar heating also contributes to the degradation of the waterproofing bitumen protecting a roof membrane since this process is essentially a photooxidative reaction which is accelerated by heat.

[1/] Figures in brackets refer to literature references at the end of this paper.

When a roof is exposed to solar radiation the heat absorbed causes its surface temperature to rise above the ambient air temperature. As the roof continues to absorb heat, it begins to lose heat by radiation and convection to the surroundings. The temperature finally attained by the roofing is a result of the balance of heat absorbed and the heat lost by radiation and convection. Important material properties that influence surface temperature are the solar absorption coefficient and the emissivity of the surface. Therefore, to characterize a surface during solar heating, it is necessary to know its solar absorptance and its emissivity over the spectral range represented by solar radiation. For practical purposes, solar radiation is confined to the ratiation spectrum between 0.3 and 2.5 microns with the peak intensity at about 0.5 microns.

Another factor, not as well known as solar heating, but equally as important when roof temperatures are considered, is radiative 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 predominately in the form of long-wave infrared radiation which cannot be seen, but which can sometimes be detected by its cooling effect on the material. This outgoing radiation can have a significant influence on roof surface temperature. For example, on clear nights when the roof radiates to the sky, the temperature of a roof surface can go below the ambient air temperature.

Solar heating and radiative cooling may 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 decreases 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 (cooling below ambient) of the roof surface.

The magnitude and rate of the temperature increase or decrease will depend on the following factors: intensity of solar radiation (direct and diffuse), the absorptance of the surface for solar radiation, rate at which surface emits radiation to sky and surroundings, unit convective conductance for heat transfer between air and roof surface including the effects of wind velocity, thermal properties of the roof system, and ambient air temperature. The effects of wind velocity have been discussed by Hendry and Page [4]. Their computations indicated that the maximum temperature of a flat, dark, 6-inch concrete roof slab on a still day would be 30°F higher than on a day with a 12 mph wind and 16°F higher than on a day with a 4 mph wind when exposed at a latitude of 20°N.

2.1 Experimental

Ten, 18- by 18-in., built-up roof constructions were prepared on 2-in. thick concrete decks and ten similar constructions were prepared on 3/4-in. exterior plywood decks. A four-ply asphalt - asphalt-saturated organic felt membrane was applied directly to the deck on five of the concrete and on five of the plywood constructions. On the remaining five of each type deck, two inches (two one-inch layers) of expanded polyurethane was used to separate the four-ply membrane from the respective deck. Each construction contained copper-constantan thermocouples at selected locations for recording temperatures continuously 24 hours a day. Figure 1 is a schematic diagram of typical specimens.

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 outdoor exposures.

2.1.1 Substrates

The materials which were used as substrates for the built-up membrane were dense concrete, 3/4-inch plywood and expanded polyurethane insulation. These materials had measured densities of 140-, 40-, and 2-pounds per cubic foot, respectively, as determined in the laboratory. These densities were selected to represent the range of those of roof membrane substrates used in service.

2.1.2 Protecting Surfaces

Five surfaces representing those commonly used on built-up roofs were used in the experimental work. Table 1 lists the materials used together with their pertinent properties.

TABLE 1.

SOME PROPERTIES OF SURFACINGS FOR BUILT-UP MEMBRANES

Material	Color	Weight Used	Estimated Solar Absorptance
		lbs/ft^2	Coefficient*
Asphalt	Black	25	0.9
Stone (crushed)	Gray	400	0.7
Scoria	Maroon	150	0.7
Marble (crushed)	White	200	0.5
Polyvinyl Fluroide Film	White	.002" thickness	0.2

*Estimated from solar absorptances of similar materials reported in: Thermal Radiation Properties Survey, 2nd Edition, p. 245, Minneapolis-Honeywell Regulator Company (1960).

2.2 Experimental Results

2.2.1 Solar Heating

The influence of the substrate 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 3, The maximum temperatures attained by the black asphalt-surfaced membranes over concrete, wood and insulation on a summer day in August 1962 were 120°F, 145°F, and 165°F, respectively.

In respect to temperature fluctuations, the temperatures of the membranes over concrete, wood and insulation declined 15°F., 30°F., and 45°F., respectively, between the hours of 5:30 p.m. (1730) and 6:00 p.m. (1800), due to a change in atmospheric conditions.

One might infer from this information that all insulated roof membranes are subjected to greater extremes in both temperatures and temperature variations. This is apparently true if other factors are similar. However, other variables come into play which limit these extremes. For example, Figure 4 shows the effect of surface color (solar absorptance) on the thermal cycle of an asphalt surfaced and a white polyvinyl fluoride smooth-surfaced built-up roof membrane placed over two inches of polyurethane 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 p.m. (1300) when the sun was obscured by clouds 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 1:00 p.m. (1300) and 3:00 p.m. (1500).

The influence of such other surfaces as crushed stone and marble chips on the thermal cycles of membranes placed over insulation and over concrete are illustrated in Figure 5. These results show that the lower the solar absorptance of a roof surface, the smaller the temperature difference between the insulated and non-insulated membranes, and also a lesser total rise in temperature.

Figure 6 illustrates the effect of the protecting surface on the temperature and temperature changes of membranes placed over insulation on a sunny June day while Figure 7 gives time-temperature curves for identical systems on a sunny January day with the ambient temperature reaching a maximum of 30°F. 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 roof temperature is not related to the type or kind of deck when an efficient insulation is used. The time-temperature curves for the scoria surfaced membranes approximated those of the crushed stone and therefore have been eliminated from both the figures and following tables.

The maximum temperatures which were recorded in membranes protected with the selected surfaces during summer and winter exposures are listed in tables 2 and 3, respectively.

TABLE 2.

EFFECT OF SURFACE TREATMENT ON ROOF TEMPERATURE DURING SUMMER EXPOSURE

Surface	Max. Temp.	Temperature Rise from Ambient
	°F	°F
Asphalt (Black)	166	81
Crushed Stone	148	63
Marble Chips	118	33
Polyvinyl Fluoride (white)	93	8
Ambient	85	--

TABLE 3.

EFFECT OF SURFACE TREATMENT ON ROOF TEMPERATURE DURING WINTER EXPOSURE

Surface	Max. Temp.	Temperature Rise From Ambient
	°F	°F
Asphalt (Black)	75	45
Crushed Stone	55	25
Marble Chips	35	5
Polyvinyl Fluoride (White)	30	0
Ambient	30	----

It has been reported by Cullen and Appleton [5] 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 from the top of the deck or placed beneath the deck, the relative thermal movement in the roof deck may be considerable due to solar heating and radiative cooling. The question, therefore, arises as to the magnitude of the temperature changes which occur between a structural deck that is separated from the membrane by insulation and one that is not. Figure 8 shows the extent of the temperature changes by the time-temperature curve for both the built-up membrane and the concrete deck as recorded on both insulated and uninsulated specimens on a summer day during August 1962. Incidently, Curve 2 coincides with the ambient temperature. The temperature fluctuations and temperature rise in the uninsulated concrete deck were considerably less than those which occurred in a built-up membrane placed over insulation.

A snow cover was an important factor in stabilizing membrane temperatures of the roof constructions used in the experimental work. During winter exposures in December 1962 and January 1963 when the specimens were covered with snow, little variation was recorded between the ambient temperature and that of the roof membrane either during daytime or nighttime exposures regardless of the type of substrate and surface treatment employed. However, when there was an absence of snow the membrane temperature showed considerable variation both above and below the ambient temperature due to solar heating and radiative cooling as shown in Figure 7.

2.2.2 Radiative Cooling

The reradiation of energy from a roof surface to a clear night sky often results in roof membrane temperatures less than ambient. The degree of sub-cooling depends on a number of factors including the properties of the substrate, and atmospheric conditions. Figure 9 serves to illustrate these points. The ambient temperature (Curve 1) and that of uninsulated membranes protected with a black and white surface (Curves 2 & 3) and the membranes with similar surfaces insulated from the deck (Curves 4 & 5) coincided with one another on a night when the sky was cloudy until 1:00 a.m. (0100 hours) at which time the cloud cover lifted. This event was soon apparent by comparing the ambient temperature with that of membranes insulated and not-insulated from the concrete decks. The temperature of the membrane placed on insulation was about 12°F cooler than those placed directly on the concrete deck and about 20°F cooler than the ambient. In each case, the white surfaced membranes (Curves 3 & 5) were slightly cooler than their black surfaced counterparts.

The emissivity of most non-metallic roofing materials, unlike their absorptance, are for all practical purposes independent of surface color or texture [2]. A case in point is illustrated in Figure 10 where the marked effect of solar heating on the black surfaced membrane as opposed to the white was clearly indicated at 1:00 p.m. (1300), but at 7:00 p.m. (1900) the temperatures of both the black and the white surfaced membranes were about the same.

3. THERMAL MOVEMENT OF COMPONENTS OF A ROOF SYSTEM

It is well known that with few exceptions the dimensions of materials increase as the temperature of the material increases and decrease as the temperature decreases.

