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NATIONAL BUREAU OF STANDARDS REPORT

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THE EFFECT OF MOISTURE ON HEAT TRANSFER THROUGH INSULATED FLAT ROOF CONSTRUCTIONS

by

H. E. Robinson and F. J. Powell

Final Report
to
Office of the Chief of Engineers
Bureau of Yards and Docks
Department of the Air Force
Washington 25, D. C.

NBS

U. S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS

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H. E. Robinson and F. J. Powell
Heat Transfer Section
Building Technology Division

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IMPORTANT NOTICE

U. S. DEPARTMENT OF COMMERCE

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TABLE OF CONTENTS

THE EFFECT OF MOISTURE ON HEAT TRANSFER THROUGH INSULATED FLAT ROOF CONSTRUCTIONS

I. INTRODUCTION

The roof constructions used on many Government, industrial, and commercial buildings commonly consist of an approximately flat roof deck of monolithic concrete or gypsum, pre-cast slabs or tiles, steel, or boards, protected from the weather by a built-up roofing of several plies of saturated roofing felt laminated by moppings of a suitable compatible bituminous mastic. Thermal insulation of roofs of this type is usually accomplished by placing on the roof deck a layer of insulating material, which then is covered by the roofing. Among the insulating materials used for this purpose are factory-made board types (e.g., mineral or vegetable fiber insulating board, cork board, cellular glass or plastic, and pre-cast insulating slabs of various kinds), and poured-in-place or castable materials (e.g., lightweight insulating concretes, gypsum, and insulating fills consolidated in place). The thicknesses of the various materials are adjusted to yield the desired insulating value for the roof, depending on available information on the thermal conductivity of the materials.

Such data are available for most roof insulating materials <u>in a substantially dry state</u>, but useful information on their insulating value if moisture is present in them is not available. The lack of information is only partly due to the difficulty of conductivity measurements on moist materials. It is due also to the facts that moisture contents in service are likely to be unpredictable, and that because of moisture migrations in the material, the effect of a given amount of moisture is markedly influenced by the variations of temperature in the insulating material imposed by the climatic exposure of the top surface, including solar heating.

It is highly probable that moisture will be present in most insulated roof constructions, either from the outset, or at some time in the service life of the roof. In construction practice, the chances are not inconsiderable that a board-type insulation, shipped from the factory in a substantially-dry condition, may be wetted by precipitation or dew, in transport, site storage, or during application, before it is protected by the built-up roofing. For hygroscopic insulating materials, exposure to the relative humidity of the atmosphere during the construction process may result in a significant moisture content in the material

when the roofing is applied. Poured-in-place insulations, such as insulating concrete or gypsum, which are pre-mixed with water, are almost certain to contain water in excess of that required for hydration or chemical combination, and these, as well as insulations consolidated in place without water, may be wetted by dew or precipitation before the roofing is applied. In addition to these possibilities, which may be referred to as leading to initial moisture in roof insulation, there may also be accidental wetting of the insulation by water entry through leaks or punctures in the roofing, either during construction, or in service, and as the roofing ultimately deteriorates. There may also be, under some circumstances, a gradual accumulation of water due to condensation of water vapor entering through the undersurface of the roof construction.

The effect of moisture in roof insulation permeable to water or vapor is, in general, to seriously reduce its insulating value, apart from its tendency to cause physical deterioration of the roofing, or of components of the roof. Failure of a roof to develop its expected insulating value causes increased expense for heating or cooling buildings, and may lead to inadequate capacity of heating and cooling systems designed on the basis of the expected insulating value. In order to obtain information on the effect of moisture on the insulating value of various kinds of insulated flat roof constructions, by means of which designs and specifications might be improved or compensating estimates of effective insulating value be made, an experimental investigation was undertaken at the National Bureau of Standards under the joint sponsorship of the Corps of Engineers, the Bureau of Yards and Docks, and the U. S. Air Force.

This report presents a summary of results and conclusions obtained from tests covering three years and a total of 46 insulated roof specimens, each 18 inches square, exposed to successive periods of simulated summer and winter top-side temperature conditions, each with simulated daily solar heating of the top surface. The tests included exposures of specimens initially at an "as-received" moisture content, initially at an oven-dry condition, and initially oven-dry with later addition of known amounts of water.

II. METHOD OF INVESTIGATION

A primary need in this investigation was to be able to measure the effective thermal conductivity of the insulation of a roof deck specimen, and to record its changes as the

specimen was subjected to repeated daily cycles of temperature change simulating those to which a roof is subject, under both summer and winter climatic conditions.

To simulate the daily and seasonal temperature conditions in a controlled and repetitive way, the specimens were mounted horizontally between an upper and lower chamber (see Figure 2), in each of which air at controlled temperatures was caused to flow parallel to the exposed contiguous face of each specimen. Solar heating was simulated by raising the top-side air temperature for six to seven hours per day, depending on the seasonal condition. The daily air temperature cycles in the two chambers for the summer and two winter exposure conditions used in the investigation are shown in Figure 1. The temperatures shown are the averages of values taken from the circular charts of the air temperature recorders. Departures of a few degrees F from the given cycle temperatures occurred from time to time in the course of the work, chiefly in the initial stages of Phase 1, and purposely in exposure condition O of Phase 3.

The general arrangement of a roof deck specimen is shown in Figure 4, which indicates the positions of thermocouples and of a heat flow meter permanently attached on the roofing of the specimen. If steady-temperature conditions prevail, the observed heat flow meter reading and the temperature drop across the insulation enable calculation of the effective thermal conductivity of the layer of insulation.

As Figure 1 shows, the air temperatures in the chambers were substantially constant from 2 to 8 A.M. Figures 5 to 8 give, for two insulations representing extremes in thickness and heat capacity, temperatures and heat flow rates observed at 75-minute intervals throughout typical 24-hour cycles of the imposed summer and winter exposure conditions. These figures show that the temperatures in the specimens became nearly constant from 5 A.M., or earlier, to 10 A.M. The heat flow meter readings also became substantially constant in this period. Thus, with substantially steady conditions prevailing for more than five hours prior to 10 A.M., observations of heat flow and temperature difference across the insulation, made between 8:30 and 10 A.M., should yield reasonably comparable values of the effective thermal conductivity of the insulation at its existing moisture content and distribution. It was expected that the thermal conductivities so obtained would be influenced by, and serve as a measure of, the combined effect of both the amount of moisture in the insulation, and its average distribution as governed by the imposed temperature cycle.

III. EXPERIMENTAL EXPOSURE CONDITIONS

If liquid water is present in a roof construction, the distribution of moisture and the migration of vapor are subject to the saturated vapor pressures of water at the various temperatures existing within the construction at points where there is liquid water, as well as to such properties of the insulation and other components as absorptiveness, capillarity, and vapor permeability. The movement of moisture as vapor, and thus its effect on insulating value, is therefore affected very substantially by the temperature differences within the construction, and by the temperature level, since the vapor pressure of water increases more than linearly with temperature. It was necessary in this work, therefore, to select experimentally-feasible temperature conditions which would be representative in significant respects of those to which the generality of roofs in this country are exposed in service.

For summer conditions, it was assumed that the temperature of the roll roofing of a flat insulated roof would be about 75°F at night, on the average. During the day when the roofing was subject to solar heating, its temperature was assumed to rise to about 145 to 150°F. For the condition designated as winter, it was assumed that the temperature of the roofing at night would be about 38°F, and that due to solar heating it would rise during the day to about 75°F. For the condition designated as severe winter, the roofing temperature was assumed to be about 22°F at night, and 55°F when heated by the sun.

The conditions selected for the air underneath the test specimens were 90°F and 70 percent R.H., corresponding to a dewpoint of 79°F and a vapor pressure of 1.00 inch Hg. These conditions were maintained closely throughout all winter exposures, but during the summer exposures, the bottom air temperature tended to rise in response to heat transmitted downward through the test specimens during the solar heating period, as shown on Figures 5 and 7.

The temperature and relative humidity selected for the bottom air are higher than might be expected in the majority of buildings in winter, at least, but were adopted with the view of speeding the rate of moisture accumulation in specimens under winter exposures.

The 79°F dewpoint maintained under the specimens was always higher than the roofing temperature during the winter conditions, and in the "night-hours" of the summer condition,

and therefore during these times, the vapor pressure difference was such as to cause vapor flow into the specimen. During the solar-heating hours of the summer exposure, however, the vapor pressure difference was directed outward. In view of the much greater vapor pressures that would exist in a wet specimen at the relatively high temperatures prevailing in the insulation during the solar-heating period, it was estimated that the somewhat high bottom air vapor pressure would cause only a small percentage reduction in the outwardly-directed vapor pressure difference. (See page 9, Phase 3.)

The settings for the controllers of the air temperatures in the top chamber had to be adjusted to values a few degrees different from those indicated above, in order that the roofing might attain the desired temperatures. The relative humidity of the top chamber air was not controlled, since the roofing constituted an almost perfect vapor barrier between the air and the specimen insulation.

IV. TEST APPARATUS

A schematic drawing of the apparatus used is shown in Figure 2. Figure 3 is a photograph showing the top sides of 15 roof specimens installed in the apparatus.

The apparatus was constructed as two sections of a box, with the insulated top half capable of being raised by cables for access to the interior. The fifteen 18-inch square specimens, arranged in three rows of five each, were supported on a steel grid frame in the bottom section. The areas at the ends and sides of the frame were covered with insulated panels to complete the division of the box into top and bottom chambers. Insulation was packed between and against the vertical sides of the specimens to reduce transverse flow of heat and edge effects in each specimen. Air in the top and bottom chambers was circulated by blowers in the paths indicated in Figure 2.

The air temperatures in the top and bottom chambers were maintained at the selected values by means of electric heaters controlled by sensitive mercury-in-glass temperature regulators. In the top chamber, low air temperatures were obtained by means of the refrigerating coil in the air flow circuit, with a small amount of electrical reheating to control to the selected air temperature. An electric time clock and relays were used to switch automatically to the appropriate temperature regulators, heaters, and refrigeration controls to produce periodic temperature cycles each day, as

shown in Figure 1. The relative humidity of the air in the bottom chamber was measured and automatically controlled by means of Dunmore-type hygrometer sensing elements, which governed the moisture output of the humidifier by on-off operation of a small blower in the humidifier.

All temperatures in the chambers and in the specimens were measured by means of 30-gage copper-constantan thermocouples in conjunction with a manually-operated potentiometer capable of being read to within one microvolt, corresponding to a temperature within 0.05 deg. F. Continuous 24-hour records of the air temperatures in the top and bottom chambers, and in the surrounding laboratory, were obtained using circular-chart recording thermometers. The blowers circulated the air past the specimens at an average velocity on the order of 140 ft/min. In passing from the first to the second air temperature thermocouple in its path (see Figure 2), the air changed in temperature by less than 1/8 deg. F in the bottom chamber, and in the top chamber by less than 0.4 and 1.0 deg. F under summer and winter night-time conditions, respectively.

The apparatus operated automatically and continuously to subject the specimens to the reiterated daily cycles of the selected temperature exposure without shut-downs for week-ends or holidays, at which times manually-made observations of data were not taken.

The heat flow meters used were of the Gier and Dunkle type, of bakelite 3/64 inch thick and 4 1/2 inches square, having a stated response of approximately 1/8 millivolt per Btu/hr ft^2. The heat flow meter was cemented with a rubber adhesive to the top of the roll roofing at the center, as shown in Figure 4. Initial observations showed that the meter reading fluctuated undesirably in response to rapid slight fluctuations in the temperature of the air passing over its surface. These fluctuations were substantially damped out by covering the meter with a 4-inch square of 5/8-inch steel. The thermal resistance of the meter and steel together was estimated to be less than one percent of the over-all resistance of a dry specimen, and thus to have negligible effect on heat flow measurements under steady conditions. Heat flow meter readings were measured manually, by means of the potentiometer used for thermocouple readings.

The 15 heat flow meters were supplied with individual calibration factors (with corrections for the meter temperature) which were approximately alike. Initial observations,

and some meter calibrations that were made subsequently, indicated that, in general, the response was only about two-thirds of that stated. However, since the results of this investigation are expressed in relative terms, involving the ratio of readings of the same meter at different times, the calibration factor of the meter, if constant, is cancelled out. As applied and used, each meter was cemented to a specimen, and was not subject to motion or high humidities, and therefore its calibration factor should have been substantially unchanged. All meter readings were corrected for mean temperature in accordance with the manufacturer's temperature correction curve.

V. TEST PHASES: OBJECTIVES AND SPECIMENS

The investigation was conducted in three phases, each consisting of alternations of periods of exposure of 15 specimens to temperatures simulating winter or summer conditions. Each period consisted of repeated 24-hour cycles of the appropriate daily temperatures to simulate night-time and solar heating conditions, as indicated in Figure 1. The seasonal periods were of several weeks duration each, varying in length as necessary to observe apparent trends in the insulating value of a majority of the simultaneously-exposed specimens.

The three phases were aimed at somewhat different objectives, reflecting the changing emphases of the investigation as it progressed. In accordance with the objectives, the designs of the specimen constructions, or their initial and later conditioning, were changed in the successive phases. Summarized briefly, the chief objectives and the general nature of the specimens employed in each phase were as follows.

Phase 1. Investigation of the insulating value of roof constructions insulated with board-type or light-weight concrete insulations placed on a 3-inch dense concrete deck slab, with and/or without a vapor barrier, under simulated summer and winter seasonal temperature conditions, including daily solar heating. This was done with specimens assembled from materials which were at "as-received" moisture contents, i.e., factory-made materials were taken from cartons stored a few months in the laboratory; dense concrete slabs were air-dried approximately four months in the laboratory; insulating concretes were air-dried in the laboratory from three to seven weeks.

Particulars of the individual specimens of Phase 1 are given in Table I. The typical specimen design is shown in Figure 4, which includes details of the edge-sealing of a specimen and the method of installing it in the apparatus.

Referring to Figure 4, the asphalt edge-seal (7) was approximately 1/8 inch thick, applied hot, and was additionally enveloped by a double wrapping of thin Saran plastic film (6) sealed against the specimen faces by pressure and mastic, as shown. The roofing was similarly held down at its edges. The bakelite tubing inserts (13) were connected to mercury manometers, to indicate internal pressures within specimens, or to limp balloons of 0.004-inch polyethylene to allow for relief at atmospheric pressure of expanded gases within specimens without entire loss of the moisture contained in the relieved gases. If a vapor barrier was used, it was sealed around the inlet of the tubing insert by mastic.

Phase 2. Investigation of the effects of known amounts of moisture on the insulating value of various insulated roof constructions, under the simulated seasonal exposure conditions. This was done using 11 specimens which were oven-dried prior to installation, into 6 of which water was introduced during later exposure periods in incremental amounts of 1, 2, and 7 percent by volume of the insulation. Because of the apparent high vapor resistance of the dense concrete decks observed in Phase 1, the effect of omitting the decks on the effective conductivity of the insulating material was also investigated, using 6 specimens. Four specimens were continued unchanged from Phase 1 for information as to the effects of a prolongation of exposures.

Particulars of the individual specimens of Phase 2 are given in Table II. The design of the specimens was similar to that shown in Figure 4, except that no specimen had a vapor barrier, and for six of the specimens, the 3-inch dense concrete deck was removed or omitted. Water added to selected specimens was introduced through the bakelite tubing insert in the dense concrete deck, which was kept closed except to admit water, or through a small temporary hole in the roofing, which was then sealed.

Phase 3. Investigation of the effect of (a) omission of the dense concrete decks of selected specimens, and (b) pressure-relieving vents through the roofing, on the effective conductivity of various types of insulations when subjected to a succession of alternated simulated summer and winter exposure conditions.

To investigate to some degree the effect of the bottom air conditions in the apparatus, they were changed at week 147 from 90°F and 70 percent R.H. (vapor pressure 1.00 inch Hg, dewpoint = 79°F) to 80°F and 50 percent R.H. (vapor pressure 0.52 inch Hg, dewpoint = 60°F). At week 151, the bottom air conditions were changed again, to 88°F and 39 percent R. H. (vapor pressure 0.52 inch Hg, dewpoint = 60°F), or, to approximately the original temperature, but half the original vapor pressure.

The specimens of Phase 3 are individually described in Table III. All were oven-dried prior to installation; the amount of moisture removed by oven-drying was re-introduced into 10 of the specimens during a later exposure condition. Twelve of the 15 specimens had 3-inch dense concrete decks, 8 had a vapor barrier, and 11 were equipped with openable vents through the roofing. Specimen 32 was installed in place of specimen 31 at the end of week 134.

