NATIONAL BUREAU OF STANDARDS REPORT

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1. INTRODUCTION

Asphalt and coal-tar-pitch built-up roofings are widely used by the U. S. Department of Defense to protect large buildings having relatively flat roofs (slopes less than 2 in./ft.) located throughout the world. As a result of the widespread locations, these roofing systems are expected to withstand various climatic conditions ranging from the hot, humid Tropics to the cold Arctic and perform adequately for periods in excess of 20 years. Experience has indicated that these expectations are not fulfilled due to premature failure of components of the systems. For example, an extensive survey of roofing in Alaska in 1957 revealed that approximately 50% of the flat roofs, the majority of which had no slope, installed since 1951 had failed and many of the failures occurred when the roofs were only one or two years old [1].* Similar experiences can be cited for the performance of bituminous built-up roofings in other climates. Obviously, the maintenance, repair, and replacement cost of the prematurely failed roofs is quite large. Therefore, 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 identify the factors involved in premature failures and to study the relation of the pertinent factors to roof performance.

2. SOME CAUSES OF FAILURE

Field experience with built-up roof performance on military structures has shown that many failures can be attributed to:

(a) Faulty workmanship.
(b) Faulty design.
(c) Application during inclement weather.
(d) Improper use of materials.
(e) Poorly designed and/or installed flashing systems.

*Numbers in brackets refer to literature references at the end of this report.

These causes and their effects are generally readily apparent and can be eliminated to a large extent. However, the causes of other serious failures common to built-up roofings, such as splitting, membrane shrinkage, wrinkle formation, and wrinkle cracking are not as well known. In our opinion, the primary causes of splitting and shrinkage failures are different from those resulting in wrinkling and wrinkle cracking, although some factors as solar heating and radiative cooling are common to both.

A number of possible causes of wrinkling and subsequent wrinkle cracking failures have been suggested by Joy [2] and Brotherson [3] as: water-vapor pressure; absorption of moisture condensed on felts over insulation joints; and movement in substrate (deck or insulation) with changing moisture content. Cullen and Appleton [4] suggested the thermal cycle produced by solar heating may contribute to the dimensional changes which occur in the system components and result in the formation of wrinkles and wrinkle cracking.

Although the seriousness of wrinkle formation and wrinkle cracking are recognized, it is believed that failures due to splitting and membrane shrinkage result in more serious consequences. Field observations have confirmed the widespread incidence of these failures, especially in cold climates. For example, Figures 1, 2, and 3 represent some results of membrane shrinkage. Figure 1 shows the number of splits which were observed in the roof on one large structure, while Figures 2 and 3 indicate the amount of displacement of the flashings at an expansion joint and at the gravel stop on the same structure, due to membrane shrinkage.

Although many membrane failures can be traced to the movement of a building component beneath the roof [5] which is transferred to the membrane, ample evidence exists that thermal movement is also involved. Therefore, in order to provide for the movement and minimize the failures, the extent of the movement as well as other engineering properties of a bituminous membrane should be known over the temperature range to which the roofing may be subjected.

3. ENGINEERING PROPERTIES OF BITUMINOUS BUILT-UP MEMBRANES

In attempting to relate the engineering properties of a bituminous built-up roof to splitting and shrinkage failures, three properties should be considered: breaking load, breaking strain, and thermal movement.