Many of the common built-up roof failures which occur in the field can be directly or indirectly traced to thermal movements within a specific component of the roof system or by the differential movement among the various components and, therefore, it is desirable to know the extent of the movements.

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 of interest are given in Table 4. The temperatures at which the determinations were made were not reported.

However, no published information was found for the thermal expansion coefficient of a composite membrane consisting of alternate layers of bitumen and felt. Therefore, a program was undertaken to measure this property of a number of composite membranes.

3.1 Experimental

The samples consisted of 12-in. by 12-in. sections of built-up membranes constructed in the laboratory with alternate layers of felt and hot bitumen in accordance with good roofing practice. Approximately 20 pounds/100 sq. ft. of bitumen were used between the plies and no surfacing was applied to the specimens. Table 5 identifies the membranes.

TABLE 4.

LINEAR EXPANSION OF MATERIALS USED AS COMPONENTS OF A ROOF SYSTEM

Material	Coefficient of Linear Expansion
	$\frac{\text{in.}}{\text{in. °F}}$
Roof Decks	
Steel	6.7 x 10^{-6} [a]
Concrete	4.0 to 6.0 x 10^{-6} [b]
Wood	1.7 to 2.5 x 10^{-6} [c] (along grain)
Plywood	3.0 to 4.2 x 10^{-6} [c]
Gypsum	8.1 x 10^{-6} [b]
Insulations	
Foam Glass	4.6 x 10^{-6} [d]
Polystyrene	35 x 10^{-6} [e]
Polyurethane	30 x 10^{-6} [f]
Flashing Metals	
Aluminum	13 x 10^{-6} [a]
Copper	9.8 x 10^{-6} [a]
Gal. Iron	6.7 x 10^{-6} [a]
Lead	15 x 10^{-6} [a]

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[a] N. A. Lange, Handbook of Chemistry, 6th Edition, 772 (1946).

[b] L. S. Wells, W. C. Clark, E. S. Newman and D. L. Bishop, Building materials and structures Report No. 121, National Bureau of Standards, 34 (1951).

[c] Wood Handbook No. 72, Department of Agriculture, 47-48 (1955).

[d] AIA File No. 37-B (1963).

[e] AIA File No. 37-0-1 (1963).

[f] AIA File No. 37-D-1 (1963).

TABLE 5.

MEMBRANES FOR EXPANSION MEASUREMENTS

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

Duplicate specimens, 12-in. by 12-in., were cut from the samples so that the long dimension coincided with the machine direction of the felt. Brass reference plugs, 1/4-in. in diameter, were inserted and sealed with an epoxy adhesive into a hole drilled into the specimens near each end. The plugs were spaced about 10 in. apart when measured at 70°F. The specimens were placed unrestrained on a flat surface dusted with talc to prevent sticking 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 temperature in the chamber was gradually raised to 140°F in increments of about 10°F. and after the specimens reached equilibrium at each increment the distance between the reference plugs in each specimen was measured to the nearest ten thousandth of an inch with a Whittemore Strain Gauge. The experiments were performed on duplicate specimens of each built-up membrane three times over the temperature cycle of -60°F. to 140°F. and back down to -60°F. The measurements over a complete temperature cycle required approximately 8 hours.

3.2 Results

The averaged results of the thermal expansion measurements are reported in Table 6. The apparent expansion coefficient of each membrane over the temperature range indicated is expressed in inches per inch per °F.

TABLE 6.

APPARENT EXPANSION COEFFICIENTS FOR BUILT-UP MEMBRANES

Sample No.	Description	Spec. No.	Apparent Expansion Coefficient in/in/°F		
			-60° to 0°F	0°F to 70°F	70°F to 140°F
1	Asphalt-Organic	1	18×10^{-6}	5×10^{-6}	3×10^{-6}
		2	18×10^{-6}	5×10^{-6}	3×10^{-6}
2	Asphalt-Glass	1	27×10^{-6}	6×10^{-6}	3×10^{-6}
		2	31×10^{-6}	6×10^{-6}	3×10^{-6}
3	Coal-tar-Organic	1	15×10^{-6}	12×10^{-6}	a/
		2	14×10^{-6}	13×10^{-6}	a/
4	Asphalt-Asbestos	1	11×10^{-6}	5×10^{-6}	2×10^{-6}
		2	10×10^{-6}	6×10^{-6}	2×10^{-6}

a/ Decrease in length observed.

The length-temperature curves for a typical specimen of each respective membrane over the complete thermal cycle are shown in Figures 11, 12, 13, and 14. The actual data points which were obtained at 10°F intervals are not shown. Data points did not depart from the curves shown by more than ±5%.

4. SUMMARY AND DISCUSSION

The data which were obtained in this study indicated that:

1. Built-up membranes are heated by natural solar radiation. The temperature increase depends on: a) the mass, density and thermal properties of the substrate; b) thermal radiation properties of the exposed surface; c) atmospheric conditions; and d) presence or absence of a snow cover.

2. Built-up roof membranes may be sub-cooled by night sky radiation. The magnitude of sub-cooling is dependent on: a) the mass, density and thermal properties of the substrate; b) the emissivity of the exposed surface; c) atmospheric conditions; and d) the presence or absence of a snow cover.

3. Built-up roof membranes apparently undergo greater thermal expansive and contractive movements than most other components of a roof system at low temperatures.

4. Thermal movement of a built-up bituminous membrane is not linear with temperature and decreases markedly as the temperature is increased.

The data for thermal movements of composite bituminous membranes showed that the movements caused by temperature change are most critical in the low temperature ranges as compared to the minimal movements observed in the higher temperature ranges. This behavior is caused, at least in part, by the visco-elastic behavior of roofing bitumens. It is apparent from data presented in Figures 11, 12, 13, and 14 that there was little or no positive movement of the membranes at the higher temperatures which suggest that plastic flow was occurring.

Field observations regarding splitting and membrane shrinkage indicated that thermal movement is a factor in many such failures. Solar heating and radiative cooling can cause such failures; therefore, they must be considered. Nighttime sub-cooling of a membrane appears significant, especially if the membrane is applied over a low density substrate.

In addition, the observations of the stabilizing effects of a snow cover are in agreement with reports that the greater number of complaints involving roof splitting failures and membrane shrinkage are received after extended periods of cold weather with no snow cover.

In comparing field experience to the data obtained in the laboratory, it is apparent that other common failures of built-up roof systems observed in the field result directly or indirectly from solar heating, radiative cooling and the resulting thermal movement. For example, 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 both differences in emissivity and by their different apparent coefficients of linear expansion.

Temperature and temperature changes are 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 appears to be a most important factor when a slippage of roof membrane occurs.

In connection with the weathering of the roofing bitumen, it has been demonstrated that the chemical degradation of asphalt is accelerated by increased temperatures. In addition, experience has indicated that the thermal shock due to rapid temperature changes may be responsible for accelerating the physical deterioration of the bitumen.

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

Thermal movement at low temperature may be a factor in relating certain roofing failure to thermal shock properties of materials in the roof system. McCawley [6] has used the term "thermal shock" to describe a condition when a roof is subjected to a drop of 100°F or more in a few hours. According to Marin [7] in discussing the mechanical behavior of engineering materials, the best materials for thermal shock resistance were found to have good thermal conductance, low coefficient of expansion, low modulus of elasticity and high tensile strength. He equates the thermal shock resistance, R, to the above variables as follows:

$$R = \frac{k\ S}{E\ \alpha} \qquad \text{where:}$$

k = thermal conductivity
S = tensile strength
E = Modulus of elasticity
α = Expansion coefficient

Although the pertinent properties of built-up roof membranes, other than thermal movement, were not demonstrated experimentally in this program, it is believed that the thermal shock concept may be useful in predicting the performance of built-up roof membranes especially at low temperatures.

5. REFERENCES

[1] N. S. Billington, J. Inst. of Heat and Vent. Eng. 19, 112 (1951).

[2] H. E. Beckett, J. Inst. of Heat and Vent. Eng. 3, 79 (1935-6).

[3] W. H. McAdams, Heat Transmission (McGraw-Hill Book Company), 62 (1954).

[4] A. W. Hendry and J. K. Page, "Thermal Movements and Stresses in Concrete Slabs in Relation to Tropical Conditions", International Symposium on Concrete and Reinforced Concrete in Hot Countries", Haifa, Israel (RILEM, 12 rue Brancion, Paris XV°, France) (1960).