The design and installation of the specimens resembled the details shown in Figure 4. Exceptions were that the edge-seal (7) was made not with asphalt but with 1/32-inch neoprene sheet cemented to the specimen with a rubber adhesive, that 3 specimens were installed without a dense concrete deck, and that no specimen had a tube inserted through the deck. For each specimen equipped with a vent through the roofing, the top of the insulation was scored with a groove, 1/4 inch wide and 1/4 inch deep, outlining a square enclosing the central half of the face area, at one corner of which a 3/16-inch i.d. bakelite tube was installed projecting through the roofing. The vent-tube was used also as a means of introducing water into the specimen early in Phase 3.

VI. PRESENTATION OF RESULTS

The summarized heat transfer data obtained in the investigation are presented graphically in Figures 9, 10, and 11, in which, for each specimen, values of the ratio k/k_o are plotted as ordinates versus time as the tests progressed.

In the ratio k/k_o, k is the observed effective thermal conductivity of the insulation of a specimen at a given time, and k_o is the approximately minimum value of conductivity observed for the specimen during its exposures. For each specimen (except specimens 13 and 21), the value of k_o selected was the value of k obtained under winter exposure conditions for the insulation when it was in an oven-dry

condition, or, if the specimen had not been oven-dried, when its observed conductivity was minimal. As will be seen, the observed conductivity under winter exposure conditions of an insulation containing only moderate amounts of moisture approached closely to that of the oven-dry insulation.

The values of conductivity k were obtained from the experimental data in accordance with the equation

$$k = \frac{qx}{A(\Delta t)}$$

where k = thermal conductivity, Btu/hr ft^2(deg F/in.)
x = insulation thickness as installed, in.
q/A = heat flow* as indicated by the heat flow meter attached to the roofing, Btu/hr ft^2
Δt = temperature difference* across the insulation, deg F

*Observed daily during the substantially steady temperature conditions prevailing just prior to the start of the solar heating period.

Each plotted value of k/k_o is the average of the (usually) five values obtained during each week of the tests.

Use of the ratio k/k_o to represent the data has several advantages: (a) It indicates proportionate increases of conductivity (e.g., a k/k_o of 1.5 indicates a 50 percent increase in effective conductivity above the winter value for the substantially dry insulation), (b) relative changes of conductivity of different insulations are readily compared, (c) the absolute calibration constant of the heat flow meter is not involved, provided only that it remained substantially constant.

The time scale of Figures 9, 10, and 11 is expressed in elapsed weeks, starting from the beginning of Phase 1. The time scale is also subdivided into periods designated by letters, each of which represents a sustained seasonal exposure condition. Phase 1 comprised seasonal conditions A to D; Phase 2, E to J; and Phase 3, K to Q. The type of exposure condition is indicated by the line spanning the lettered period, a summer exposure condition being shown by a solid line, and a winter condition by a hatched line. The exposure conditions were substantially those shown in Figure 1 (the more severe winter condition was used only in exposure period C). Plotted data for individual specimens are identified by

distinctive symbols, and by the specimen number in accordance with the listing and description of the specimens at the right side of the figure.

Tables IV, V, and VI give data on the weights of the specimens at the start and end of their exposures, and on the moisture contents of major components of the constructions where these could be ascertained. Final moisture content data for insulations and concrete decks were determined from their weights before and after oven-drying them at 215°F. The column headed "Exposure Gain (or Loss)" indicates, as well as could be determined, the over-all effect of the succession of imposed exposure conditions on the weight of the specimen, an allowance being made for the weight of water purposely added to it, if any.

VII. CONCLUSIONS AND RELEVANT DISCUSSION OF RESULTS

Conclusions are given below which summarize generally the data obtained. Each conclusion is followed immediately by a discussion in detail of the specific data which it summarizes.

1. Effect of Moisture on Insulating Value, and the Influence of Exposure Conditions on this Effect.

Appreciable amounts of moisture in permeable roof insulations seriously reduced their insulating value under both simulated winter and summer exposure conditions. For approximately the same moisture content, the effective conductivity of a permeable insulation was considerably greater under the summer conditions than under the winter conditions, both of which included simulated solar heating of the roof for part of the daily cycle of temperature exposure.

For some insulations containing considerable but probably not untypical amounts of moisture (e.g., an insulating concrete), effective conductivities observed were as much as four times the value for the dry insulation, under the summer exposure condition, and two times the value dry, under the winter exposure condition. For nearly-dry insulations, the increases and seasonal differences were much smaller.

A possible explanation for the greater effect of a given amount of moisture under summer conditions is that for the simulated summer exposure condition used, the temperature gradients in the insulation definitely reversed direction daily. The reversal would tend to cause moisture to migrate back and forth each day, thus keeping it distributed throughout the insulation during the summer condition and available for latent heat transfer.

Under the simulated winter condition used, there was no daily reversal of direction of the temperature gradient (except possibly in the upper portion of the insulation) and the moisture would therefore tend to migrate to and concentrate in the upper (colder) part of the insulation, leaving the remainder relatively dry.

Evidence of the relative effects of approximately the same moisture content in summer and winter is afforded by the plotted data for practically all of the specimens which contained significant moisture.

For example, consider specimen 11 (Figure 10). In expoure period A (summer), values of k/k_o approximated 3.0. In periods B and C (both winter), the values were about 1.8; on resuming a summer condition (D), k/k_o again approximated 3.0. These tests were made with the insulating concrete and dense deck at "as-received" moisture contents (moderately air-dried). At conclusion of D, specimen 11 was oven-dried (it lost 12 lb in being dried; see Table IV), and assigned the new number 26. In summer exposure E, the value of k/k_o for the oven-dry specimen 26 approximated 1.2, and in winter exposure F, about 1.0. After a cumulative amount of water equal to 10 percent of the insulation volume (6.7 lb) had been introduced into the originally oven-dried specimen during winter exposure H, the value of k/k_o rose sharply from about 1.1 to 2.0, and slowly decreased, presumably as the moisture redistributed. In summer period I, k/k_o rose to values in excess of 2.0. Quite similar behavior was recorded during the corresponding exposure conditions for other insulating materials similarly treated. See insulating concrete specimens 12(27) and 14(29), and board-type insulation specimens 2(17) and 5(20). For the permeable board-type insulations, the behavior was similar, although less extreme (in Phase 1, these insulations contained initially only hygroscopic moisture, although the dense concrete decks were only "air-dry").

A contrast to the performance in Phase 1 of permeable insulations containing moisture is afforded by the practically vapor-impermeable board-type insulations of specimens 9 and 10 (Figure 11). These showed little change in effective conductivity under summer and winter conditions (A, B, C, D), even though the dense concrete deck, and vapor permeation through the deck during B and C, would have been sources of moisture to cause an effect during D if the insulations had been permeable.

It should be noted that the only specimens having vapor barriers in Phase 1 (3, 6, 15) duplicated in C and D their performances in B and A, respectively, and that they were the only specimens showing a loss in weight in Phase 1 (see Table IV), presumably as a result of drying of the dense deck, the moisture in which could not enter the insulation during the winter exposures B and C. Why a similar loss of weight did not occur for specimens 9 and 10, which had quite vapor-resistant insulations, although no vapor barriers, has not been accounted for.

Further evidence of the relative effects of moisture under summer conditions as compared with winter conditions is amply afforded in Phase 3, in which their originally-held moisture was restored during exposure M to selected initially oven-dried specimens, as indicated in Figures 9, 10, and 11. In Phase 3, however, the effects change in some specimens (34, 37, 46) because of apparent drying-out of the specimens under the exposure conditions (see Conclusion 3).

2. Effects of Vapor Barriers and of Dense Concrete Decks.

Changes in the effective conductivity of permeable roof insulations with time (for the same exposure condition) were almost inappreciable when a sheet vapor barrier (0.08 perm, approx.) separated the insulation and the dense concrete deck. In most cases, changes were also materially retarded when the insulation was placed directly on the deck without the sheet vapor barrier, apparently because of the effective resistance to moisture transfer of the dense concrete deck.

For roof insulations that are dry, a vapor barrier and a (dry) dense concrete deck are advantageous, since they help keep them dry. But for roof insulations which initially contain appreciable moisture, or those made wet (as by a leak in the roofing during service), the moisture transfer resistance of a vapor barrier and/or of the dense concrete deck impedes drying of the insulation through its under-surface, and keeps the insulation in a moisture condition at which its insulating value may be seriously reduced.

A vapor barrier between an initially-dry roof insulation and a concrete deck that is not dry prevents dampening of the insulation by moisture from the deck, which otherwise would occur. (It is estimated that the "air-dried" 3-inch dense concrete decks used in Phase 1 had moisture contents of 3-4 percent by weight, or approximately 1.3 lb of water per square foot of deck.)

In Phase 1, three specimens (3, 6, and 15, Figures 9 and 11) had a sheet vapor barrier under the insulation, the others did not. In exposure period D, the values of k/k_o for these three specimens were substantially the same as at the end of exposure A, although they had been subjected for 19 weeks to winter conditions B and C, during which moisture from the dense concrete deck or the air below would ordinarily have tended to migrate into the insulation. The similar specimens 1 & 2, 4 & 5, and 13 & 14, which had no sheet vapor barriers, had average values of k/k_o in period D appreciably greater than those in period A, indicating increases in insulation moisture content due to the winter exposures B and C. Similar behavior was recorded for the insulations of specimens 7 and 8, which were initially fairly dry and were moderately vapor-permeable, but not for the insulations of specimens 9 and 10, which had very low vapor permeability.

Further evidence of the effect of a vapor barrier is afforded by specimens 39 and 44. Both were oven-dry at the start of exposure period K (Figure 11); specimen 39 had a sheet vapor barrier, 44 had only a dense concrete deck. Throughout all the exposures of Phase 3, these insulations had k/k_o ratios only moderately greater than 1.0; although for both the ratios showed a tendency to increase slowly (in successive similar exposure conditions). For specimen 39, the increase of k/k_o was relatively less than for 44, incicating the effect of the vapor barrier. It should be noticed, however, that the dense concrete deck of specimen 44 evidently had substantial vapor resistance, and also that the deck was initially oven-dry and therefore unable to contribute moisture of its own to the oven-dried insulation. Similar behavior of other dry insulations with sheet vapor barriers was recorded for specimens 31 and 33.

On the other hand, k/k_o ratios for moist insulations used with a sheet vapor barrier remained large throughout their exposures. This resistance to change was also evident for specimens with moist insulation over dense concrete decks. For example, see specimens 41 and 45 (Figure 11), following the restoration of (original) moisture early in exposure period M. Throughout the subsequent 54 weeks of various exposures, the k/k_o ratios for these specimens continued at approximately unchanged summer and winter values. Approximately similar behavior is noted for specimens 38 and 40, which had dense decks but no sheet vapor barriers, and to which original moisture was restored in M, and for specimens 1, 4, 8, and 13 in period D of Phase 1 and throughout Phase 2.

These data, and the contrasting data discussed under Conclusion 3, are evidence of the effect of a vapor barrier, and of a dense concrete deck, to act as an impedance to change of the k/k_0 ratio of the insulation for given exposure conditions, and also, presumably, to change of the moisture content of the insulation.

3. Behavior of Specimens Having No Dense Concrete Deck or Vapor Barrier.

   Apparent self-drying tendencies were observed for some roof specimens consisting of roofing and a layer of insulating material installed without a dense concrete deck or a sheet vapor barrier underneath.

   For some insulations of only moderate permeability and relatively high absorptive capacity installed in this way, it was found that the originally high effective conductivity of the initially moist insulation tended to decrease rapidly during the simulated summer exposures, and to approach a value not much greater than that of the dry insulation, presumably as a consequence of drying through the undersurface. Increases of conductivity during winter exposures were observable, but relatively small and slow, even when the insulation was initially oven-dry. The evidence obtained indicated that, for suitable insulating materials (e.g., some insulating concretes), the effective conductivity, whether the insulation was dry or moist initially, tended to reach an approximately stable level value, or plateau, not greatly different from that of the substantially dry material during corresponding seasonal conditions.

   The same general type of behavior was observed for all specimens without dense concrete decks underneath, but for those of high permeability and low absorptive capacity, the changes in effective conductivity in each seasonal exposure (especially winter) were extreme, and the over-all average level of conductivity was unsatisfactory.

   Specimens of certain insulations used without dense concrete decks, initially at appreciable moisture contents, attained low values of effective conductivity in one or two alternations of the imposed summer and winter exposure periods. In contrast, for specimens of similar insulations, also initially appreciably moist, placed on

dense concrete decks with or without a sheet vapor barrier, effective conductivities remained at substantially their original high values throughout the same exposure periods.

In the following, the k/k_o ratios for all specimens not having a dense concrete deck are discussed, and comparisons made with those for similar specimens having a dense deck and in some cases a sheet vapor barrier also.

Specimens 37 and 40 (Figure 10) were similar, except that 37 had no dense deck. Both were initially oven-dried, and both had water added to them at week 111 in the amounts removed when they were dried (18.6 and 23.0 lb, respectively; see Table VI). The k/k_o ratios were approximately the same for both specimens prior to week 111; addition of the water caused an immediate sharp increase for both, but during the remainder of summer exposure M, k/k_o for specimen 37 decreased very considerably (from 3.6 to 2.0), while for 40, it showed only minor change (from 4.5 to 4.0, approx.). In subsequent winter condition N, values of k/k_o were markedly different (1.65 for 37 versus 2.7 for 40). In summer condition O, k/k_o for 37 dropped to 1.1, while k/k_o for 40 reduced to only about 3.5. In winter condition P, and summer condition Q, k/k_o for specimen 37 reproduced closely the values obtained in exposures K and L when it was substantially oven-dry. But for specimen 40, k/k_o in exposure P and Q had values only a little smaller than those in exposures M and N, when the specimen contained much moisture. (The changed bottom air conditions during weeks 147 and 151 unquestionably increased the obtained values of k/k_o for the following five weeks, for all specimens containing much moisture at that time, although the change had much less effect on simultaneously-exposed specimens containing little moisture, indicating the changed effect was due to a new moisture distribution.

Table VI shows that specimen 37 had an "exposure loss" of weight of 15.2 lb, and specimen 40 a loss of 3.3 lb. The final moisture content of the insulation of specimen 37 was 7.7 percent as compared with 63.4 percent, the presumable moisture content at week 111 when its original moisture was restored. For specimen 40, only the final moisture content (50.5 percent) of the insulation could be ascertained, because separation of the insulation from the dense deck was not feasible earlier.

Similar but not as rapid reduction of the k/k_o ratio was observed for specimen 34 (no deck), which compares with specimen 38 (with a dense deck). Similarly also, compare

specimen 46 (no deck) with specimen 41 (deck) and specimen 45 (deck plus sheet vapor barrier), on Figure 11. It should be noted, in passing, that specimens without decks (37, 34, and 46, and also 36) showed a tendency for the k/k_o ratio to increase slightly during winter condition exposures (see periods L, N, and P), and, apparently because of moisture gains during these periods, to have k/k_o values at the start of the following summer exposure slightly greater than the values at the end of the preceding summer exposure. For this reason, specimen 36 is of especial interest. It had no deck, was oven-dried before installation, and had no moisture added to it except as a result of its exposures. Specimen 44 was similar, but had a dense concrete deck. Tracing the values of k/k_o for the two specimens from the start to the end (periods K to Q), it is seen that values for specimen 36 were larger than those for specimen 44 for most of the exposure periods, but at the end the values for specimen 44 were slightly larger than those for 36.

It is instructive to compare specimens 36 and 46, which were similar (no decks) and initially oven-dried. Their k/k_o ratios were almost identical until water was added to specimen 46 early in exposure M. As further exposures took place, the k/k_o ratios for specimen 46 tended to decrease, and those for 36 to increase slightly. At the end of summer period Q, they were approximately 1.45 and 1.25, respectively, and the final moisture contents of the insulations were 9.3 and 6.7 percent, respectively (Table VI). In short, without dense concrete decks underneath them, the insulating concretes, one initially oven-dry and one starting at 20.6 percent moisture content, tended toward the same operating values (plateaus) of k/k_o and of insulation moisture content, approximately attaining them in a relatively short time.

Although there was no other pair of like insulating concrete specimens without decks with which to examine this tendency for convergence to a plateau-value, it is evident that specimen 37 rapidly approached k/k_o and moisture content values typical of fairly dry insulation, and that specimen 34 appeared to be tending in a similar direction, but at a considerably slower rate. In connection with the levels of k/k_o and moisture content which appear to be the plateau-values in the tests conducted, it is important to appreciate that the bottom air dewpoint for exposures following week 147 was 60°F. For lower bottom air dewpoints, which would be probable for most buildings in summer and practically certain for all ordinary buildings in winter, the plateau-values of k/k_o and insulating concrete moisture content should be lower than those indicated.