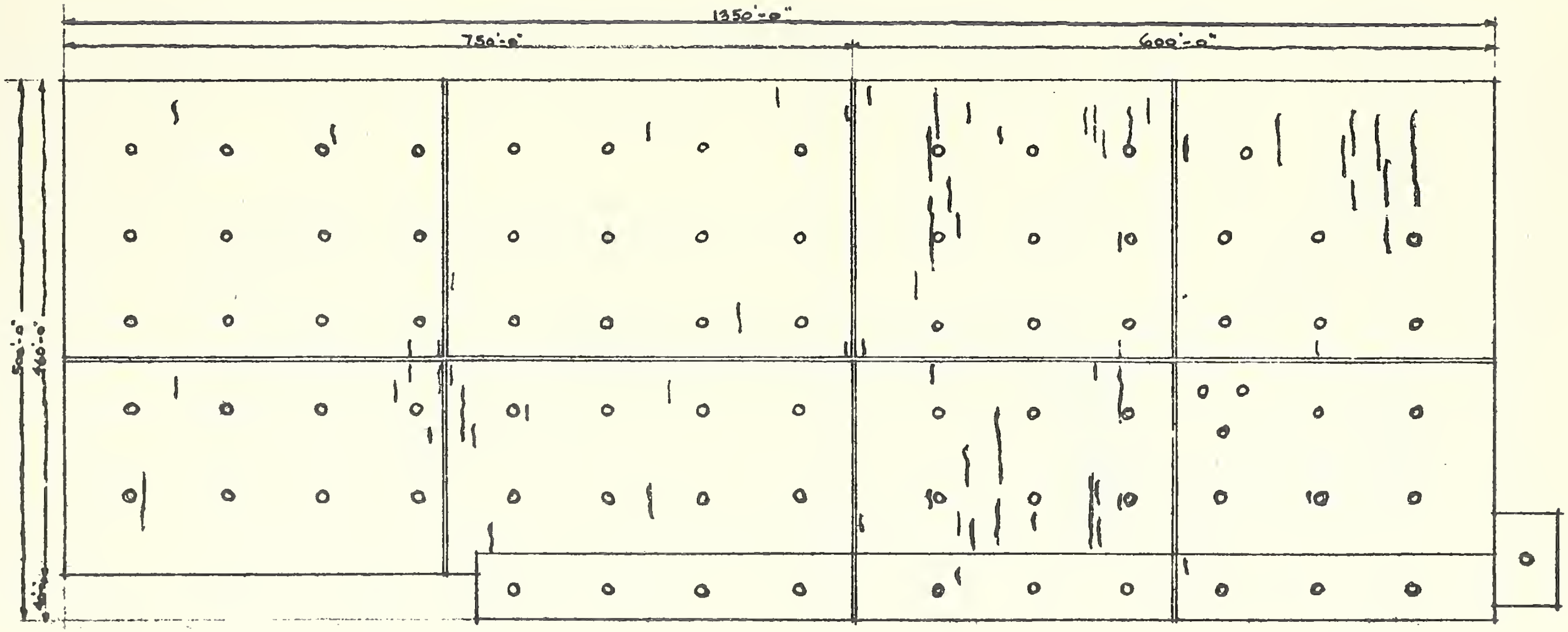

FIGURE 1. SPLITTING FAILURES ATTRIBUTED TO MEMBRANE SHRINKAGE. SECTIONS ON LEFT WERE APPROXIMATELY 3 YEARS OLD. SECTIONS ON RIGHT WERE APPROXIMATELY 9 YEARS OLD.