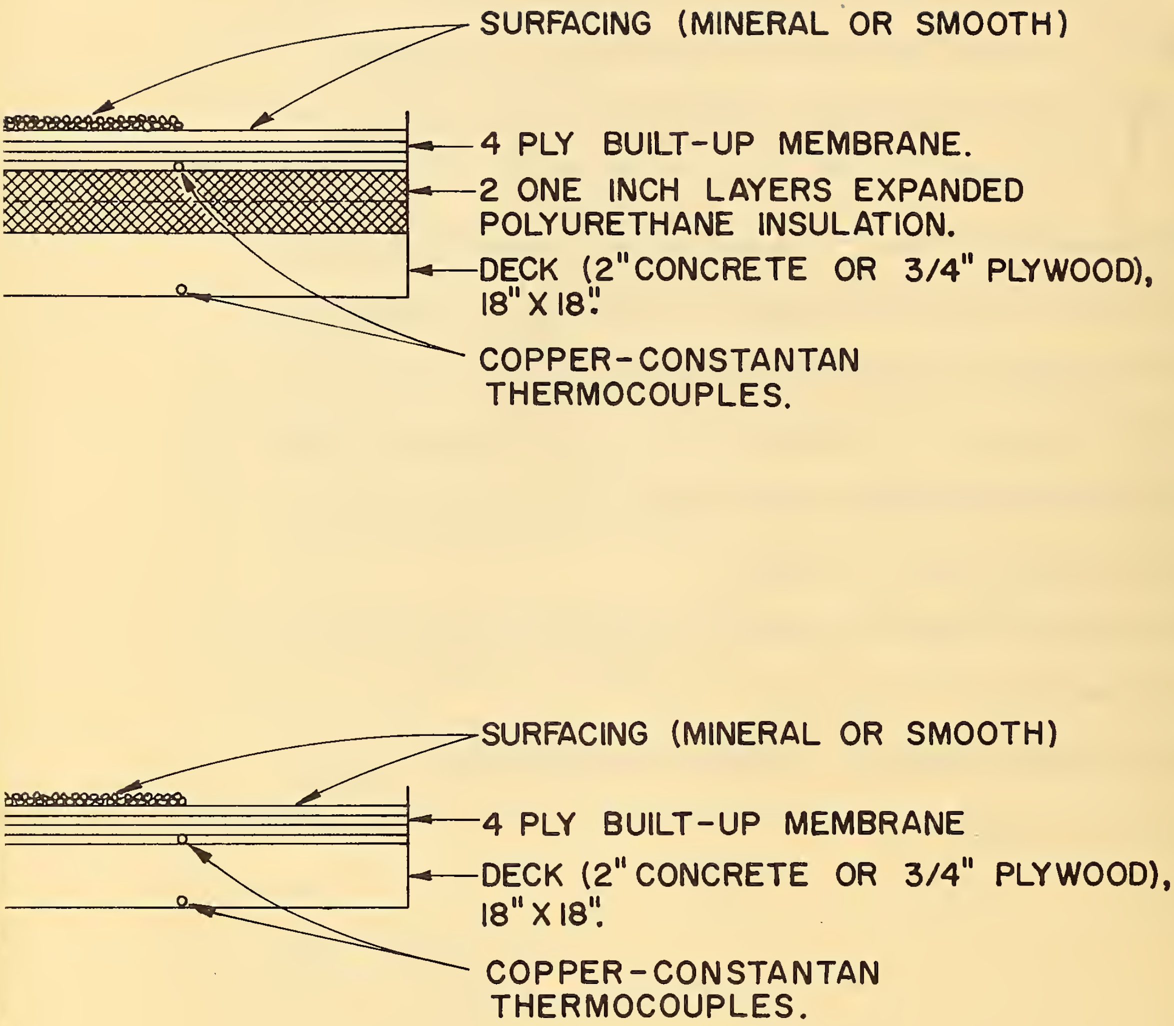
[5] W. C. Cullen and W. H. Appleton, Am. Roofer and Building Improvement Contractor 53, No. 3, 19 (1963).

[6] James McCawley, Am. Roofer and Building Improvement Contractor 52, No. 10, 11 (1962).

[7] J. Marin, Mechanical Behavior of Engineering Materials (Prentice-Hall, Inc.), 338 (1962).

The author acknowledges with thanks the assistance of William H. Appleton who constructed and instrumented the built-up roof specimens and prepared the specimens for and made the measurements of the coefficients of thermal expansion of the roof membranes. The author also acknowledges with appreciation the advice and encouragement given to him by W. W. Walton, Chief of the Organic Building Materials Section, National Bureau of Standards, and the members of the Tri-Service Committee.

This investigation was conducted under the Tri-Service Engineering Investigations of Building Construction and Equipment, National Bureau of Standards, sponsored by the Directorate of Engineering, U. S. Air Force, Bureau of Yards and Docks, U. S. Navy, and the Office of the Chief of Engineers, U. S. Army.



IGURE 1. SCHEMATIC DIAGRAM OF TYPICAL BUILT-UP ROOF SPECIMENS EXPOSED OUTDOORS.

FIGURE 2. BUILT-UP ROOF SECTIONS EXPOSED AT WASHINGTON, D. C.

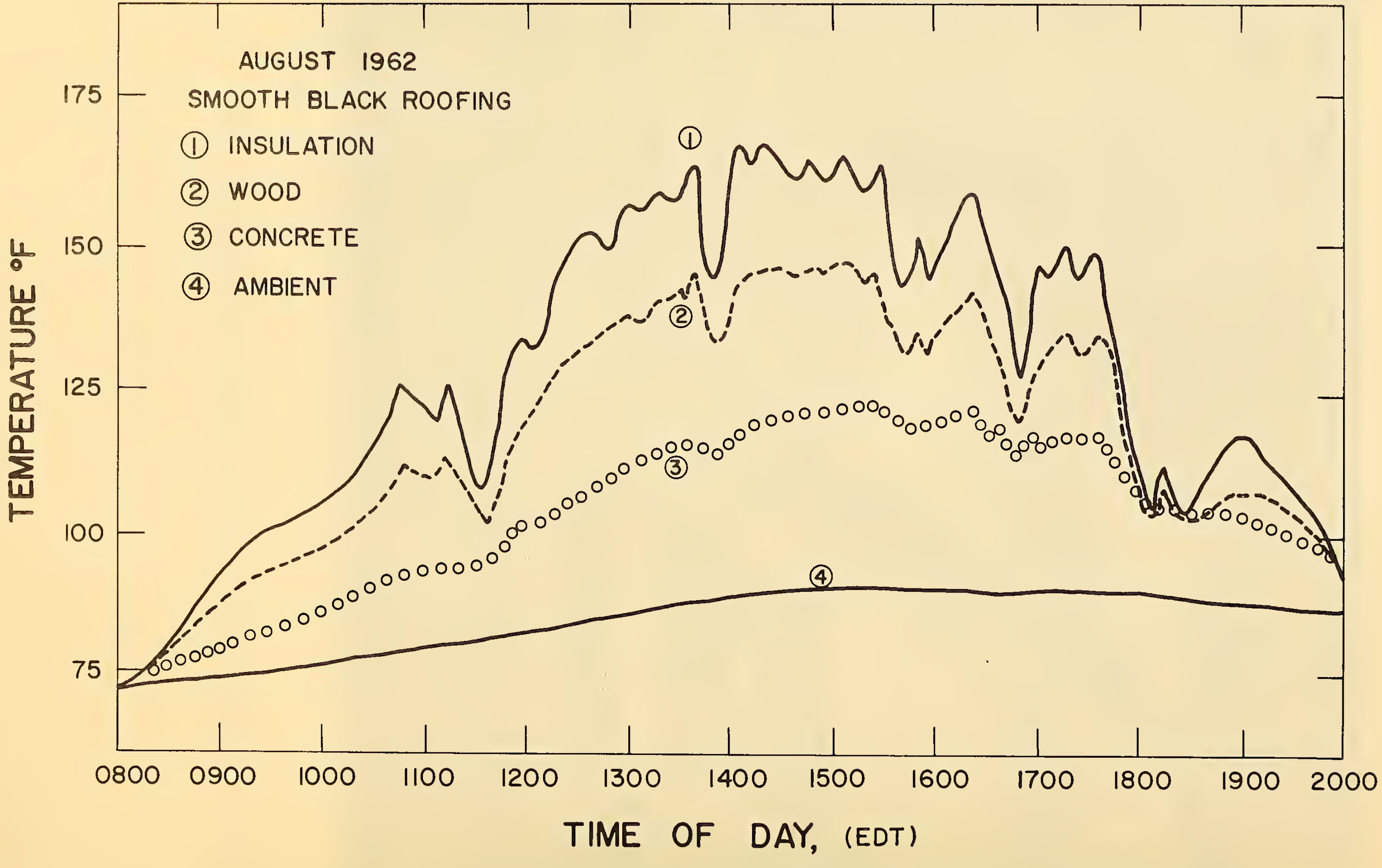


FIGURE 3. EFFECT OF SUBSTRATE ON SOLAR HEATING OF ASPHALT-SURFACED, INSULATED BUILT-UP MEMBRANE.