In contrast, consider specimens having dense concrete decks under the insulation. In Phase 3, k/k_o values increased slowly for specimens 39 and 44 to which no water was added, and decreased very slowly for specimens 38, 40, 41, and 45, to which water was added. It is reasonable to suppose that eventually the like specimens would reach common plateau-values of k/k_o and insulation moisture content, but evidently the time required would be many times greater than for specimens without dense concrete decks. For the latter reason, it is not possible to estimate even roughly the plateau-values that might be attained by the specimens with decks; the slight evidence available from specimens 36 and 44 suggests they would be higher for specimens with decks than for those without decks. Some additional information on the trends of values of k/k_o is afforded by the values in Phase 2 for specimens 24 & 26, and 25 & 27 (Figure 10), and specimens 29 & 30 (Figure 11).

In Phase 2, three board-type insulations were made into specimens without dense concrete decks or vapor barriers underneath. Specimen 18 was highly permeable to vapor, but of very low moisture absorptiveness; specimen 21 was moderately vapor permeable and of substantial absorptiveness; specimen 22 was of moderate to low permeability, and moderately absorptive. Data for these specimens are given in Figure 9. All were oven-dried before installation, but some may have gained moisture hygroscopically before the test exposures were started.

Specimen 18 showed, to an extreme degree, rapid increases of k/k_o during winter exposures, and rapid decreases during summer exposures, in all periods of Phase 2. This behavior would be expected for a material having its properties; it was observed, in fact, just after week 53, that a quantity of water had dripped from the undersurface of the specimen, which probably was the reason the k/k_o value decreased sharply for a time. Evidently this insulation was too permeable to vapor, and too little absorptive of moisture, to endure long winter exposure without accumulation of excessive free water, when used without a vapor resistance underneath. Its performance in the latter case is shown by that of specimen 17, which was initially oven-dry, and that of specimens 1, 2, and 3 in Phase 1, which were initially at "as-received" moisture contents.

Specimen 21 changed moderately in k/k_o values with different exposure conditions, which tended to increase slightly during winter exposures. The value of k_o used for this specimen was that of specimen 20, because it was believed the

exposed insulation of specimen 21 had gained moisture hygroscopically before the test exposures were started. The insulation appeared to be at approximately a plateau-condition throughout Phase 2, for the exposure conditions imposed, but it is believed that for longer winter exposures, some vapor protection underneath would be necessary to avoid extremes of the type evidenced by specimen 18. Performance of the insulation with a dense concrete deck underneath is shown by specimens 4, 5, 6, and 20 (the latter initially oven-dried, and later subjected to water additions).

Specimen 22 had no deck, and was oven-dried before installation. Its resistance to vapor permeance, and moisture absorption capacity, were apparently sufficient to prevent significant changes in k/k_o ratio throughout the exposures of Phase 2. It may be noted that specimen 8, installed in an "as-received" condition in Phase 1 and carried without modification through Phase 2, also showed little change in k/k_o ratio, although values are higher under summer conditions than those for specimen 22, presumably because specimen 8 gained during winter conditions B and C some of the moisture initially in the undried concrete deck.

4. Pressure-Relieving Vents.

The use of small pressure-relieving vents through the roofing of specimens having moist permeable insulations had no appreciable effect in reducing the effective conductivity of the insulation. The vents used were sufficient to relieve internal pressures in pervious insulations, but were not ventilating channels through which outdoor air might move as a result of wind forces.

In all specimens in Phase 1, a tubular connection was made between the interior of the insulation and either a manometer or a limp polyethylene balloon of about 0.1 cu ft volume when distended. Observed changes of volume of the balloon as a result of air volume changes in the specimen due to the daily temperature changes were on the order of 75 to 100 cu in., during summer exposure A, for a cellular concrete specimen which had a relatively large void volume. The mercury manometer readings indicated daily changes of internal pressure in specimens for the same period equal to not more than 3 lb per sq ft. Since the specimens to which manometers were attached did not have sheet vapor barriers, it is believed that pressure relief occurred through the dense concrete slab, since otherwise pressure differences as large as 100 to 200 lb per sq ft could be expected for the temperature changes experienced by the insulations.

In view of the breathing action observed with the limp balloons, which was approximately of the magnitude to be expected, an effort was made in Phase 3 to determine if breather-type vents through the roofing would assist in reducing the high k/k_o values obtained with moist insulations. Accordingly, such vents were installed in 10 of the Phase 3 specimens. These specimens, which were installed in oven-dried condition, had restored to them during summer exposure M the amount of moisture removed by the oven-drying process. Fifteen weeks later during winter exposure N, the vents were opened to communicate with the air over the roofing.

The criterion used for evaluating the effect of such vents was that if they had a substantial effect, it would be indicated by a change in the trend of the k/k_o ratios in period M and subsequent periods. Referring to the plotted values of k/k_o for these specimens, no trend in period M existing before the vent was opened was materially changed after it was opened, for any of the specimens. The behavior of the specimens having sheet vapor barriers (35, 42, 43, and 45) in subsequent exposure periods was substantially the same as that prior to opening of the vents. Similarly, the k/k_o ratios for specimens 38, 40, and 41, which had dense concrete decks but no sheet vapor barriers, and which, like specimen 45, had relatively high moisture contents, also showed no significant change as a result of opening the vents. In the case of specimens 34, 37, and 46, which had no dense decks, substantial trends of reduction of k/k_o values existed prior to opening of the vents, and the absence of sharp differences in these trends in the subsequent exposure periods indicates that the vents had little if any beneficial effect of this kind.

A calculation of the probable drying rate of a cellular concrete specimen as a result of the breathing action, based on daily venting of air saturated at the higher mean temperature of the insulation and its replacement by dry air as the specimen cooled (for the summer condition) indicated that years would be required to effect a change in moisture content of only a few percent. The experimental evidence appears to be in accordance with the calculated estimate.

5. Roof Insulating Materials

The roof insulating materials used in this investigation can be separated into a few groupings, those in each group having common characteristics important in connection with moisture problems and the effect on insulating

value of moisture present in the roof construction. There are differences between insulations in each group, but such differences are less important than those between groups.

The first group comprises the insulations that are practically impermeable to vapor or moisture. In this investigation, these were cellular glass and expanded polystyrene.

The second group consists of vapor permeable insulations which are delivered and installed in a substantially-dry condition. These included, in this investigation, corkboard, glass or mineral fiber insulating board, vegetable fiber insulating board, and a compacted-in-place mineral fill insulation.

The third group comprises permeable insulations mixed with water in the process of application, and any of the second group which for any reason contain moisture, when installed, in excess of their normal hygroscopic moisture content. In this investigation, these included three types of light-weight insulating concrete, and insulations of the second group made wet by adding water.

Based on the data obtained in this investigation, the common general characteristics of each group were as summarized below. (Since detailed references to the same experimental data have been made in connection with preceding conclusions, data relevant to the following summarizations are indicated merely by citing the pertinent specimen numbers.)

Group 1. Effective conductivities were substantially equal to those of the dry materials, and were the same for both summer and winter exposure conditions (within the precision of the measurements). Their conductivity did not change with exposure time, under conditions where moisture was available from the dense concrete deck underneath (9, 10).

Group 2. Installed at air-dry or oven-dry moisture contents, over a good vapor barrier, these materials maintained effective conductivities approximately corresponding to those of the dry materials, throughout the duration of the tests (3 vs. 17, 6 vs. 20, 31, 33, 35, 42, 43). Effective conductivities were perceptibly greater under summer exposure conditions than under winter exposure conditions (3, 6, 33, but not 31). There was some evidence that conductivities tended to increase slightly with time, presumably as a result of slow moisture gain through the vapor barrier (33, 35, but not 42 or 43, or 31 as long as it was observed).

Installed over "air-dry" dense concrete decks without a vapor barrier, the insulations apparently gained enough moisture from the decks in a relatively short time to cause perceptible increases in effective conductivity during summer exposure conditions, but not during winter conditions (1, 2, 4, 5, 7, 8). Effective conductivities increased slowly with exposure time, the increases becoming observable during both summer and winter conditions (1, 4, 8).

Upon addition of appreciable water to these insulations, effective conductivity values increased markedly, and were substantially greater during summer exposure conditions than during winter conditions. Conductivity values with water added in the amount of 10 percent of the insulation volume were from 50 to 100 percent higher than values dry, under the summer exposure conditions, and from 0 to 20 percent higher under the winter conditions (17, 20). The specimens so treated had oven-dried dense concrete decks but no vapor barriers; if there had been vapor barriers to impede transfer of some of the added water to the concrete deck, the effective conductivities would almost certainly have been still larger.

Installed without a dense deck, or a vapor barrier, so that the insulation was exposed to the air underneath, these insulations were subject to apparent gains of moisture during the winter exposure conditions and losses during summer exposure conditions, as indicated by changes in effective conductivity values (18, 21, but not 22). These changes were apparently dependent on the permeability and moisture absorptive capacity of the insulation. (See discussion under Conclusion 3, pages 18-19.)

The essential conclusions concerning the permeable insulations of Group 2 are (a) that when dry, and kept dry by a vapor barrier, they yield approximately their dry-value insulating effect, (b) that with a vapor barrier, and more so when placed directly on a dense concrete deck without a vapor barrier, they tend to decrease slowly in insulating value (especially for summer conditions), and (c) that if they are wetted, as by a leak through the roofing, or are installed with excessive moisture, their insulating effect is very seriously reduced (especially for summer conditions), and is thereafter kept indefinitely at reduced values as a result of the moisture transfer resistance of a dense concrete deck and/or of the vapor barrier usually placed under these insulations. Except for insulations of this kind of quite low permeability and high moisture absorptiveness, they should not be used directly exposed to the air underneath.

Group 3. The water-mixed insulations of this group (insulating light-weight concretes) had free moisture contents between 20 and 60 percent by weight after several days of air drying (Table VI). When used as specimens at these air-dry moisture contents, their insulating effects were from two to four times less than their observed values when oven-dry, depending on whether they were being subjected to winter or summer exposure conditions, respectively (34, 37, 38, 40, 41, 45, 46). When the insulations were placed on dense concrete decks, the impaired insulating values continued almost without significant improvement, throughout the period of observation (38, 40, 41, 45). The lack of improvement is considered due to the effective resistance or impedance of the dense concrete decks to moisture escape from the undersurface of the insulation.

The same insulations, exposed to the air below without a dense concrete deck underneath, increased rapidly in insulating effect during exposure to a few alternations of the imposed summer and winter exposure conditions (34, 37, 46). In one case, the insulation attained, during the period of observation, an apparent plateau-value of insulating effect scarcely different from that of the substantially dry material, although its moisture content had been increased to about 63 percent by weight at the start (37). Similarly-treated specimens of other insulating concretes without decks showed an approach to the same behavior, but at a less rapid rate (34, 46).

Specimens of these insulations, without decks, installed in an oven-dried condition, decreased perceptibly in insulating value when subjected to alternations of the test summer and winter exposures, and tended to approach, from a dry initial condition (24, 25, 36), the approximate plateau-value of insulating effect being reached from the other extreme by similar insulations to which water had been added (34, 37, 30, 46, respectively).

VIII. REMARKS AND COMMENTS

A. Test Conditions.

Surprisingly large values of effective conductivity were obtained in this investigation for moist insulations during the imposed summer exposure condition. In many cases, they were so much larger than the values obtained for the same materials when dry that it seems necessary to attribute a large part of the increase to latent heat transfer involving evaporation of moisture at one place, its migration as vapor to a cooler region, and its condensation there.

In a non-capillary permeable insulating material subjected to a steady temperature gradient in one direction, this distillation process usually results in a concentration of the moisture in the cooler parts of the insulation. Thus, most of the insulation contains only the moisture corresponding to its hygroscopicity at humidities lower than 100 percent, and the over-all effective conductivity is only moderately increased by the loss of thermal resistance of the wetter portion. This was, in fact, approximately the result observed during the winter conditions of this investigation for insulations containing moderate amounts of moisture.

Under the imposed summer conditions of this investigation, however, the daily simulated solar heating caused daily reversals of temperature gradient in the insulation and thus, by distillation back and forth in each day, kept probably the whole thickness of the insulation at a condition of sufficient free water content to allow substantial latent heat transfer. This process affords reason to believe that the solar heating period in the imposed summer exposure condition was the essential cause for the large effective conductivities observed with moist insulations. In this connection it should be noted that for substantially dry insulations, effective conductivities were approximately the same during the imposed summer and winter conditions (i.e., when there were, and when there were not, daily temperature gradient reversals, respectively), and therefore that heat capacity effects at the times when conductivities were determined were not the cause.

Whether the very high effective conductivities indicated for moist permeable insulations in this investigation actually occur in roofs in service - in other words, whether this finding is important practically - depends therefore upon whether daily temperature gradient reversals do occur in roof insulations in service, during summer or other seasons.

There is little doubt that in summer, at least, in most areas of this country, the top surface of an insulated roof is considerably hotter than its undersurface during the sun-hours of the day, and that at night the undersurface of the roof is warmer, for buildings not air conditioned, and possibly also for air conditioned buildings, than its top surface, since the latter is subject to comparatively rapid cooling by the night air and by radiation to a clear sky. Accordingly, one must conclude that free moisture (that in excess of the hygroscopic capacity of an insulation) very seriously impairs the insulating effect of a permeable roof insulation in service under summer exposure conditions. It is felt, in fact, that if the investigation had been conducted without a simulated daily solar heating period causing temperature gradient reversals, this practically-important finding might easily have been missed.

It is pointed out that in this investigation, effective conductivities were obtained during the substantially steady temperature conditions existing just before the onset of the solar heating period. However, during the solar heating period, and subsequently while the insulation was regaining the steady temperature conditions mentioned above, considerably steeper temperature gradients must have existed within the insulation. Consequently, latent heat transfer must have been occurring at greater rates at these times than at the time measurements were made. Because of heat capacity effects, it is not feasible to estimate the over-all effective conductivity of the insulation during the times of changing temperatures. Nevertheless, it seems reasonable that at such times over-all effective conductivities of moist insulations were not less than, and that probably they were greater than, the values at the time observations were made. In other words, the indicated effective conductivities are probably less than the average values over the 24-hour daily cycle.

One further point should be made concerning the exposure conditions used. The roofing surface temperatures were probably reasonably typical for roofs in service, but the 79°F dewpoint temperature maintained under the specimens throughout most of the tests undoubtedly was higher than typical for ordinary buildings. More typical maximum dewpoints would probably not exceed 65°F in summer and 40°F in winter. The effect of the 79°F dewpoint in these tests was in the direction of greater gain, and smaller loss, of moisture by a specimen through its undersurface, than would occur at lower under-roof dewpoints. The effect was therefore to increase to some extent the "plateau-values" of effective

conductivity discerned in these results. The effect on values obtained for specimens containing considerable free moisture was probably small, but the inferred "drying-rates" observed would probably have been greater with lower under-roof dewpoints. Some slight evidence of increased drying-rates was obtained for specimens 34, 37, and possibly 45, during weeks 151-156 when the bottom air dewpoint was lowered to 60°F.

B. The Moisture Problem.

As mentioned in the Introduction (pages 1-2) there are several avenues by which excessive moisture can become present in an insulated roof construction in service. The degree to which precipitation or roofing faults or punctures during construction may contribute moisture is an imponderable, or peculiar to each application and its history. Possibly in the same category is the moisture content of a dense concrete roof deck on which an insulation may be placed without a vapor barrier - but almost certainly, such a deck contains some excess moisture.

Insulations of appreciable hygroscopicity very probably contain moderate amounts of moisture when installed, depending on the ambient relative humidity. If the average moisture content is not well below the maximum hygroscopic capacity of the insulation, it is likely that its concentration by a temperature gradient would yield "free moisture" in parts of it, and that latent heat transfer effects would be appreciable with reversing temperature gradients. It must be added that even hygroscopic moisture redistributes under a temperature gradient, and that for permeable insulations of high hygroscopicity some latent heat transfer will occur, at least while temperatures are changing.

Water-mixed insulations plainly must be considered as containing excess moisture when roofed over. In view of the serious effects of this moisture, the only practical recourse appears to be to arrange matters so that these initially-moist insulations will dry out in a comparatively short time in service. As discussed below (C), this appears to be a possibility.