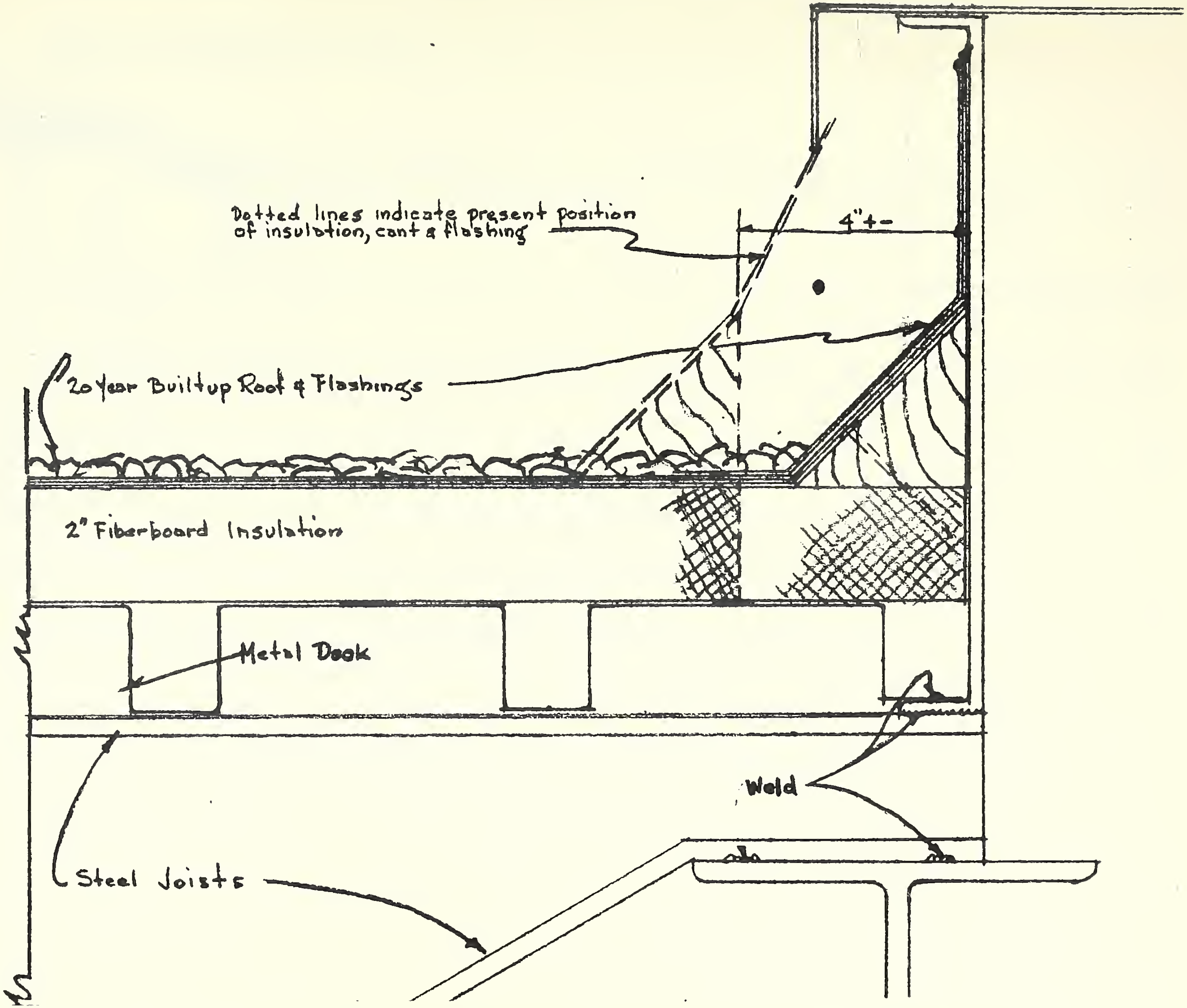

FIGURE 2. DISPLACEMENT OF FLASHING AT EXPANSION JOINT DUE TO MEMBRANE SHRINKAGE.