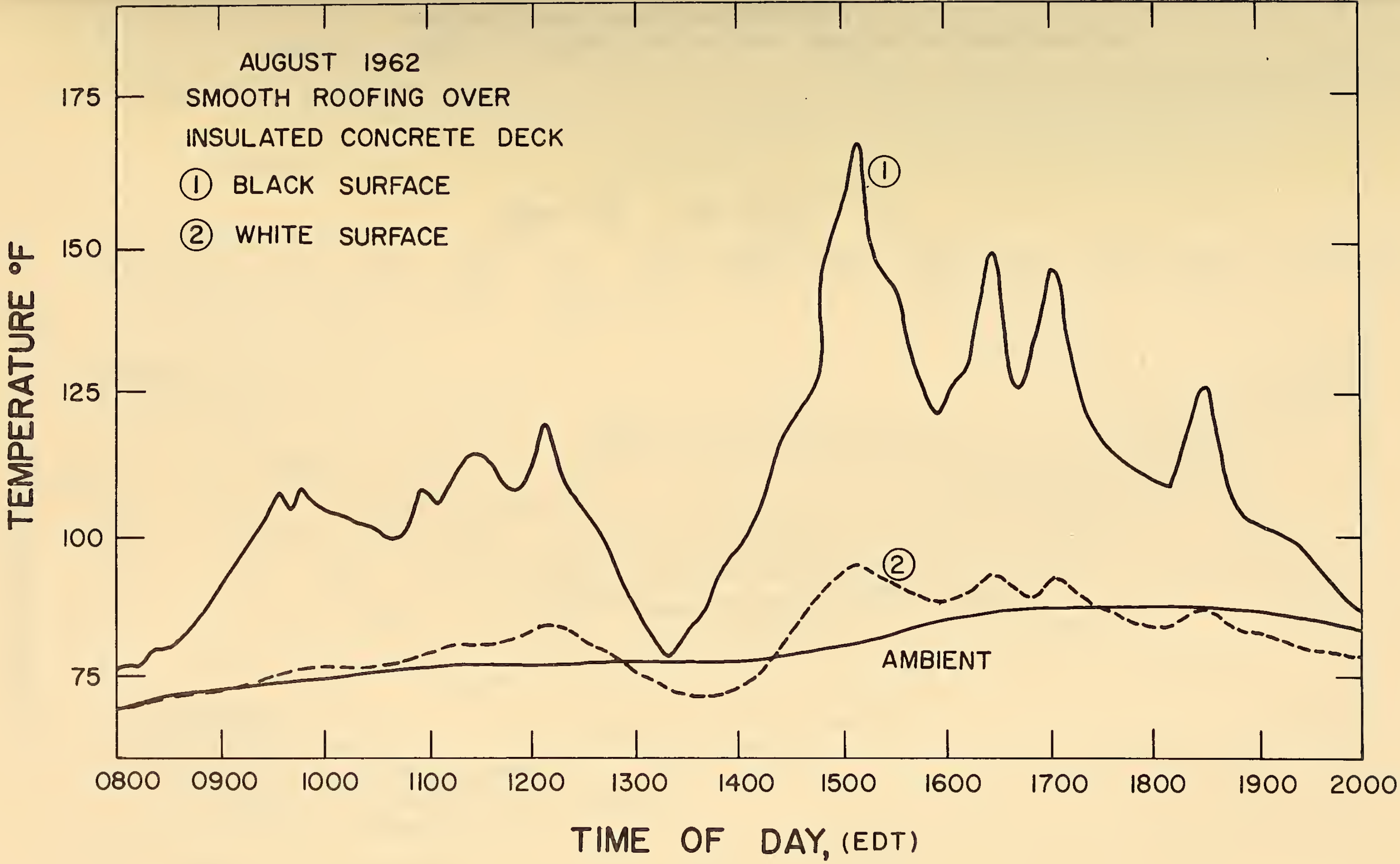


FIGURE 4. EFFECT OF SURFACE COLOR ON SOLAR HEATING OF A SMOOTH-SURFACED, INSULATED MEMBRANE ON A CONCRETE DECK.

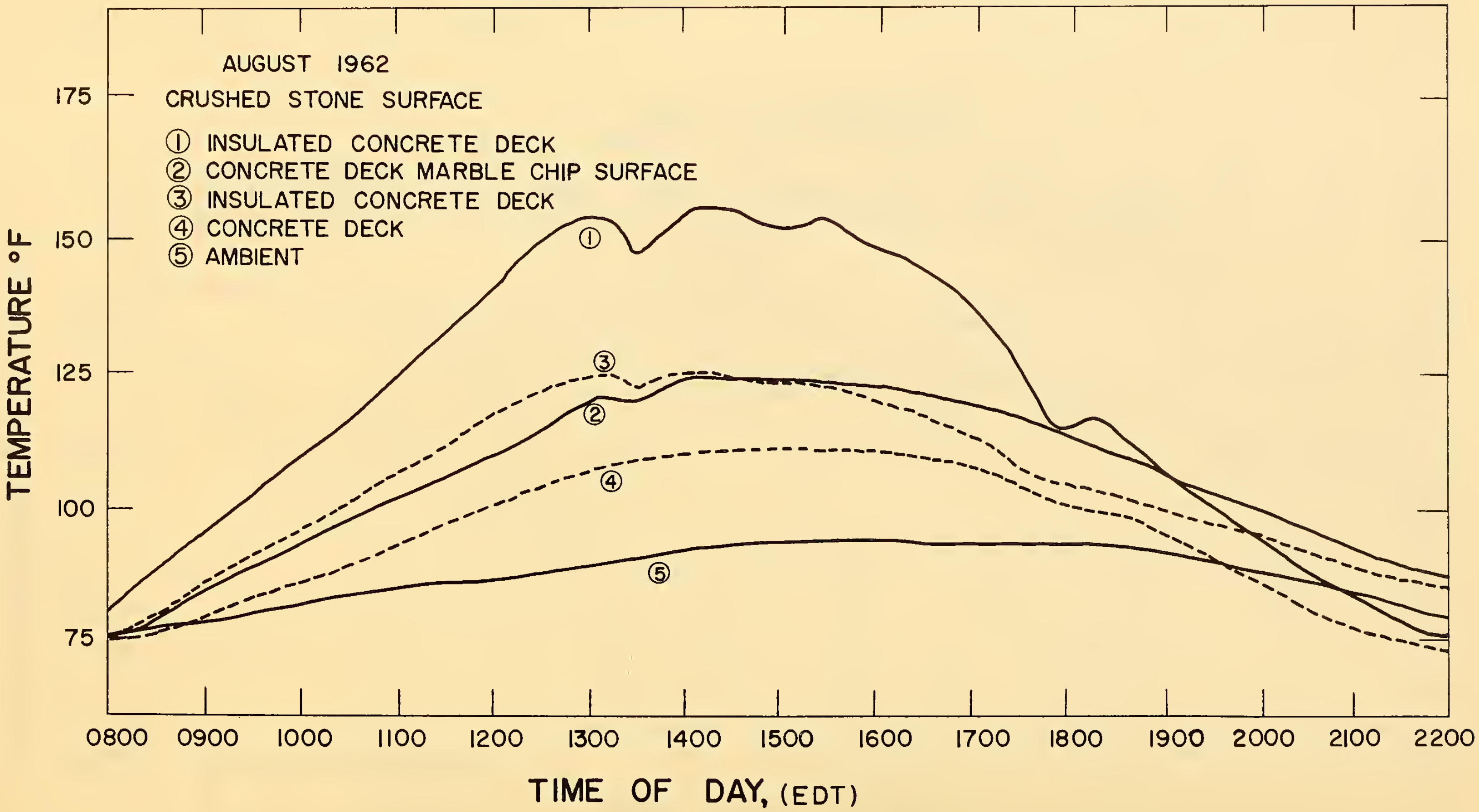


FIGURE 5. EFFECT OF SURFACING ON SOLAR HEATING OF INSULATED AND NON-INSULATED BUILT-UP MEMBRANES.