The most difficult problem is that of in-leakage of water through leaks in the roofing. The possible quantity is an imponderable, except that usually a leak is not suspected until water has appeared at the undersurface of the roof. Apart from accidental leaks in new roofs, it must be regarded as a practical certainty that eventually leaks will occur as the roofing ages. In such event, maintenance of satisfactory insulation performance would require either that the insulation

be removed and dried or replaced, or that the roof construction be capable of adequate self-drying in service. In this respect, insulations wetted by leaks and the water-mixed insulations are allied, and a common solution is required.

C. Self-Drying Roofs.

By a self-drying roof is meant an insulated roof construction which under its in-service exposure conditions will expel excessive moisture from its insulation in a relatively short time, i.e., in one summer or one year, and which subsequently will yield an insulating effect approximating that to be expected with the insulation dry. It is assumed that the moisture expulsion will take place through the undersurface of the roof, rather than through ventilating channels or ports in the roof (which may constitute an effective means of drying a wet roof construction).

In this investigation, and for the exposure conditions used, it was found that wet insulations over vapor barriers, or on dense concrete decks, dried very slowly if at all. On the other hand, roof specimens of thick monolithic insulating concrete exposed to the under-roof air dried quite substantially in 20 or 30 weeks of the imposed summer conditions. In one case, the insulation attained, after being wetted, the performance it had when installed oven-dried.

It is necessary to appreciate clearly what has been shown - namely, and merely, that a dense concrete deck under an insulating concrete impedes its necessary drying, and that without this deck satisfactory drying occurs. Apart from the important practical questions of the strength, and feasibility, of a roof of monolithic insulating concrete, one must consider that a form-board or decking is necessary to pour the roof. The question enlarges therefore to a consideration of practical permanent deckings other than dense concrete, and what properties these must have so as not to impede drying, or allow excessive moisture gain under winter conditions. It would in fact be desirable for a number of reasons to investigate self-drying designs for a wider selection of insulations than only the water-mixed insulating concretes, in view of the ubiquitous problem of roof leaks.

At present, understanding of the mechanisms of movement of moisture as water or vapor in materials is quite incomplete. When a problem involves differences in temperatures, and changing differences, as in the case of roofs, our present knowledge is not adequate for the complexities

involved, although it does indicate possible fruitful lines of attack. For instance, the impedance of a dense concrete deck for outward moisture passage has been thought here to be possibly a result of the relatively small temperature gradient in it because of its high conductivity. If this should be so, a deck material of low conductivity and probably of moderate permeability might be much more satisfactory for the construction of self-drying roofs. Because of the complexity of the total problem, and the need for temperature regimes simulating those of a roof construction in service, however, it is believed necessary at present to examine the various possibilities by means of roof exposure tests.

TABLE I - Description of Roof Specimens 1-15, Phase 1--Exposure Periods A-D

Specimen Construction

Dense concrete deck[a,b] - 3 x 18 x 18 in.

Optional vapor barrier - 0.004-in. polyethylene sheet.

Insulation - of thickness to yield a calculated U-value for the specimen of 0.12 Btu/hr ft^2 deg F on basis of conductivity of dry insulation. Insulations were installed at the moisture contents existing after laboratory storage.

Roofing - 5-plies hot-mopped asphalt-saturated 15-lb roofing felt, pre-assembled, and adhered to top of insulation with hot asphalt.

Details of Specimens

Spec. No.	Type of Insul.	Insul. Thickness, in.	Vapor Barrier	Internal Pressure Connection	Insulation Properties, Oven-Dry: Density lb/ft^3	Insulation Properties, Oven-Dry: Th. Cond. at 75°F Btu/hr ft^2(F/in.)
1	Glass Fib. Bd.	1 3/4	No	Balloon	12.0	0.27
2	Glass Fib. Bd.	1 3/4	No	Manometer	"	"
3	Glass Fib. Bd.	1 3/4	Yes	Balloon	"	"
4	Roof Insul. Bd.	2 1/4	No	Balloon	12.3	0.33
5	Roof Insul. Bd.	2 1/4	No	Manometer	"	"
6	Roof Insul. Bd.	2 1/4	Yes	Balloon	12.3	0.33
7	Corkboard	1 3/4	No	Balloon	8.1	0.29
8	Corkboard	1 3/4	No	Manometer	"	"
9	Cellular Glass	2 1/2	No	Balloon	9.1	0.41
10	Cell. Polystyrene[c]	3	No	Balloon	1.8	0.29
11	Perlite Conc.[d]	5 3/4	No	Balloon	30.0	0.84
12	Vermiculite Conc.[e]	5 3/4	No	Balloon	29.3	0.98
13	Cellular Conc.[f]	5 11/16	No	Balloon	30.1	0.90
14	Cellular Conc.[f]	5 11/16	No	Manometer	"	"
15	Cellular Conc.[f]	5 11/16	Yes	Balloon	"	"

(a) Specimens 1 to 15 each had a tube insert in the concrete deck for an internal pressure connection (see (13), Figure 4).

(b) Mix: 100 lb Type I cement, 260 lb sand, 390 lb gravel (3/4-in. max.), 58 lb water. Compressive strength 4110-5075 psi, (28 days, 6 x 12-in. cyl.), dry density 145 lb/ft^3.

(c) The estimated U-value of Specimen 10 was 0.09 Btu/hr ft^2 deg F.

(d) Mix: 94 lb Type III cement, 6 ft^3 perlite, 12 gal. water. Compressive strength 340 psi, for 6 x 12-in. cylinders at 7 days (5 days air-dry).

(e) Mix: 94 lb Type III cement, 6 ft^3 vermiculite, 18 gal. water. Compressive strength 220 psi, for 6 x 12-in. cylinders at 7 days (5 days air-dry).

(f) Mix: 94 lb Type III cement, 6.2 lb foam, 46.4 lb water. Compressive strength 185-270 psi, for 6 x 12-in. cylinders at 7 days (5 days air-dry).

TABLE II

Description of Roof Specimens 16-30
Phase 2--Exposure Periods E-J

Specimen Constructions

For 11 of the Phase 2 specimens, the materials were those used in the corresponding Phase 1 specimens having a specimen number less by 15 than the number of the Phase 2 specimen. Four of the 11 were continued without change or modification from Phase 1, and for this reason are referred to in Results by their original numbers (1, 4, 8, 13). Seven of the 11 were modified by being oven-dried, and 2 of the 7 were installed with the dense concrete slab removed. As noted, 4 of the Phase 2 specimens were fabricated with previously un-used insulating materials.

During exposure periods F, G, and H, water was added to the insulations of 6 of the initially oven-dried specimens, in successive increments of 1, 2, and 7 percent by volume.

No specimen of Phase 2 had a vapor barrier under the insulation, and internal pressure connection tubes were not used. All Phase 2 specimens were oven-dried at the conclusion of exposure period J.

Details of Specimens

Spec. No.	Type of Insul.	Insul. Thickness in.	Dense Deck Used	Oven-Dried Before Expos. E	Water Added to Insul. in Expos. F,G,H
(16)1	Glass Fib. Bd.	1 3/4	Yes	No	No
17	Glass Fib. Bd.	1 3/4	Yes	Yes	Yes
18	Glass Fib. Bd.	1 3/4	No	Yes	No
(19)4	Roof Insul. Bd.	2 1/4	Yes	No	No
20	Roof Insul. Bd.	2 1/4	Yes	Yes	Yes
21	Roof Insul. Bd.	2 1/4	No	Yes	No
22	Corkboard[a]	1 3/4	No	Yes	No
(23)8	Corkboard	1 3/4	Yes	No	No
24	Perlite Conc.[b]	6	No	Yes	No
25	Vermiculite Conc.[c]	6	No	Yes	No
26	Perlite Conc.	5 3/4	Yes	Yes	Yes
27	Vermiculite Conc.	5 3/4	Yes	Yes	Yes
(28)13	Cellular Conc.	5 11/16	Yes	No	No
29	Cellular Conc.	5 11/16	Yes	Yes	Yes
30	Cellular Conc.	5 11/16	No	Yes	Yes

(a) New sample of corkboard, taken from same carton as the other corkboard insulations.
(b) New perlite conc. insul.; same mix as for Spec. 11.
(c) New vermiculite conc. insul.; same mix as for Spec. 12.
(d) New cellular conc. insul.; same mix as for Spec. 13-15.

TABLE IV

Specimen Weight Data
Phase 1--Specimens 1-15

Spec. Wt[b], lb   Change in   Final Moisture

Specimen Construction

All specimens were newly constr
Phases 1 and 2. Two new types of in

All specimens were oven-dried p
selected specimens early in exposure

Details of Specimens

Spec. No.	Type of Insul.	Insul. Thickness in.	I D 1
31	Glass Fib. Bd.	1 3/4	
32	All-Weather Crete	2 7/8	
33	Roof Insul. Bd.	2 3/8	
34	Perlite Conc.[c]	6	
35	Roof Insul. Bd.	2 3/8	
36	Cellular Conc.[d]	6	
37	Vermiculite Conc.[e]	6	
38	Perlite Conc.[c]	6 1/8	
39	Cellular Conc.[d]	6	
40	Vermiculite Conc.[e]	6 1/8	
41	Cellular Conc.[d]	6	
42	Glass Fib. Bd.	1 3/4	
43	Fesco Bd.	2 1/2	
44	Cellular Conc.[d]	6	
45	Cellular Conc.[d]	6	
46	Cellular Conc.[d]	5 13/16	

(a) Moisture content of conc. Insu
Moisture content of dense deck
(b) Average moisture content for i
(c) Mix: 94 lb Type III cement, 6
(d) Mix: 94 lb Type III cement, 8
(e) Mix: 94 lb Type III cement, 6
(f) Original moisture content was
weight of insulation.

TABLE III

Description of Roof Specimens 31-46
Phase 3--Exposure Periods K-Q

Specimen Construction

All specimens were newly constructed, using materials from the same stock as those used for specimens in Phases 1 and 2. Two new types of insulating material were used in two specimens (32 and 43).

All specimens were oven-dried prior to exposure period K; the water removed by drying was restored to selected specimens early in exposure period M.

Details of Specimens

Spec. No.	Type of Insul.	Insul. Thickness in.	Insul. Properties, Oven-Dry: Density lb/ft^3	Insul. Properties, Oven-Dry: Th. Cond. at 75°F Btu/hr ft^2(F/in.)	Dense Deck Used	Vapor Barrier Used	Vent Through Roofing	Moisture Content of Insul. before Drying[a], %	Original Moisture in Insulation Restored
31	Glass Fib. Bd.	1 3/4	12.0	0.27	Yes	Yes	No	Negligible	No
32	All-Weather Crete	2 7/8	23.1	0.53	Yes	(Primed)	Yes	"	Yes[f]
33	Roof Insul. Bd.	2 3/8	12.3	0.33	Yes	Yes	No	7.3	No
34	Perlite Conc.[c]	6	30.0	0.84	No	No	Yes	39.1[a]	Yes
35	Roof Insul. Bd.	2 3/8	12.3	0.33	Yes	Yes	Yes	4.9	Yes
36	Cellular Conc.[d]	6	30.1	0.90	No	No	No	19.7[a]	No
37	Vermiculite Conc.[e]	6	29.3	0.98	No	No	Yes	63.4[a]	Yes
38	Perlite Conc.[c]	6 1/8	30.0	0.84	Yes	No	Yes	12.8[b]	Yes
39	Cellular Conc.[d]	6	30.1	0.90	Yes	Yes	No	35.2[a]	No
40	Vermiculite Conc.[e]	6 1/8	29.3	0.98	Yes	No	Yes	20.5[b]	Yes
41	Cellular Conc.[d]	6	30.1	0.90	Yes	No	Yes	10.1[b]	Yes
42	Glass Fib. Bd.	1 3/4	12.0	0.27	Yes	Yes	Yes	Negligible	Yes
43	Fesco Bd.	2 1/2	9.6	0.36	Yes	Yes	Yes	2.7	Yes
44	Cellular Conc.[d]	6	30.1	0.90	Yes	No	No	10.4[b]	No
45	Cellular Conc.[d]	6	30.1	0.90	Yes	Yes	Yes	26.5[a]	Yes
46	Cellular Conc.[d]	5 13/16	30.1	0.90	No	No	Yes	20.8[a]	Yes

(a) Moisture content of conc. Insul. was measured at 7 days (1 day in mold, 3 in damp-room, 3 in lab. air). Moisture content of dense deck slabs at 7 days averaged 3-4% of dry weight.
(b) Average moisture content for insulation and dense concrete deck together.
(c) Mix: 94 lb Type III cement, 6 ft^3 perlite, 14 gal. water.
(d) Mix: 94 lb Type III cement, 8.4 lb foam, 5.2 gal. water.
(e) Mix: 94 lb Type III cement, 6 ft^3 vermiculite, 19 gal. water.
(f) Original moisture content was negligible; water was added in exposure period O to equal 40 percent of dry weight of insulation.

TABLE IV

Specimen Weight Data
Phase 1--Specimens 1-15

Spec. No.	Type of Insul.	Spec. Wt[b], lb Start	End	Oven-dry	Change in Spec. Wt, lb	Final Moisture Content, %[a] Insul.	Conc. Deck
1	Glass Fib. Bd.	96.6	-[c]	-	-	-	-
2	Glass Fib. Bd.	97.3	98.3	94.2	+1.0	-	-
3	Glass Fib. Bd.	97.6	95.2	92.3	-2.4	0	3.2
4	Roof Insul. Bd.	98.6	-	-	-	-	-
5	Roof Insul. Bd.	99.2	100.3	96.2	+1.1	-	-
6	Roof Insul. Bd.	99.3	98.5	95.3	-0.8	6.0	3.2
7	Corkboard	92.9	93.9	91.3	+1.0	1.5	2.7
8	Corkboard	93.6	-	-	-	-	-
9	Cellular Glass	95.5	96.1	94.3	+0.6	0	2.3
10	Cell. Polystyrene	91.1	91.8	89.9	+0.7	0	2.4
11	Perlite Conc.	130.0	130.6	118.2	+0.6	-	-
12	Vermiculite Conc.	140.1	140.6	120.3	+0.5	-	-
13	Cellular Conc.	130.6	-	-	-	-	-
14	Cellular Conc.	130.9	132.0	122.0	+1.1	-	-
15	Cellular Conc.	130.4	129.4	122.8	-1.0	14.3	2.8

(a) Percent of oven-dry weight.
(b) Specimen weight includes from 5 to 9 lb due to the roofing, heat flow meter, seals, and wrappings.
(c) A dash in the table indicates that data were not taken at this time because the specimen was not dis-assembled at the conclusion of Phase 1. Specimens 1, 4, 8, and 13 were carried over to Phase 2 and remained installed in the apparatus at the end of Phase 1.

TABLE V

Specimen Weight Data
Phase 2--Specimens 16-30

Spec. No.	Type of Insul.	Spec. Wt[b], lb Start[a]	Spec. Wt[b], lb End	Change in Spec. Wt, lb	Water Added lb	Exposure Gain (or Loss) lb	Final Moisture Content, %[c] Insul.	Final Moisture Content, %[c] Conc. Deck
1(16)	Glass Fib. Bd.	(94.9)[d]	96.6	0	0	0	0	2.0
17	Glass Fib. Bd.	95.3	96.6	+1.3	2.0	-0.7	11.3	1.2
18	Glass Fib. Bd.	9.2	11.8	+2.6	0	+2.6	54.7	X
4(19)	Roof Insul. Bd.	(96.4)[d]	99.2	+0.6	0	+0.6	13.8	2.6
20	Roof Insul. Bd.	96.5	98.7	+2.2	2.6	-0.4	15.0	2.8
21	Roof Insul. Bd.	10.2	12.8	+2.6	0	+2.6	48.2	X
22	Corkboard	7.2	7.5	+0.3	0	+0.3	1.4	X
8(23)	Corkboard	(91.6)[d]	94.2	+0.6	0	+0.6	1.7	2.5
24	Perlite Conc.	41.9	45.0	+3.1	0	+3.1	11.6	X
25	Vermiculite Conc.	41.8	45.7	+3.9	0	+3.9	9.6	X
26	Perlite Conc.	120.3	125.5	+5.2	6.7	-1.5	16.6	2.3
27	Vermiculite Conc.	123.1	128.9	+5.8	6.9	-1.1	16.2	1.6
13(28)	Cellular Conc.	(123.5)[d]	131.2	+0.6	0	+0.6	15.5	3.5
29	Cellular Conc.	124.2	130.1	+5.9	6.7	-0.8	15.5	2.3
30	Cellular Conc.	38.1	44.9	+6.8	6.8	0	21.7	X

(a) Oven-dried.
(b) Specimen weight includes from 4 to 9 lb due to the roofing, heat flow meter, seals, and wrappings.
(c) Percent of oven-dry weight. X in table indicates specimens with no dense concrete deck.
(d) These specimens were carried over unchanged from Phase 1, and therefore their final and oven-dry weights were determined only at the end of Phase 2.