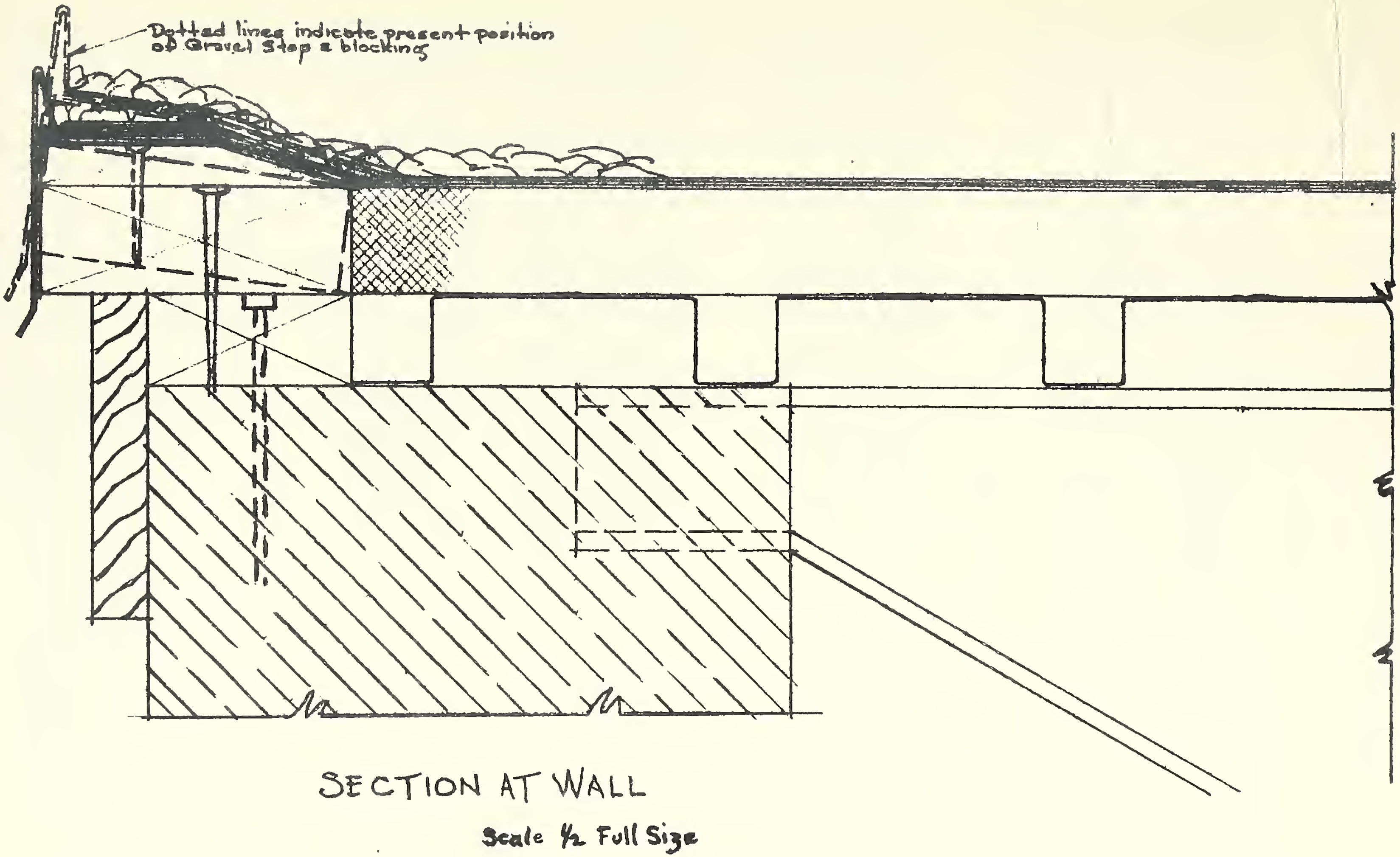

FIGURE 3. DISPLACEMENT OF GRAVEL STOP DUE TO MEMBRANE SHRINKAGE.

3.1 Breaking Load

After a comprehensive study on some engineering properties of built-up roofing, Jones [6] reported the breaking load of a built-up membrane (asphalt or coal-tar pitch - organic felt) tested in the length direction is double that of the cross direction, while that of an asphalt-glass membrane is equal in each direction and roughly the same as the organic felt membrane in the cross direction. He further reported the breaking loads of the organic felt membrane and of the glass felt membranes increased 300% and 70% respectively when the temperature was decreased from 75°F to -20°F.

3.2 Breaking Strains

In the study referenced in paragraph 3.1, Jones [6] reported the breaking strains for various bituminous membranes varied with temperature. For example, coal-tar pitch - organic membranes showed a marked decrease from 1.7% at 75°F to 0.5% at -20°F, while the asphalt-organic felt membranes decreased from 2.3% at 75°F to 1.2% at -20°F. The glass membrane decreased from 1.7% at 75°F to 1.1% at -20°F.

3.3 Thermal Movement

Generally the dimensions of all substances increase as the temperature increases and decrease as the temperature decreases. The extent of this linear movement over a specified temperature range is described as the coefficient of linear expansion. In order to relate thermal movement to the performance of built-up roofing, it is necessary not only to know the expansion coefficient of the bitumen and the saturated felt, but also that of the composite built-up membrane constructed from these components.

The coefficient of cubical expansion of asphalt and coal-tar pitch is reported to be 3.5 to 3.9 X 10^{-4} (32°F to 140°F) and 2.6 X 10^{-4} (200°F to 300°F)/°F [7]. If the assumption is made that the linear expansion is about 1/3 that of the cubical expansion, the linear expansion coefficient becomes 120 X 10^{-6} and 90 X 10^{-6} in./in./°F for asphalt and pitch over the temperature ranges indicated.

Cullen [8] reporting on a limited study of the thermal movement in relation to solar heating indicated the coefficient of linear expansion was not linear with temperature and increases markedly as the temperature is decreased. He further reported the expansion coefficient to be in the range of 10 to 31 X 10^{-6} in./in./°F for various composite bituminous built-up membranes over a temperature range of -60°F to 0°F when measured parallel to the machine direction of the reinforcing felt. However, no published information is available for the linear expansion coefficients of roofing felts nor has data been published indicating the relationship between linear expansion and direction of the felt. Therefore, a program was conducted to obtain these data.

4. MATERIALS AND TESTING PROCEDURE

Four types of bituminous-saturated felts and two types of bitumen which are conventionally used in the construction of built-up roofs were selected for study. Table 1 identifies the materials. In one case, the specimens for tests consisted of four plies of felt which were mechanically fastened to each other without the use of bitumen, while in the other the specimens consisted of alternate plies of felt cemented to each other with the appropriate bitumen (about 20 lb/sq.).