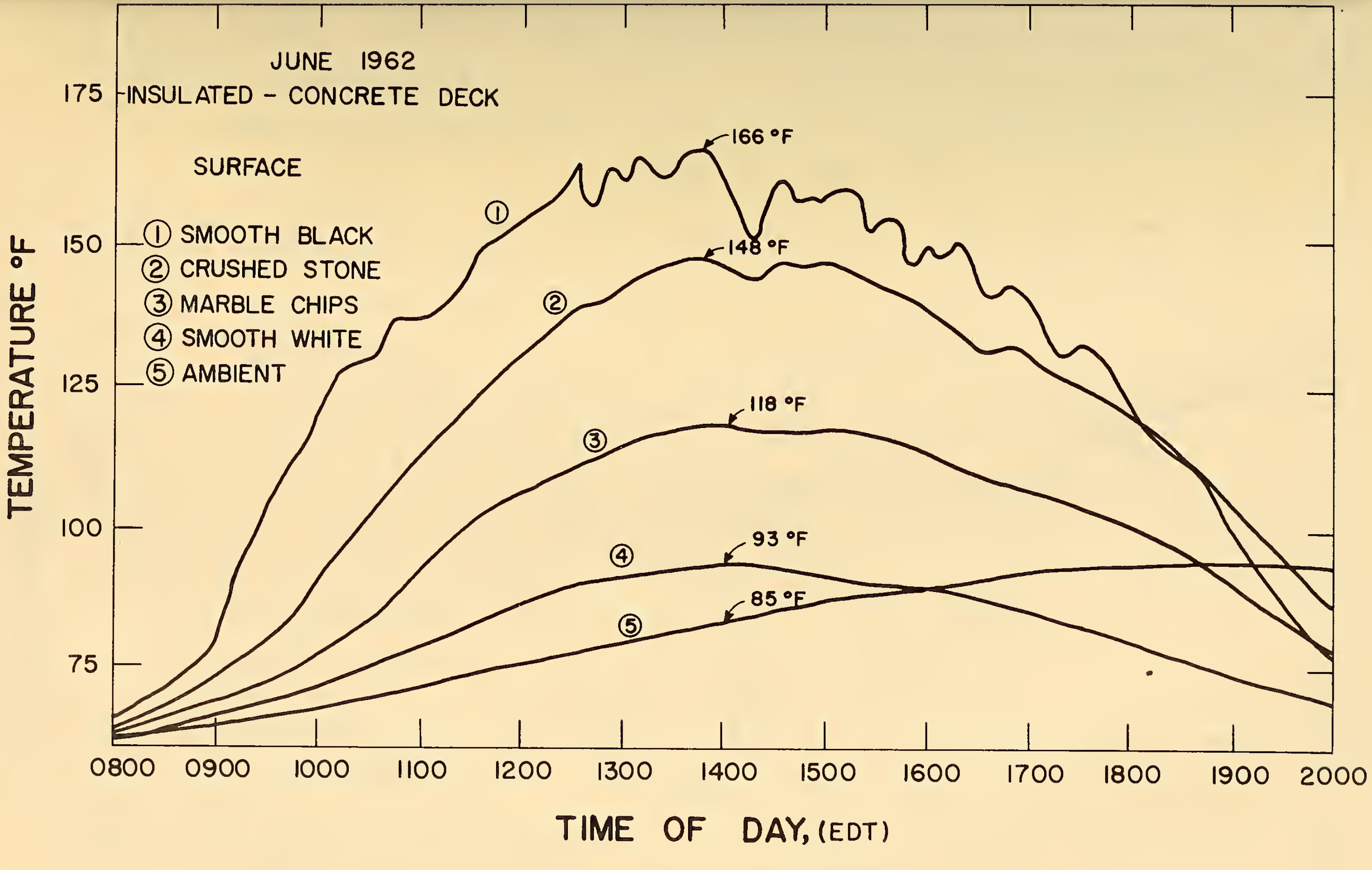


FIGURE 6. EFFECT OF SURFACE TREATMENT ON THE SOLAR HEATING OF BUILT-UP MEMBRANES DURING SUMMER EXPOSURE.

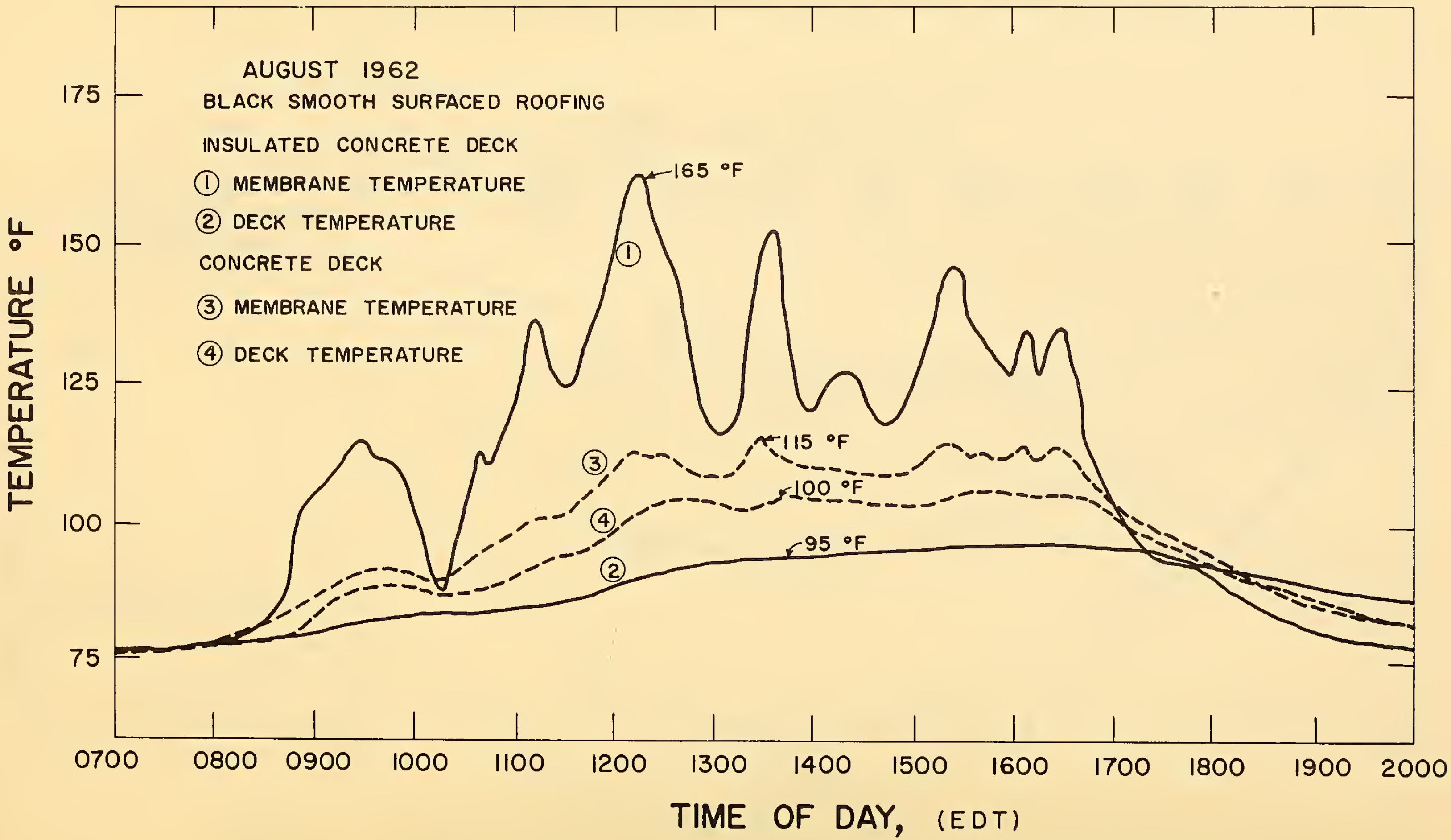


FIGURE 7. EFFECT OF SURFACE TREATMENT ON THE SOLAR HEATING OF BUILT-UP MEMBRANES DURING WINTER EXPOSURE.