TABLE VI

Specimen Weight Data
Phase 3--Specimens 31-46

Spec. No.	Type of Insul.	Spec. Wt[b], lb Start[a]	Spec. Wt[b], lb End	Change in Spec. Wt, lb	Water Added lb	Exposure Gain (or Loss) lb	Final Moisture Content, %[c] Insul.	Final Moisture Content, %[c] Conc.	Moisture Content Before Drying, %[c,d] Insul.	Moisture Content Before Drying, %[c,d] Conc.
31	Glass Fib. Bd.	91.4	92.1	0.7	0	+0.7	0.55	0.83	Neglig.	2.8
32	All-Weather Crete	103.3	107.4	4.1	5.1	-1.0	28.3	0.62	0	3.7
33	Roof Insul. Bd.	90.8	91.2	0.4	0	+0.4	5.2	0.2	7.3	2.9
34	Perlite Conc.	36.6	44.8	8.2	12.6	-4.4	21.7	X	39.1	X
35	Roof Insul. Bd.	89.5	90.5	1.0	0.26	+0.74	7.5	0.25	4.9	4.2
36	Cellular Conc.	39.9	43.1	3.2	0	+3.2	6.7	X	19.7	X
37	Vermiculite Conc.	33.6	37.0	3.4	18.6	-15.2	7.7	X	63.4	X
38	Perlite Conc.	120.4	129.6	9.2	14.9	-5.7	26.6	1.6	12.8[e]	-
39	Cellular Conc.	118.3	118.6	0.3	0	+0.3	1.2	0.76	35.2	3.6
40	Vermiculite Conc.	115.9	135.6	19.7	23.0	-3.3	50.4	4.2	20.5[e]	-
41	Cellular Conc.	121.5	132.5	11.0	11.7	-0.7	19.6	1.9	10.1[e]	-
42	Glass Fib. Bd.	92.23	92.3	0.07	0.08	-0.01	0.57	0.83	Neglig.	3.3
43	Fesco Bd.	89.3	89.8	0.5	0.09	+0.41	3.2	0.7	2.1	4.1
44	Cellular Conc.	121.1	121.2	0.1	0	+0.1	2.5	0.17	10.4[e]	-
45	Cellular Conc.	120.2	127.9	7.7	8.4	-0.7	16.6	0.5	26.5	3.9
46	Cellular Conc.	39.2	44.8	5.6	7.3	-1.7	9.3	X	20.8	X

(a) All specimens were oven-dried when installed.
(b) Specimen weight includes from 4 to 6 lb due to the roofing, heat flow meter, seals, and wrappings.
(c) Percent of oven-dry weight. X in table indicates specimens with no dense concrete deck.
(d) Measured at 7-day age (3 days air-dry) before drying in oven at 215°F.
(e) Value is for combined insulation and dense concrete slab intimately bonded.

AIR TEMPERATURE WAVE FORMS TO SIMULATE SOLAR EFFECT

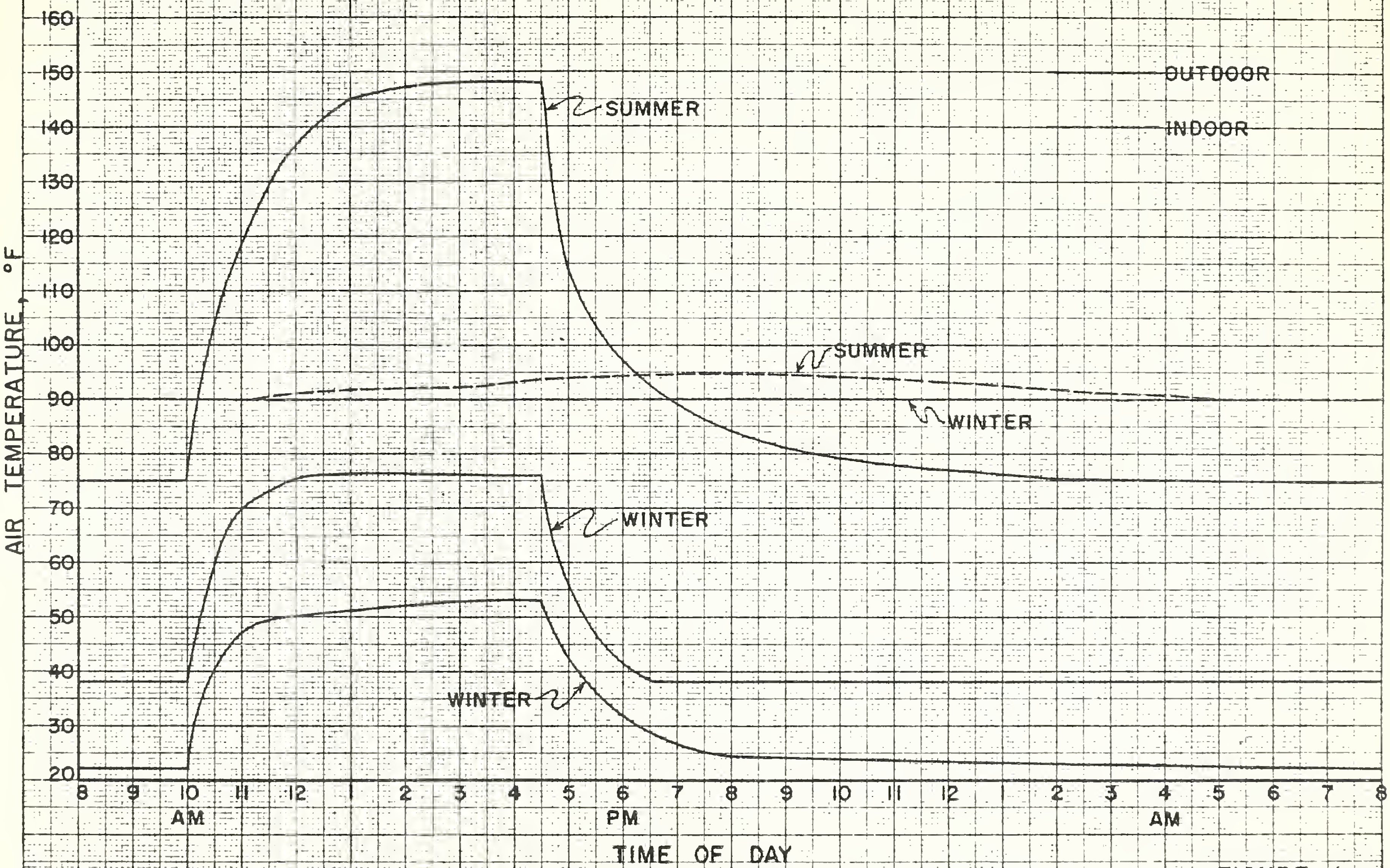
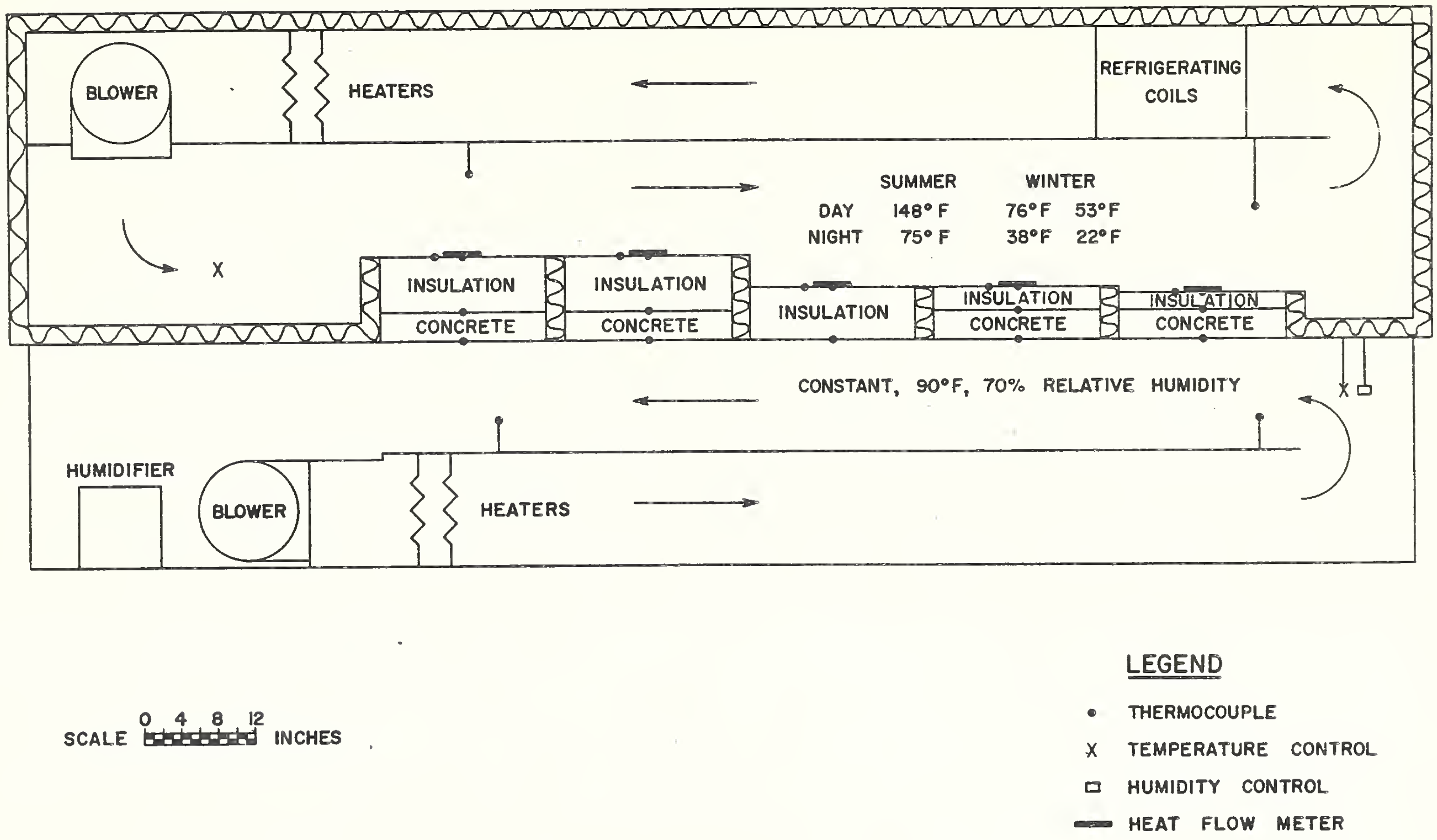


FIGURE 1.



ROOF DECK INSULATION

FIGURE 2.

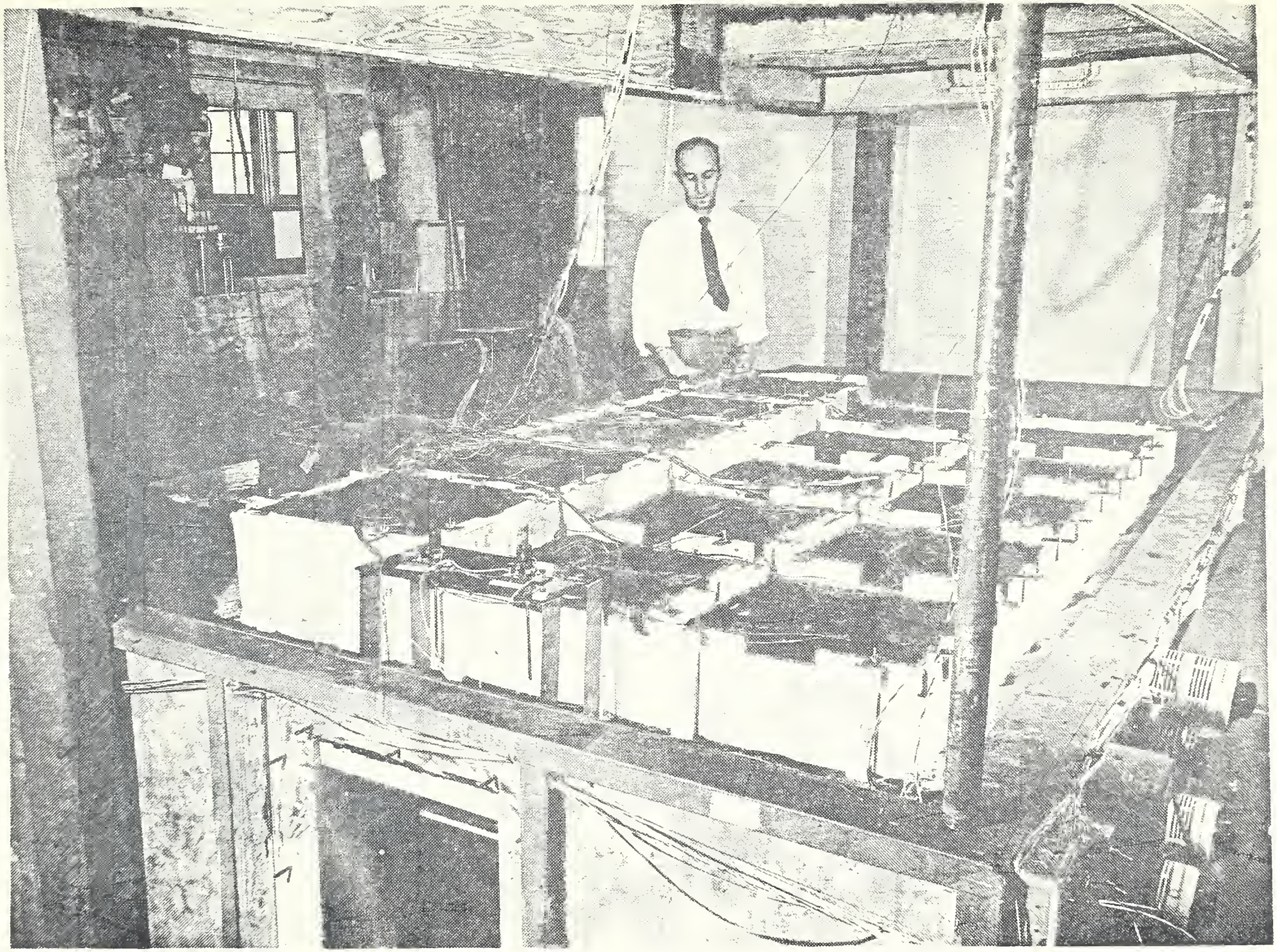
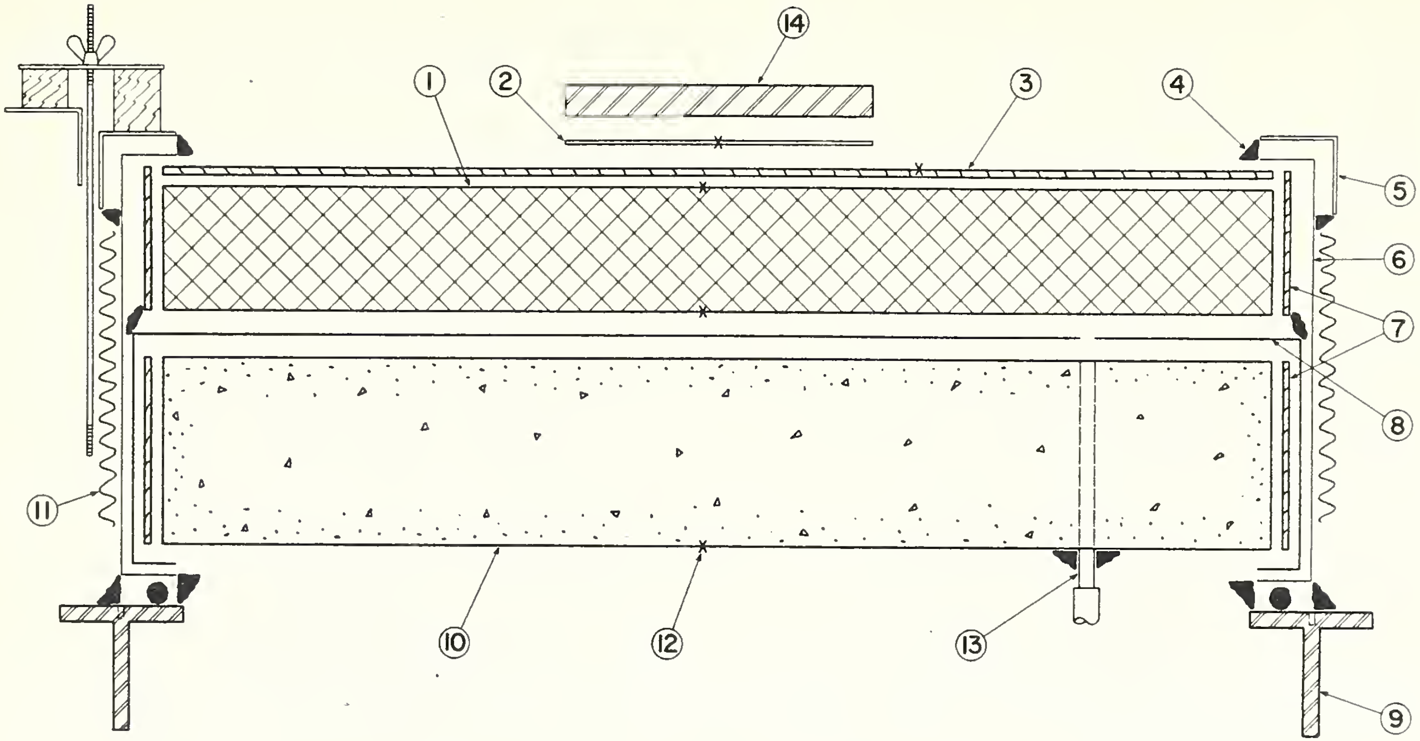


FIGURE 3.