The thermal movement measurements were made on four 12-inch by 2-inch specimens of each sample, two of which (duplicates) were prepared with the 12-inch dimension perpendicular to the machine direction of the felt and the remaining two (duplicates) were prepared with the 12-inch dimension parallel to the machine direction of the felt. Brass reference plugs, 1/4-inch in diameter, were inserted and sealed with an epoxy adhesive into holes drilled into the specimen near each end and spaced about 10 inches apart.

The specimens were placed unrestrained on a flat surface, dusted with talc to reduce friction in the conditioning chamber. The temperature of the chamber was then cycled from -60°F to 140°F and back down to -60°F. At 20°F increments, when a control specimen reached equilibrium, the distance between the reference plugs was measured to the nearest ten thousandth of an inch with a Whittemore Strain Gauge, as shown in Figure 4.

TABLE 1. MATERIALS USED FOR SPECIMEN PREPARATION

Bitumens	ASTM Specification
Asphalt	D312-44
Coal-tar pitch	D450-41, Type A
Reinforcing Felts	
Felt, Asphalt-Saturated, 15 lb.	D226-60
Felt, Asbestos, Asphalt-Saturated, 15 lb.	D250-60
Felt, Coal-tar Saturated, 15 lb.	D227-56
Felt, Glass fiber, Asphalt-Saturated, 8 lb.	D2178-63T, Type I.