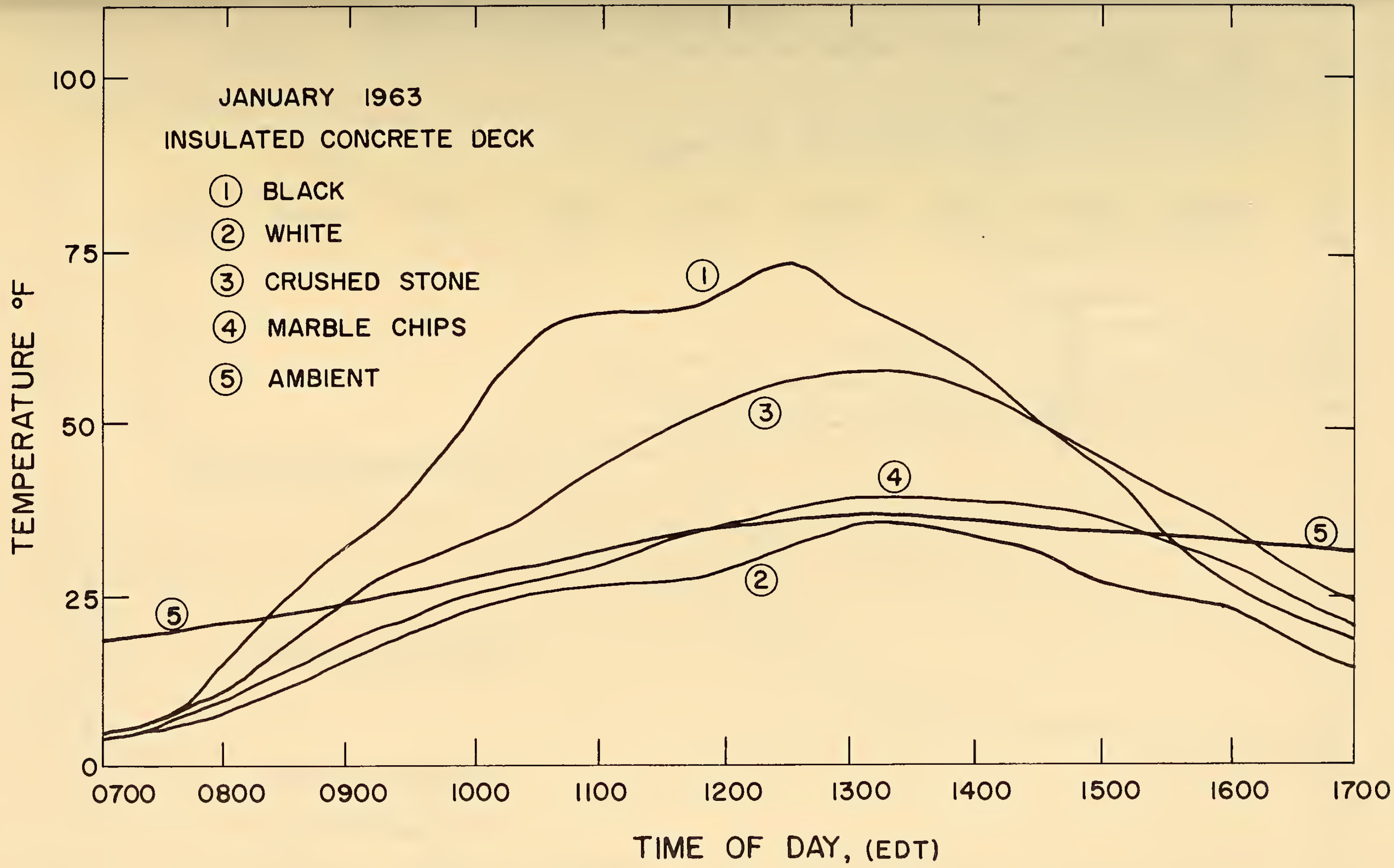


FIGURE 8. TIME-TEMPERATURE CURVES FOR BUILT-UP MEMBRANES AND CONCRETE DECKS ON INSULATED AND NON-INSULATED SPECIMENS.

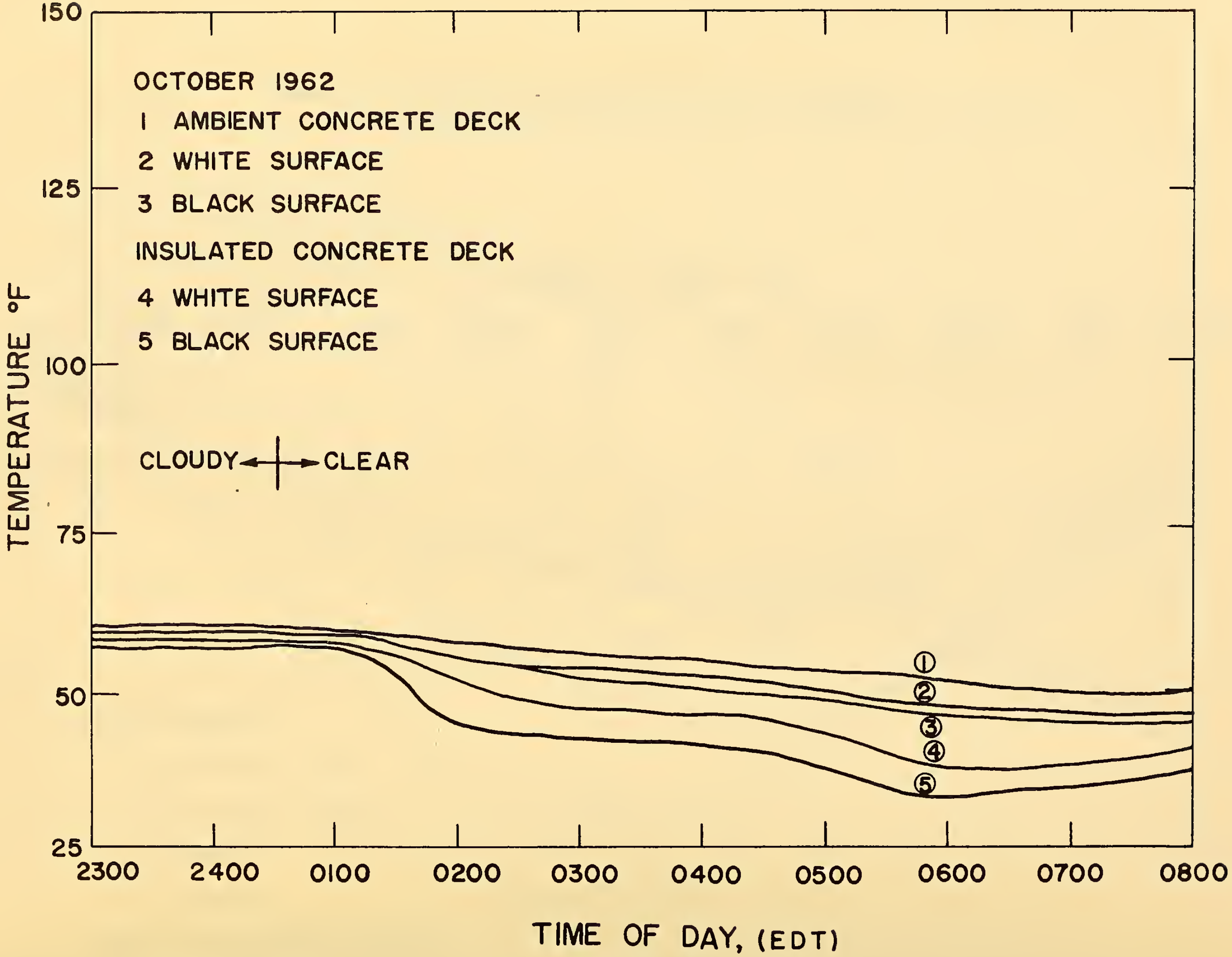


FIGURE 9. EFFECT OF RADIATIVE COOLING ON SMOOTH-SURFACED SPECIMENS OVER A CLOUDY AND UNDER A CLEAR SKY.

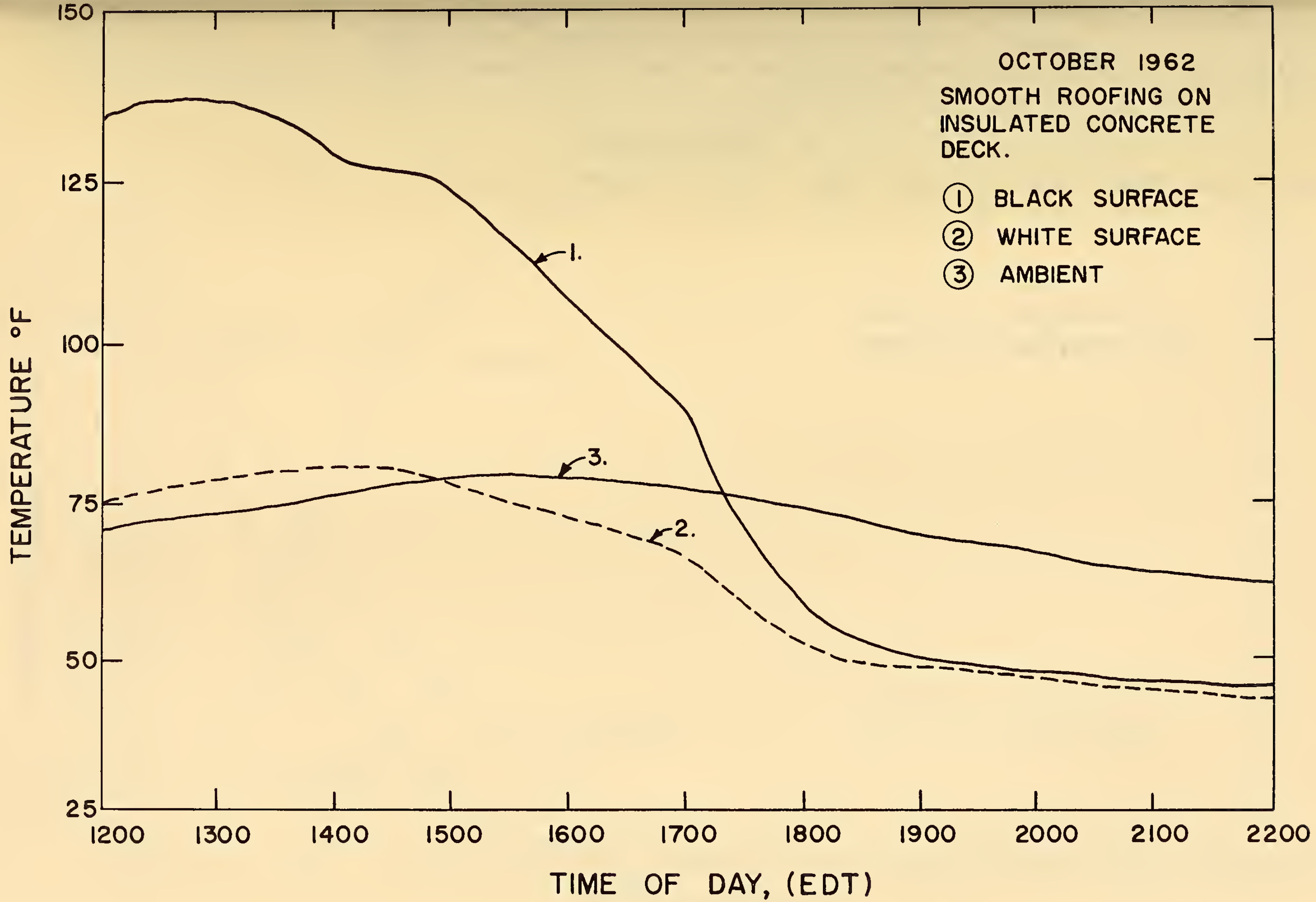


FIGURE 10. EFFECT OF SURFACE TREATMENT ON SOLAR HEATING AND RADIATIVE COOLING OF BUILT-UP ROOF SPECIMENS.