1. INSULATION SPECIMEN
2. HEAT FLOW METER
3. 5-PLY BUILT UP ROOFING
4. MASTIC
5. ALUMINUM ANGLE ABOUT PERIPHERY
6. SARAN PLASTIC FILM WRAPPING
7. ASPHALT EDGE SEAL
8. VAPOR BARRIER
9. STEEL FRAME SUPPORT
10. DENSE CONCRETE, 145 pcf
11. EDGE INSULATION
12. THERMOCOUPLE
13. TUBING INSERT
14. STEEL BLOCK

SPECIMEN SCHEMATIC

FIGURE 4.

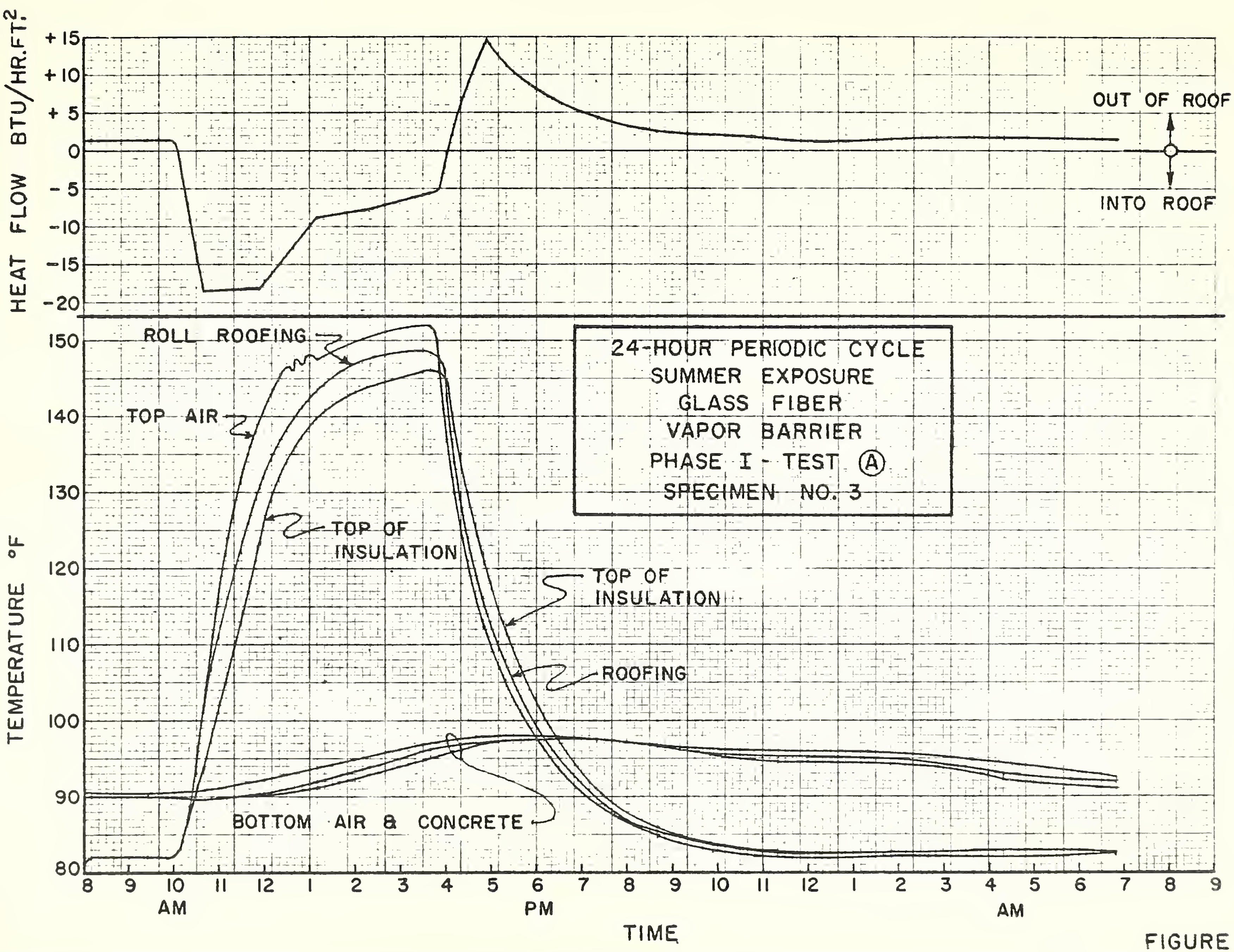

HEAT FLOW BTU/HR.FT.²
+15
+10
+5
0
-5
-10
-15
-20
OUT OF ROOF
INTO ROOF
TEMPERATURE °F
150
140
130
120
110
100
90
80
ROLL ROOFING
TOP AIR
TOP OF INSULATION
TOP OF INSULATION
ROOFING
BOTTOM AIR & CONCRETE
24-HOUR PERIODIC CYCLE
SUMMER EXPOSURE
GLASS FIBER
VAPOR BARRIER
PHASE I - TEST Ⓐ
SPECIMEN NO. 3
8 9 10 11 12 1 2 3 4 5 6 7 8 9 10 11 12 1 2 3 4 5 6 7 8 9
AM
PM
AM
TIME

FIGURE 5.

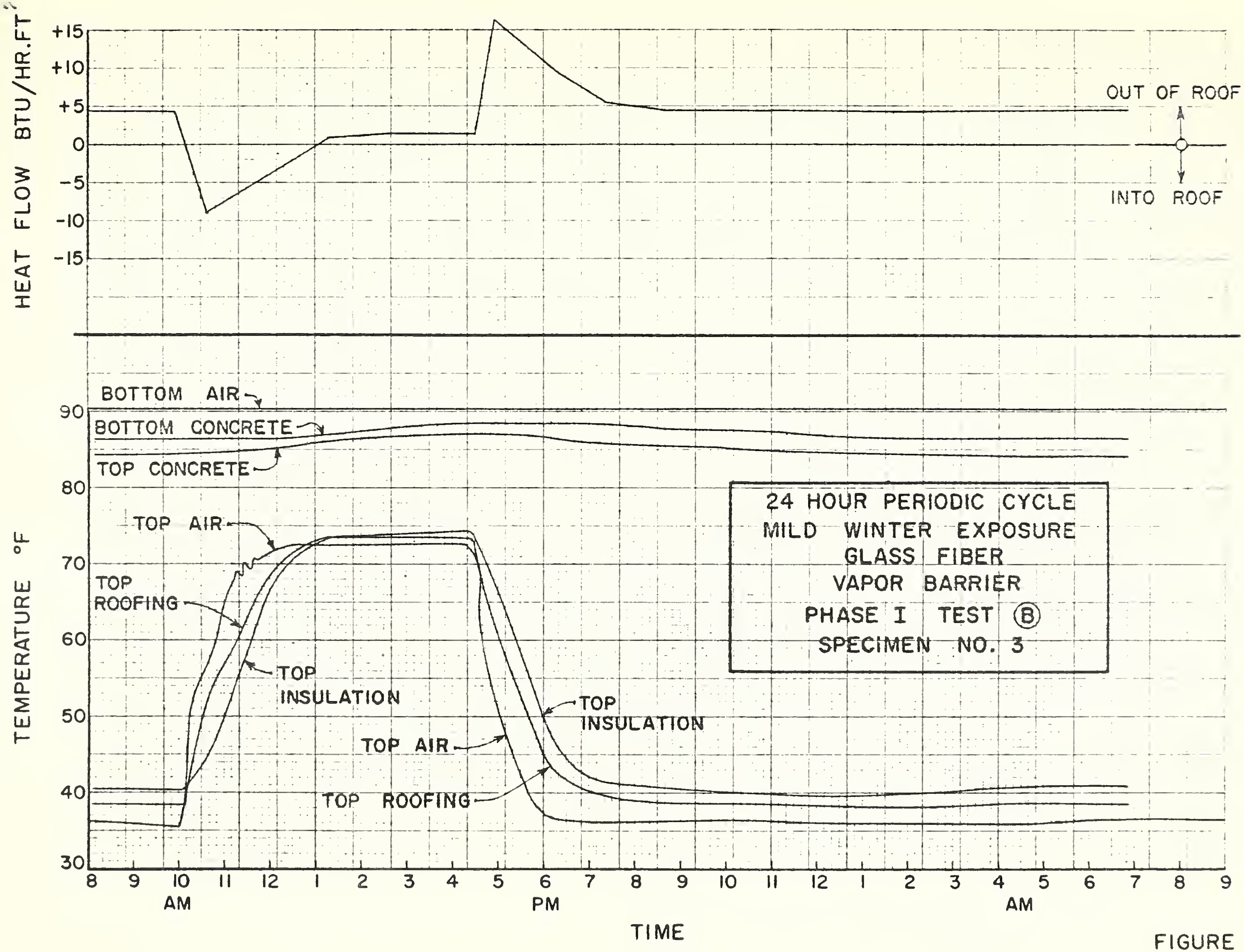

HEAT FLOW BTU/HR.FT²
+15
+10
+5
0
-5
-10
-15
OUT OF ROOF
INTO ROOF
TEMPERATURE °F
90
80
70
60
50
40
30
BOTTOM AIR
BOTTOM CONCRETE
TOP CONCRETE
TOP AIR
TOP ROOFING
TOP INSULATION
TOP AIR
TOP INSULATION
TOP ROOFING
24 HOUR PERIODIC CYCLE
MILD WINTER EXPOSURE
GLASS FIBER
VAPOR BARRIER
PHASE I TEST (B)
SPECIMEN NO. 3
8 9 10 11 12 1 2 3 4 5 6 7 8 9 10 11 12 1 2 3 4 5 6 7 8 9
AM
PM
AM
TIME

FIGURE 6.

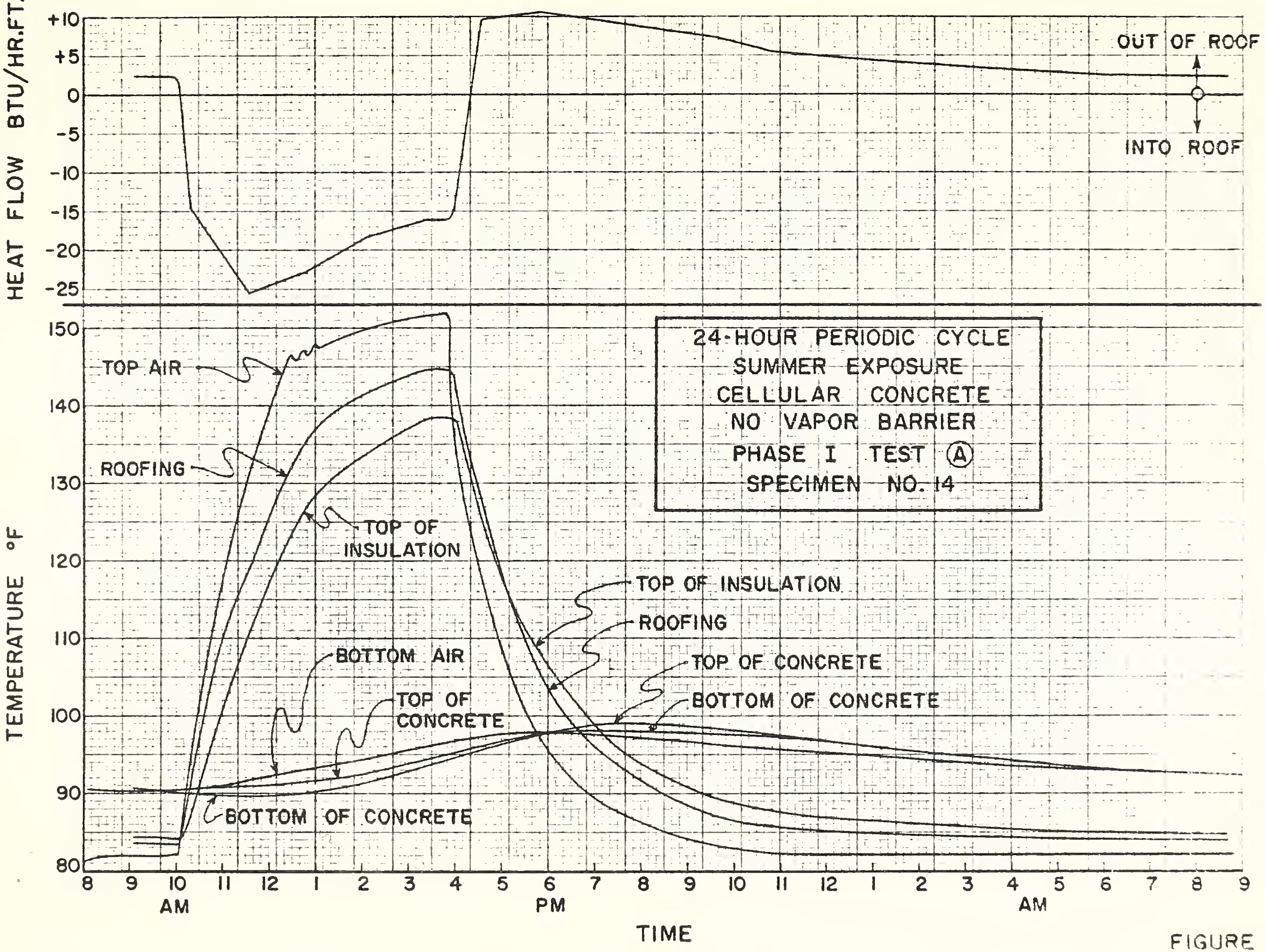
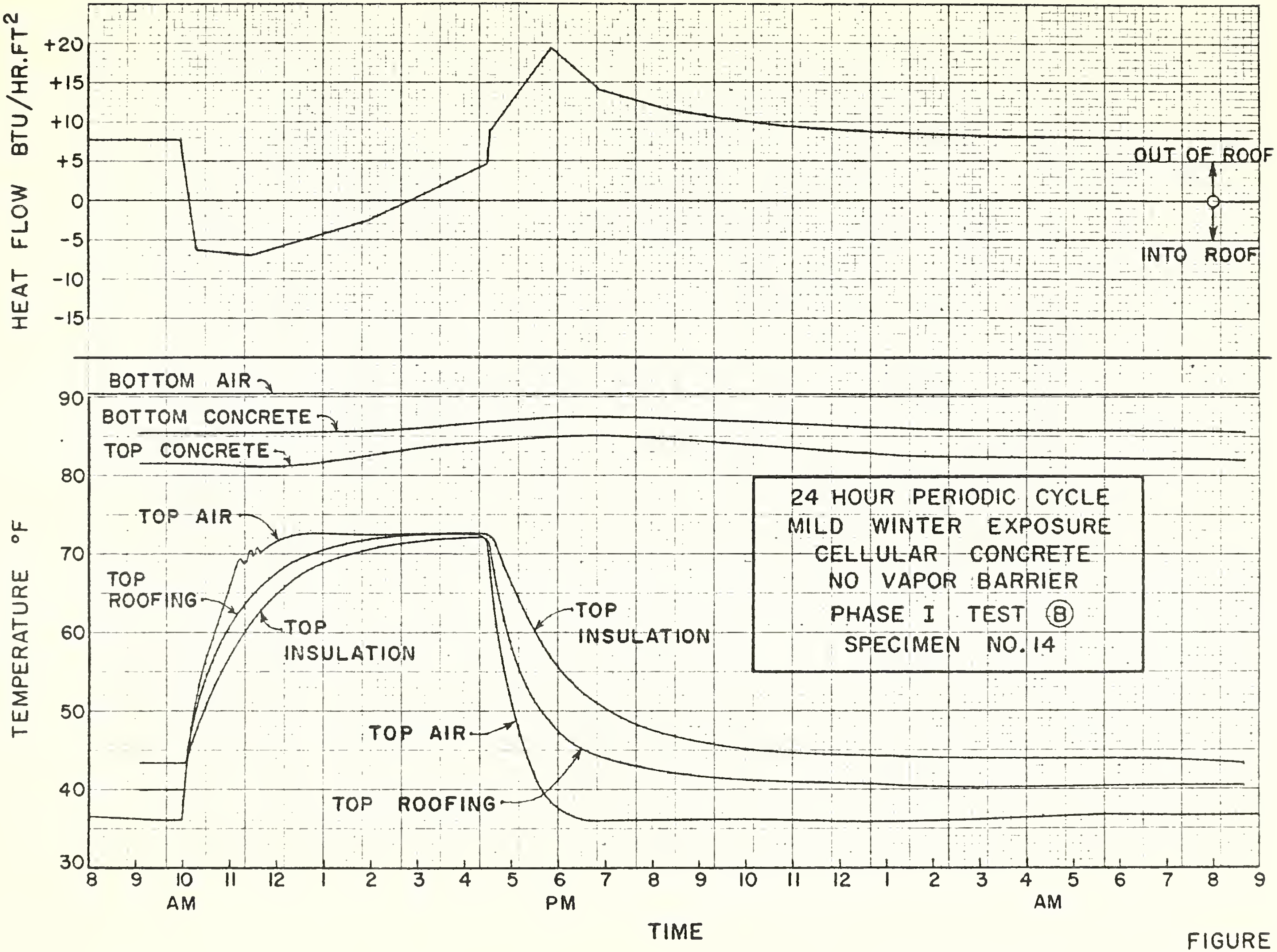
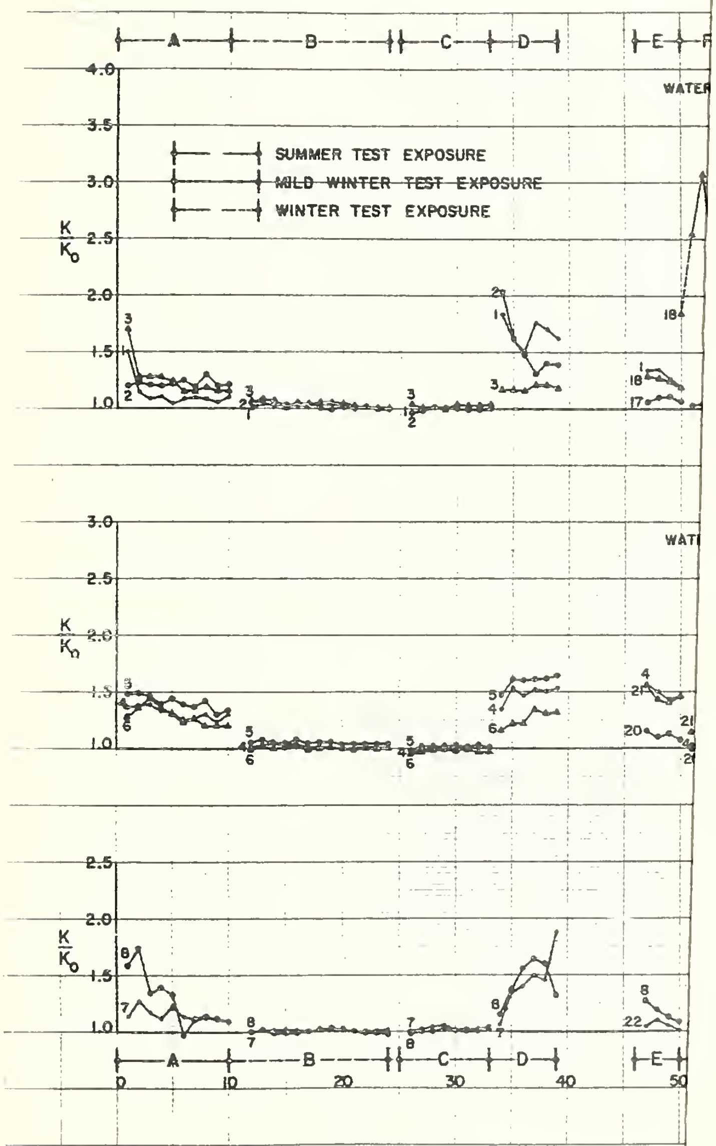