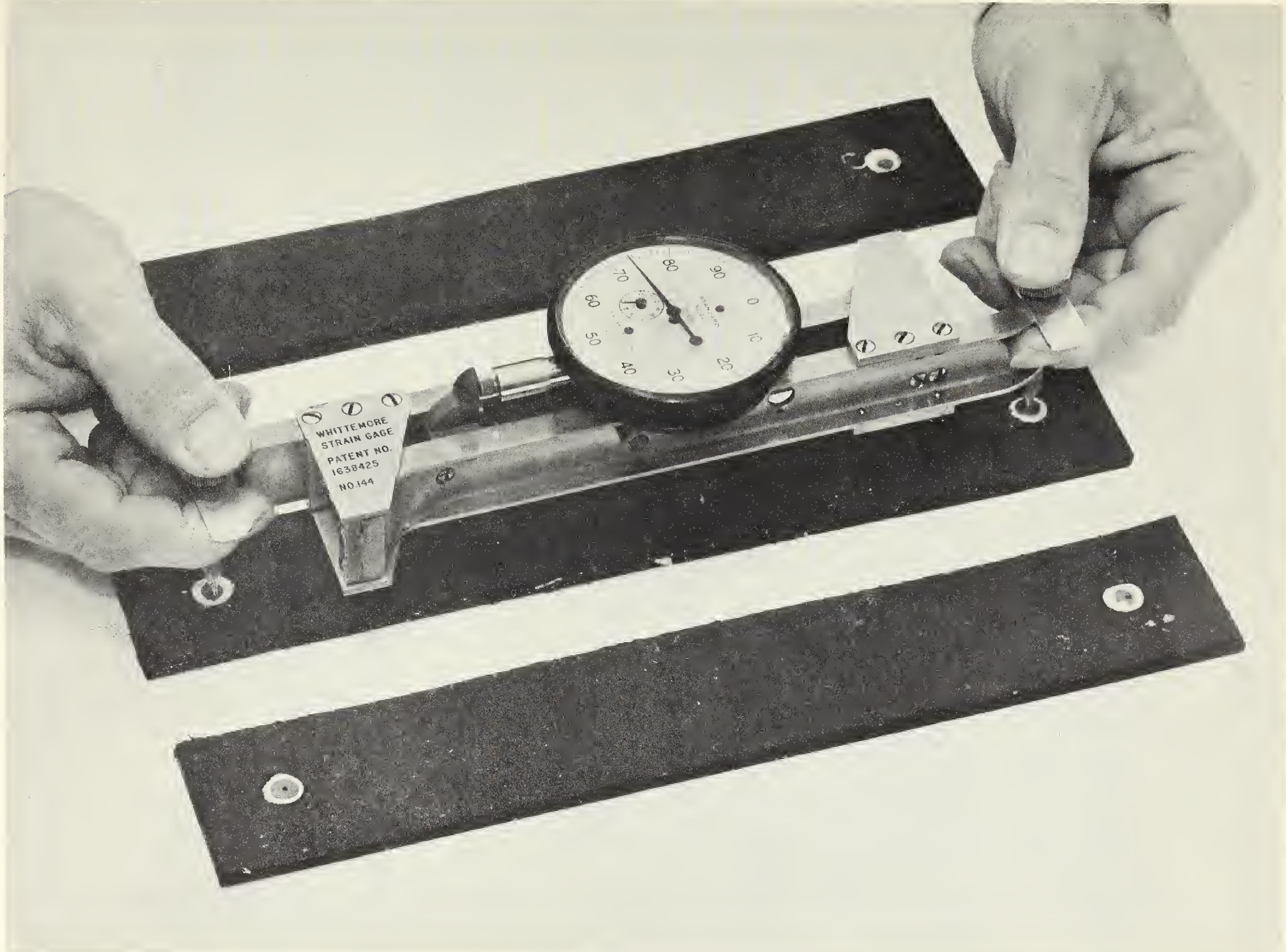

FIGURE 4. THERMAL MOVEMENT MEASUREMENT TECHNIQUE.

5. RESULTS

The averaged results expressed as the apparent linear expansion coefficient of felts and of the composite membranes obtained both "in the machine" and "across machine" directions are reported in tables 2 and 3, respectively. The coefficients which were calculated from the data obtained during the cooling cycle from 30°F to -30°F are expressed in inches per inch per degree F.

Although the determinations were made over a much larger temperature range, the coefficients were calculated over the range from +30°F to -30°F since previous work [8] showed that the movements caused by temperature changes are minimal at moderate and high roof temperatures and quite critical at low temperatures. Further it was believed that this was a realistic range for roofs exposed in many areas where splitting failures have occurred.

The results obtained compare favorably with previous results of thermal movement of composite built-up membranes in the machine direction which were obtained under Project 10447 [9].

TABLE 2. APPARENT EXPANSION COEFFICIENT OF ROOFING FELTS (TEMPERATURE RANGE 30°F TO -30°F)

Description	Expansion Coefficient, in./in./°F.	
	"With Machine"	"Across Machine"
Asphalt-Saturated Organic	6.3×10^{-6}	13.3×10^{-6}
Asphalt-Saturated Asbestos	6.3×10^{-6}	13.0×10^{-6}
Asphalt-Impregnated Glass	14.5×10^{-6}	18.2×10^{-6}
Coal-Tar-Saturated Organic	6.5×10^{-6}	15.2×10^{-6}

TABLE 3. APPARENT EXPANSION COEFFICIENT OF BUILT-UP MEMBRANES (TEMPERATURE RANGE 30°F to -30°F)

Description	Expansion Coefficient, in./in.°F.	
	"With Machine"	"Across Machine"
Asphalt - Asphalt-Sat. Organic	10.9×10^{-6}	20.8×10^{-6}
Asphalt - Asphalt-Sat. Asbestos	8.3×10^{-6}	20.3×10^{-6}
Asphalt - Asphalt-Imp. Glass	18.1×10^{-6}	29.4×10^{-6}
Coal-Tar Pitch - Coal-Tar-Sat. Org.	19.4×10^{-6}	26.1×10^{-6}

6. SUMMARY AND DISCUSSION

The data indicate:

1. Bituminous built-up membranes are subject to rather large shrinkage movements when the temperature is substantially decreased at sub-freezing temperatures.

2. The thermal movement of bituminous built-up membranes is not linear with temperature and increases as the temperature is decreased.

3. The thermal movement of the composite built-up membrane is greater than that of the felt from which it was constructed, but considerably less than that of the bitumen used as the plying cement.

4. The thermal movement in the "across machine" direction of both the bituminous saturated and impregnated felts and the built-up membrane constructed of the felts is appreciably greater than that observed in "with the machine" direction.

Field observations of splitting and membrane shrinkage failures by the author and other investigators on roofs throughout the United States have revealed some factors which are frequently common to these types of failures, as:

1. The failures are more apparent in built-up membranes placed over insulation.

2. The cracking generally occurs parallel to the machine direction of the felt.

3. The cracks or splits often coincide with the longitudinal joint between the insulation boards. Seldom do they occur over the broken joint.

4. The incidence of splitting failures is much greater in the colder climates and the failures generally occur during periods of extremely cold weather with little or no snow cover.