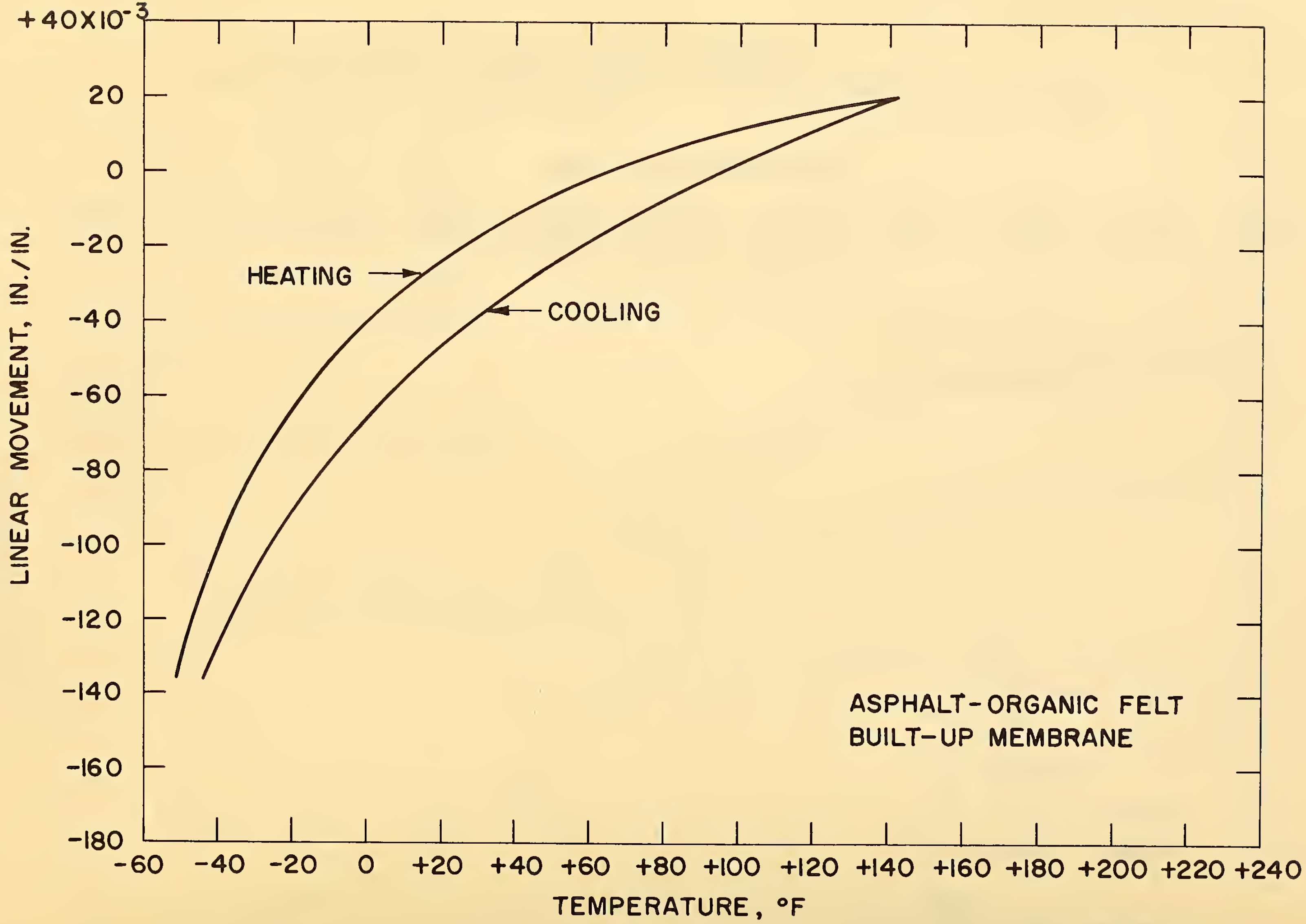


FIGURE 11. LENGTH-TEMPERATURE CURVE FOR ASPHALT - ASPHALT-SATURATED ORGANIC FELT MEMBRANE FOR A COMPLETE THERMAL CYCLE FROM -60°F TO 140°F.

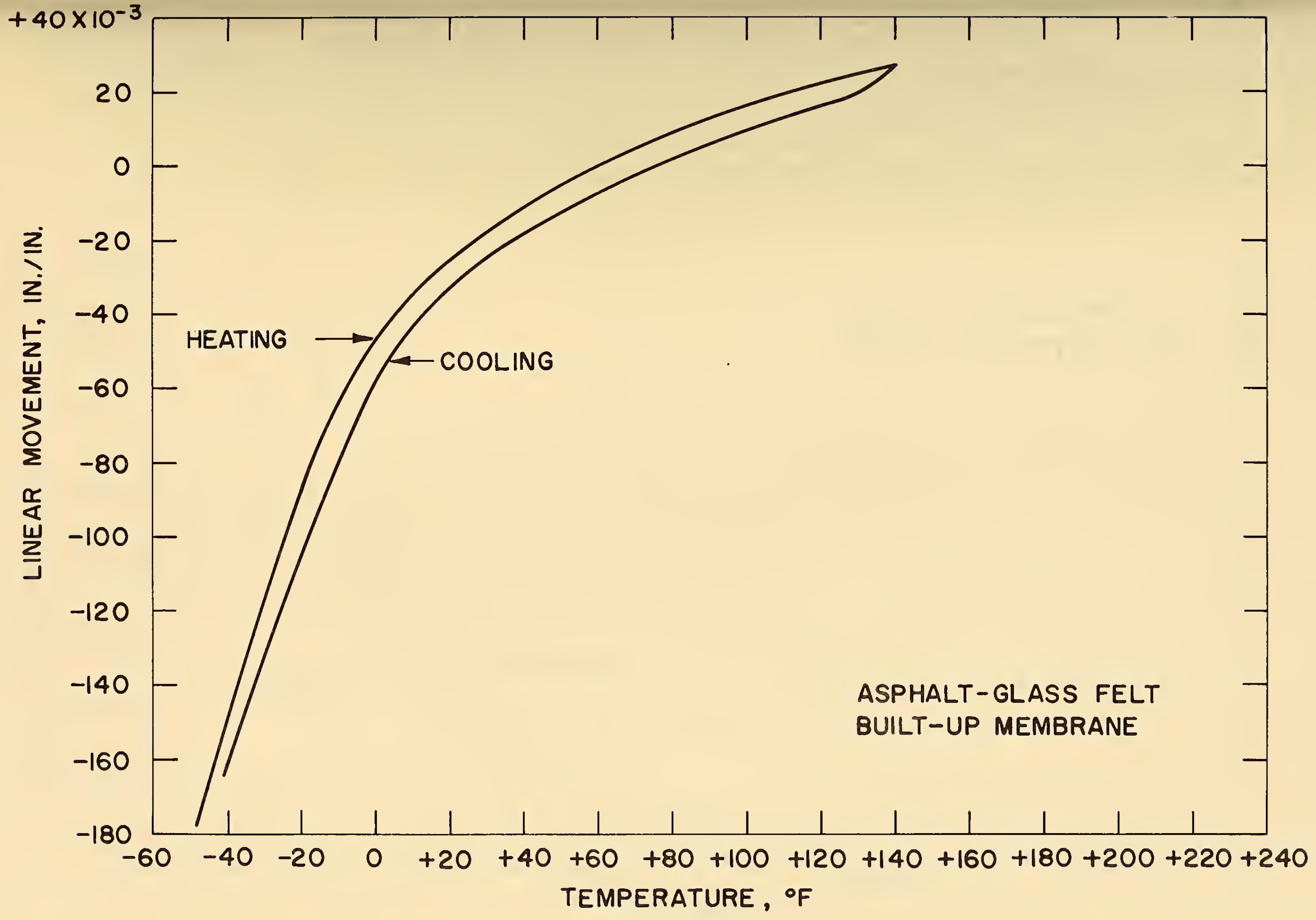


FIGURE 12. LENGTH-TEMPERATURE CURVE FOR ASPHALT - ASPHALT IMPREGNATED GLASS MAT FOR A COMPLETE THERMAL CYCLE FROM -60°F TO 140°F.