HEAT FLOW BTU/HR.FT.²
+10
+5
0
-5
-10
-15
-20
-25
OUT OF ROOF
INTO ROOF
24-HOUR PERIODIC CYCLE
SUMMER EXPOSURE
CELLULAR CONCRETE
NO VAPOR BARRIER
PHASE I TEST (A)
SPECIMEN NO. 14
TEMPERATURE °F
150
140
130
120
110
100
90
80
TOP AIR
ROOFING
TOP OF INSULATION
BOTTOM AIR
TOP OF CONCRETE
BOTTOM OF CONCRETE
TOP OF INSULATION
ROOFING
TOP OF CONCRETE
BOTTOM OF CONCRETE
8
9
10
11
12
1
2
3
4
5
6
7
8
9
10
11
12
1
2
3
4
5
6
7
8
9
AM
PM
AM
TIME

FIGURE 7.



HEAT FLOW BTU/HR.FT²
+20
+15
+10
+5
0
-5
-10
-15
OUT OF ROOF
INTO ROOF
TEMPERATURE °F
90
80
70
60
50
40
30
BOTTOM AIR
BOTTOM CONCRETE
TOP CONCRETE
TOP AIR
TOP ROOFING
TOP INSULATION
TOP INSULATION
TOP AIR
TOP ROOFING
24 HOUR PERIODIC CYCLE
MILD WINTER EXPOSURE
CELLULAR CONCRETE
NO VAPOR BARRIER
PHASE I TEST B
SPECIMEN NO. 14
8 9 10 11 12 1 2 3 4 5 6 7 8 9 10 11 12 1 2 3 4 5 6 7 8 9
AM
PM
AM
TIME

FIGURE 8.



A
B
C
D
E
F
WATER
SUMMER TEST EXPOSURE
MILD WINTER TEST EXPOSURE
WINTER TEST EXPOSURE
K/K₀
WAT
0
10
20
30
40
50

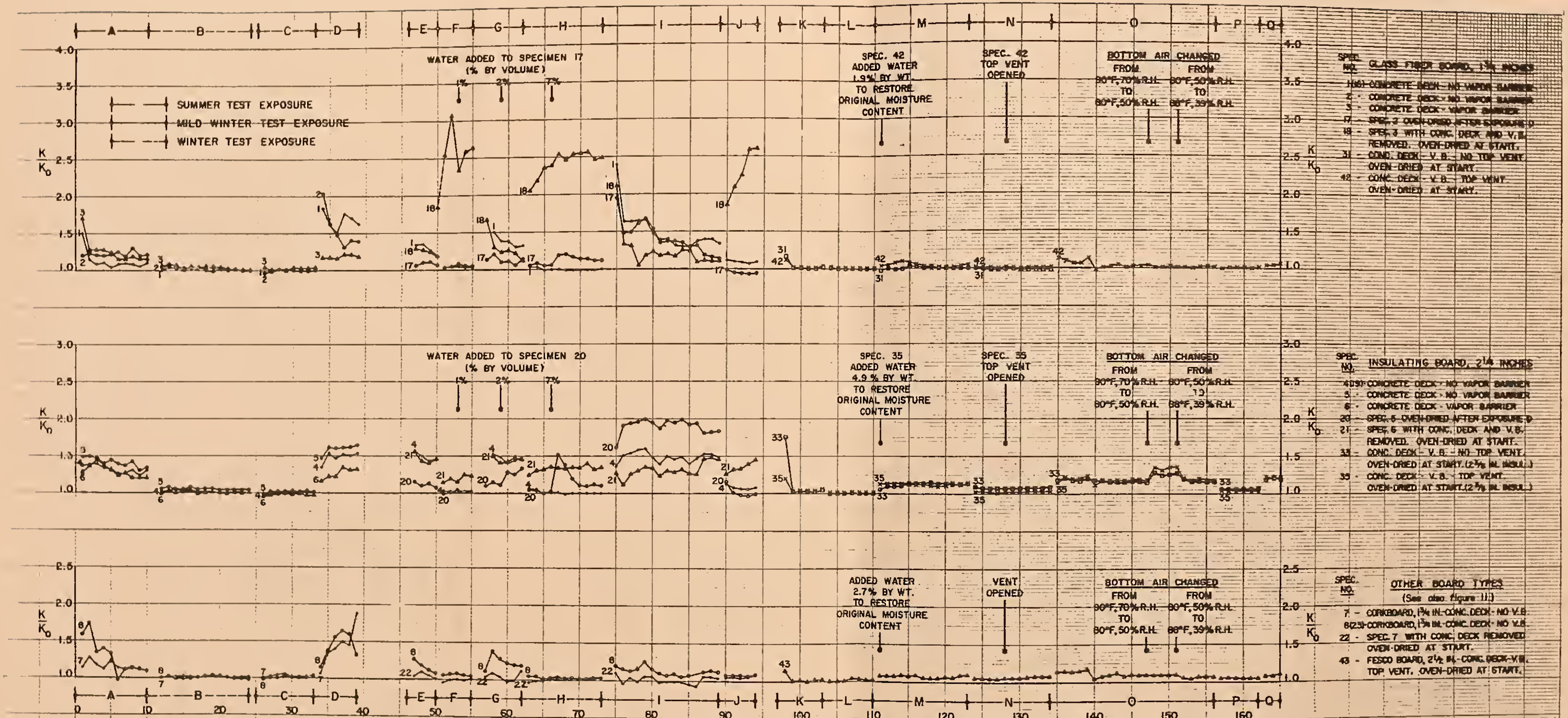
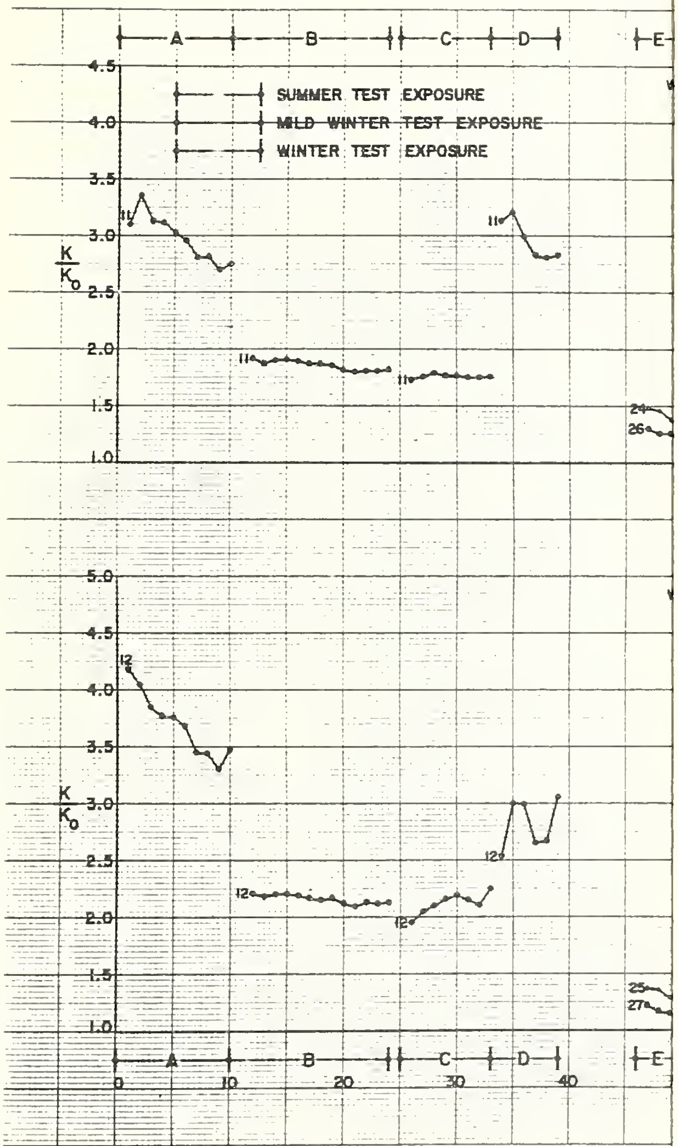


FIGURE 9.
BOARD TYPE INSULATIONS



A
B
C
D
E
SUMMER TEST EXPOSURE
MILD WINTER TEST EXPOSURE
WINTER TEST EXPOSURE
K/K₀

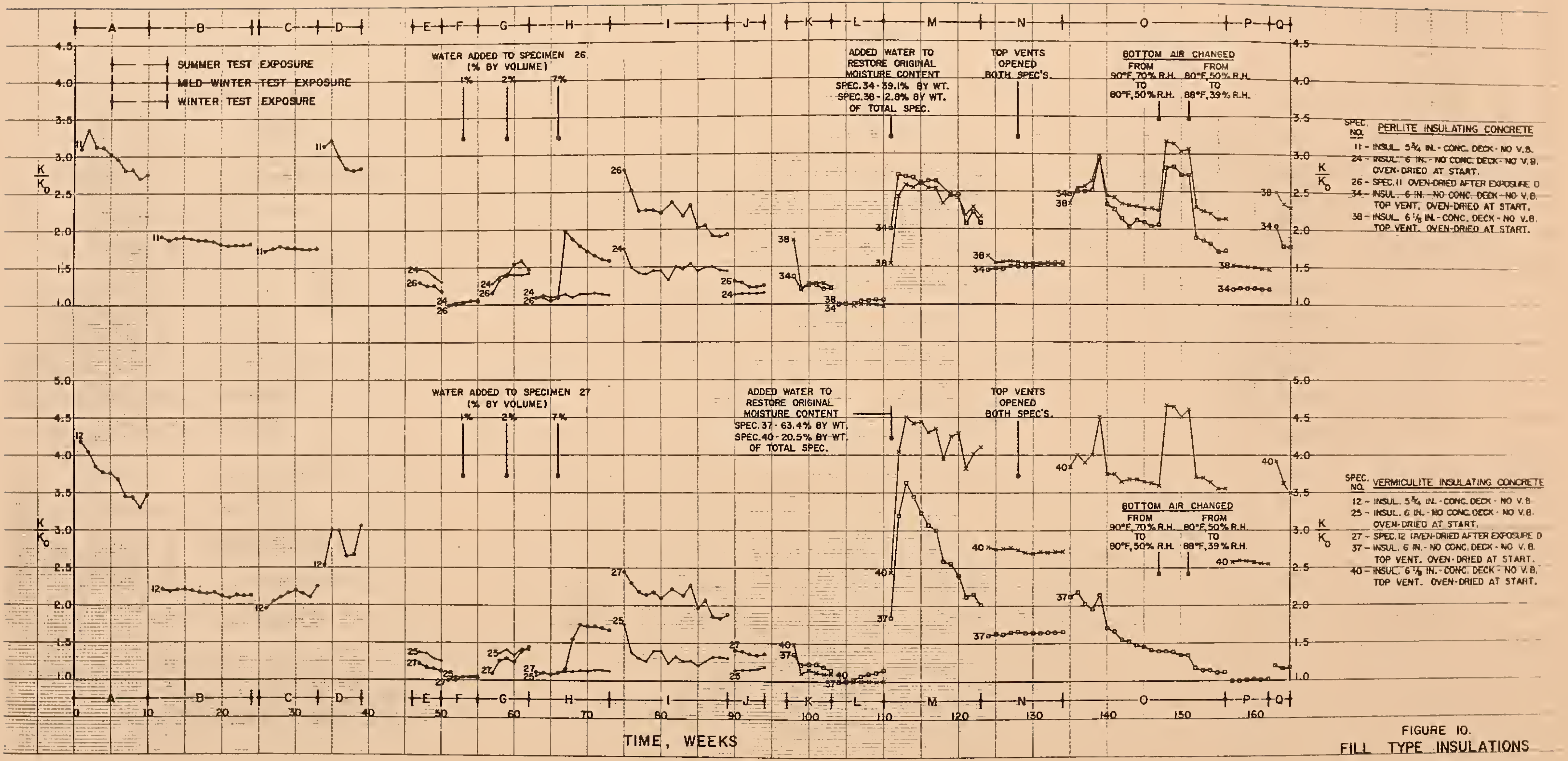
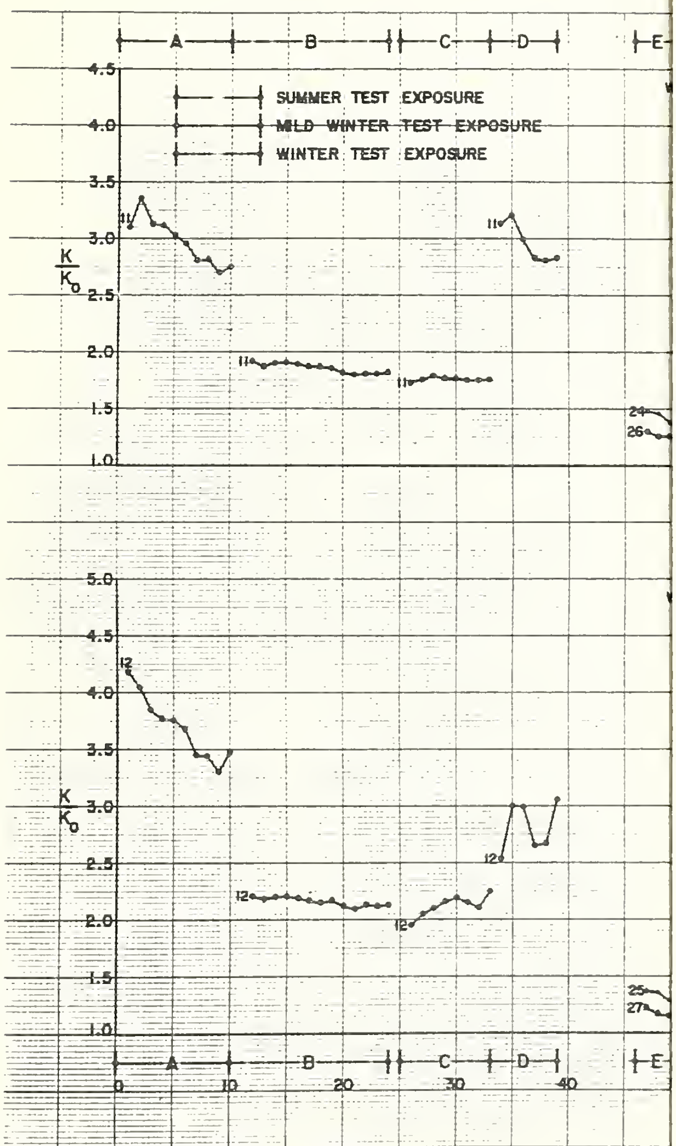