5. The roofs having large areas which are infrequently broken by expansion joints are more susceptible to splitting and membrane shrinkage failures than roofs of smaller area.

These observations would certainly suggest that thermal shrinkage of the membrane may be involved in such failures. In this connection, the results obtained in the laboratory confirm those obtained in actual field exposures. For example, it has been demonstrated experimentally in laboratory tests that roof membranes placed over insulation are subjected to greater temperature fluctuations [4] and as a consequence, greater thermal movement [9] than similar membranes placed over more dense substrates. Further it appears to be more than coincidental that the splitting failures occur more frequently in the "across machine" direction of the membrane and that laboratory measurements have established that not only is the thermal movement larger in the "across machine" direction, but the strength is considerably less in this direction [6].

The incidence of cracks occurring over joints in the substrate may be explained by a theory of stress concentration. For example, if a built-up membrane is subjected to a temperature change of 60°F (+30°F to -30°F), it can contract as much as 0.18% as calculated from the data reported herein. Now based on the data of Jones [6], a similar membrane has a breaking strain of 0.45% at -20°F. Therefore, it appears safe to assume that if the roof membrane were free to move no splitting failure would occur. On the other hand, if the membrane were solidly adhered to the substrate (as it will be in many cases), except for small areas over the joints between units of the substrate, it is possible that an area of stress concentration may develop over the joint and the strain may be of sufficient magnitude to cause failure.

The test data demonstrated that the thermal expansion coefficient of bituminous roofings increase as the temperature decreases. Therefore, it follows that such membranes are more susceptible to thermal shrinkage when exposed in cold climates.

In conclusion, it is our opinion that the data regarding the engineering properties of built-up roof membranes obtained in this and similar programs in other laboratories will prove useful in explaining and predicting the performance of built-up roofing systems during exposure. Further, we believe a better understanding of the fundamental factors involved in roofing performance may lead to deviations from conventional practices of the built-up roofing industry regarding roof application and, thereby, increase the life of the roofing.

7. SUGGESTIONS

The data obtained during the investigation as well as the observations of splitting and shrinkage failures in the field suggest that thermal movement of the built-up roofing may be involved. The question, therefore, arises as to the precautions that can be taken to avoid or reduce the incidence of these failures. Obviously, the alteration of the basic properties of bituminous roofing materials to overcome the effects of thermal movement is not economically feasible. However, the innovation of certain deviations from standard roof design and roofing procedures based on data obtained in the studies of the engineering properties of roofing materials may prove helpful in preventing premature roofing failures involving splitting and membrane shrinkage. It is with this intent that the following suggestions are made:

1. In climates where the average January temperature is 25°F or less, the roof membrane and insulation should be separated by the application of the membrane to the deck and the insulation beneath the deck, where possible. This practice will serve to reduce the large temperature fluctuations which occur in a roof membrane applied over substrates of low density due to solar heating and radiative cooling.

2. When the use of insulation between the roof membrane and the roof deck is necessary, as it will be in the majority of the cases (metal decks, isolation of structural movement, etc.), the joints between the insulation boards should be taped. This practice will serve to eliminate areas of stress concentrations over the joints between insulation boards. It is interesting to note that at least one major roofing manufacturer has recommended this practice for a number of years.

3. The insulation should be applied to the deck so that the longitudinal (continuous) joint is parallel to the short dimension of the roof, while the roofing felts should be applied parallel to the long dimension of the roof and perpendicular to the longitudinal joints of the insulation. This practice would use the greater strength of the reinforcing felts "in the machine" direction to advantage while eliminating the potential stress concentrations over joints due to the greater thermal movement of felts in the "across machine" direction.

4. The adhesive bond between the roof membrane and the substrate should be of optimum strength, i.e., strong enough to hold the membrane in place under conditions of exposure (wind uplift, etc.), but sufficiently vulnerable to failure as to permit the distribution of strains over larger areas of the membrane in the event of thermal shock. A requirement for spot, sprinkle or strip mopping in lieu of solid mopping would serve to accomplish this end. In addition, the use of a

laminated base sheet, in which both the elongation of the respective laminants and the strength of the adhesive bond between laminants could be controlled, may produce the desired effects.

5. The intelligent use of expansion joints in the roofing membrane (not structural joints) will of course reduce the incidence of failure due to thermal shrinkage of built-up membranes. The spacing of joints would vary with the climate to which the roof is exposed. The average January temperature could be used as a guide to establish spacing of expansion joints.

8. REFERENCES

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