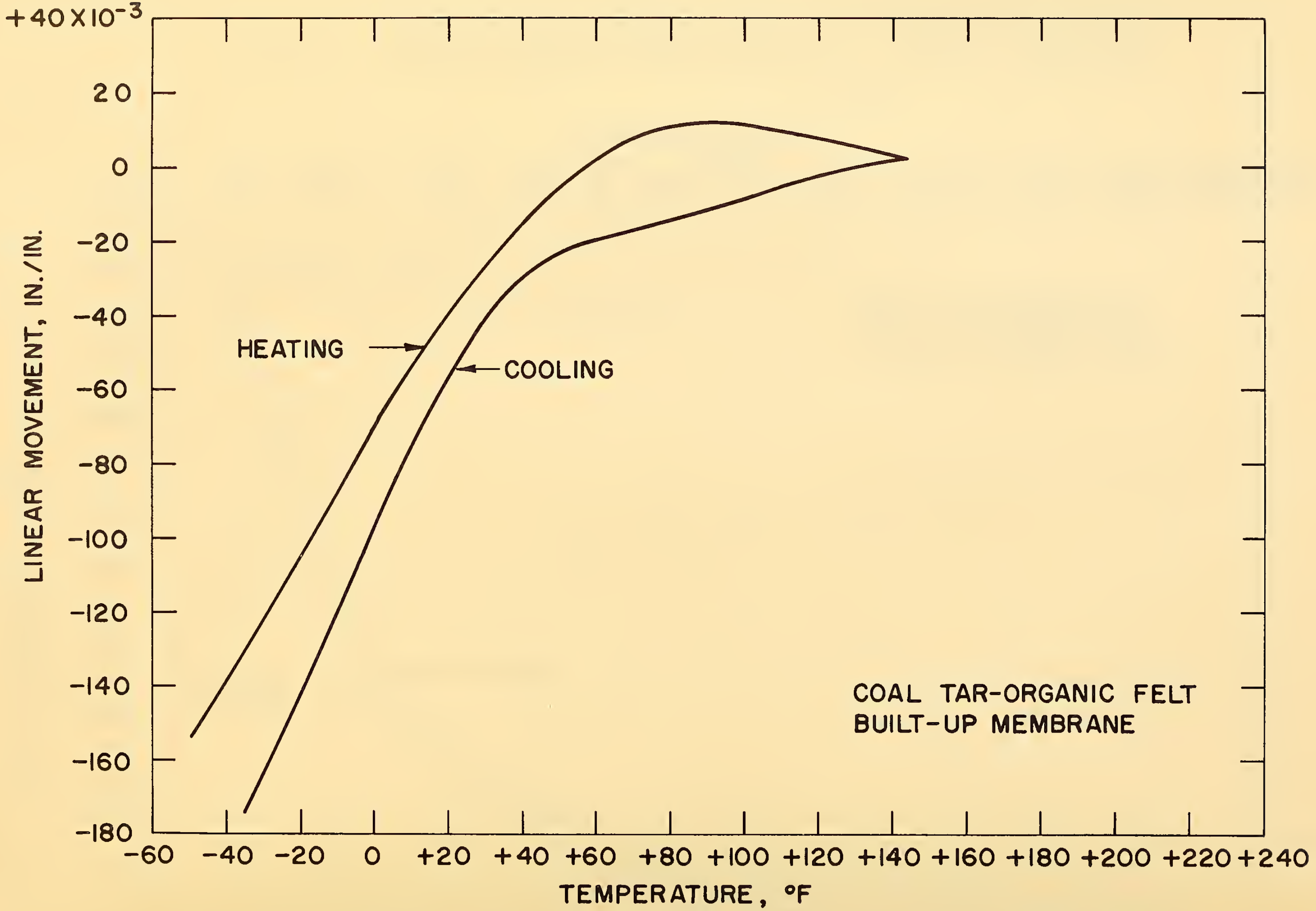


FIGURE 13. LENGTH-TEMPERATURE CURVE FOR COAL-TAR PITCH - COAL-TAR ASPHALT SATURATED ORGANIC FELT FOR A COMPLETE THERMAL CYCLE FROM -60°F TO 140°F.

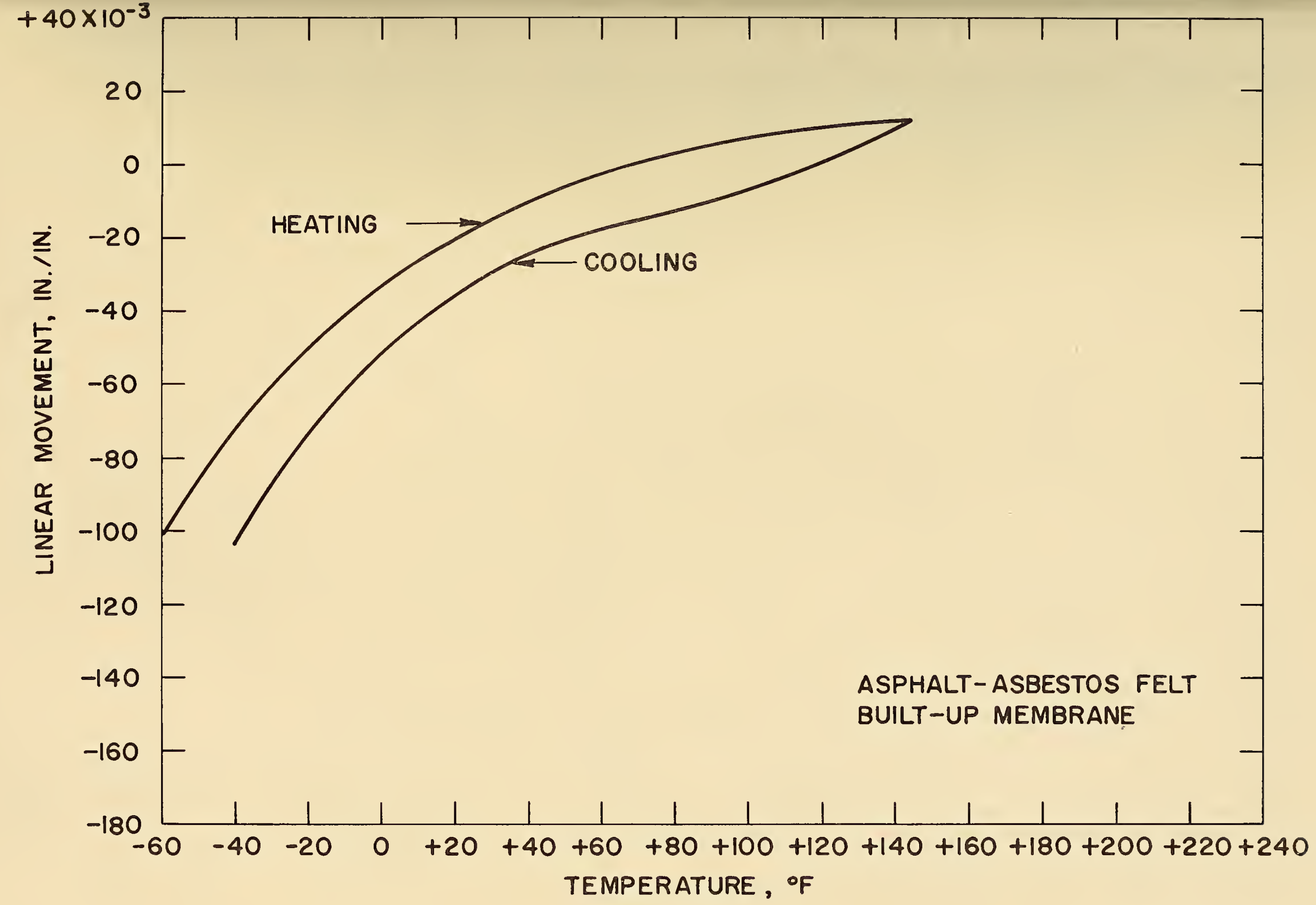


FIGURE 14. LENGTH-TEMPERATURE CURVE FOR ASPHALT - ASPHALT-SATURATED ASBESTOS FELT FOR A COMPLETE THERMAL CYCLE FROM -60°F TO 140°F.

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Office of Weights and Measures.

BOULDER, COLO.

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Troposphere and Space Telecommunications. Data Reduction Instrumentation. Radio Noise. Tropospheric Measurements. Tropospheric Analysis. Spectrum Utilization Research. Radio-Meteorology. Lower Atmosphere Physics.

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