FIGURE 10.
FILL TYPE INSULATIONS


A
B
C
D
E
SUMMER TEST EXPOSURE
MILD WINTER TEST EXPOSURE
WINTER TEST EXPOSURE
K/K0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
5.0
0
10
20
30
40

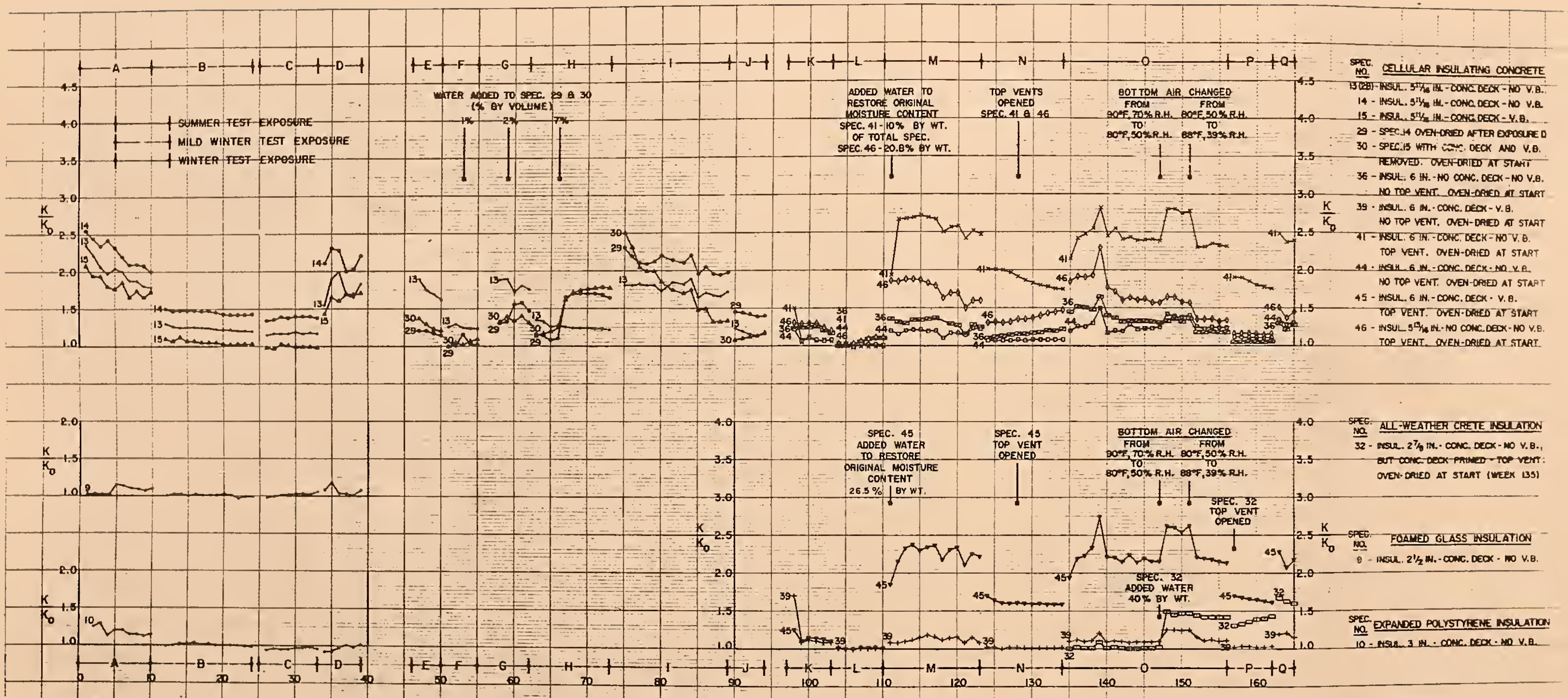
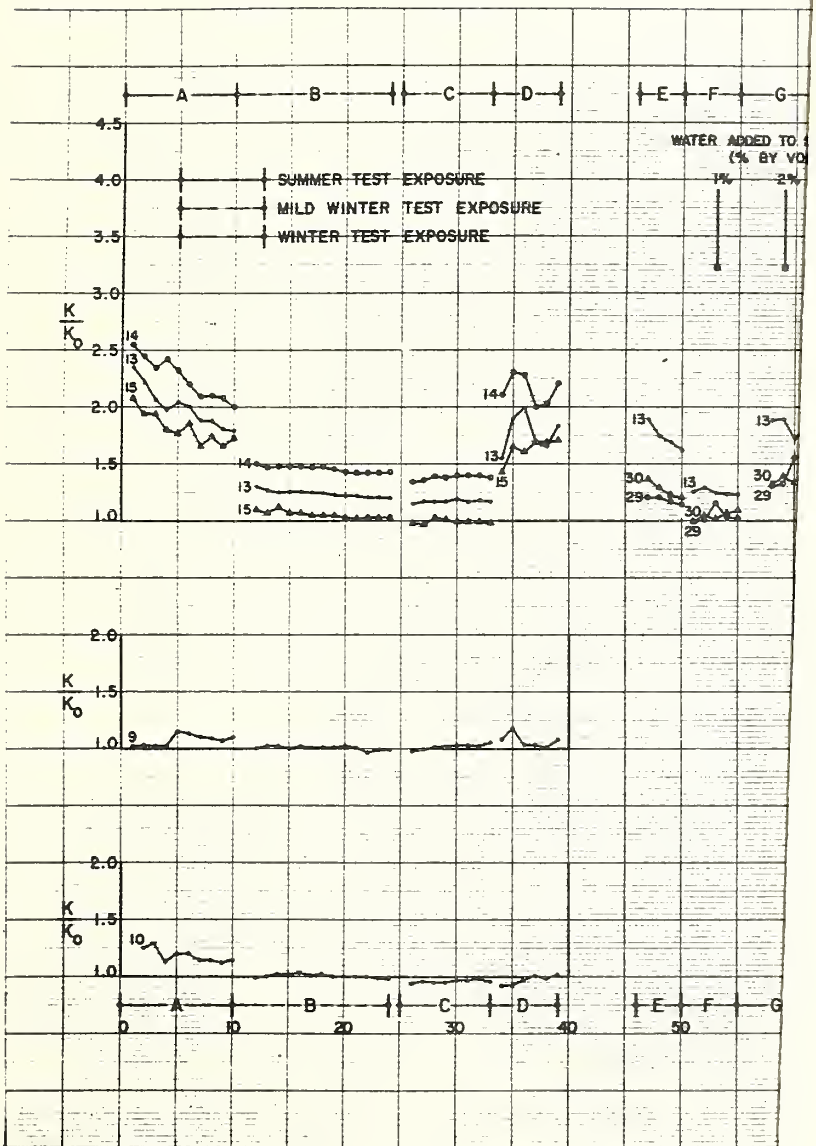


FIGURE 11.

FILL TYPE & BOARD TYPE INSULATIONS



A
B
C
D
E
F
G
SUMMER TEST EXPOSURE
MILD WINTER TEST EXPOSURE
WINTER TEST EXPOSURE
WATER ADDED TO
(% BY VO
1%
2%
K/K0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0
10
20
30
40
50

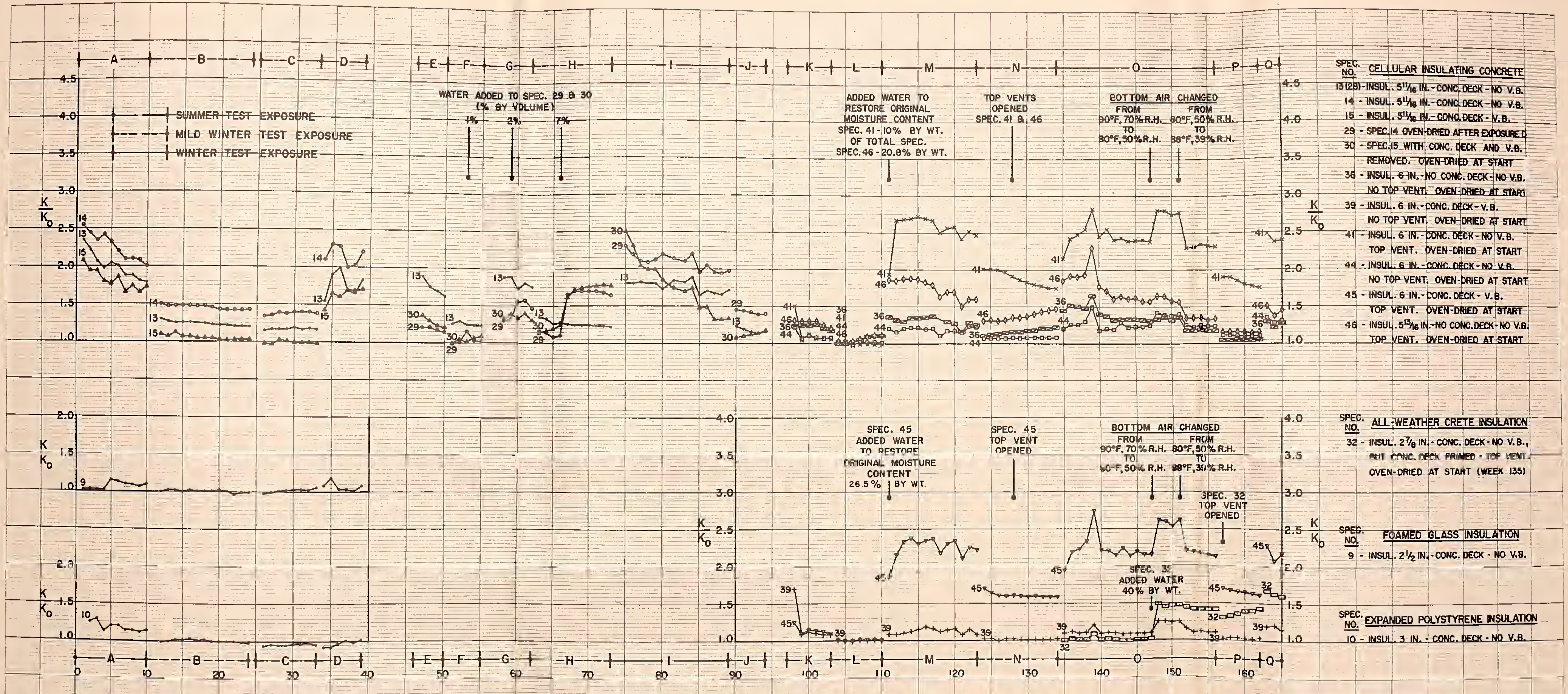
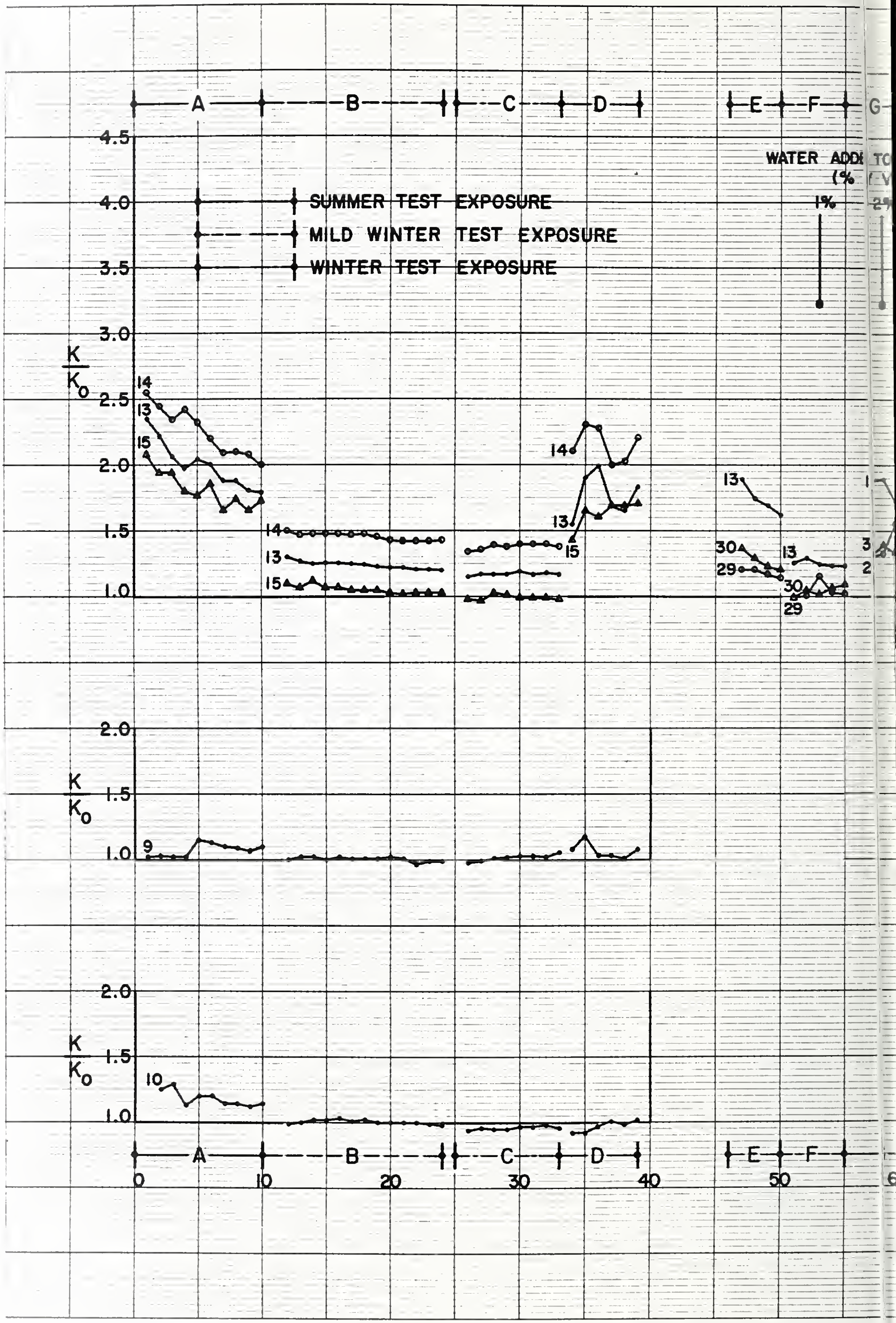
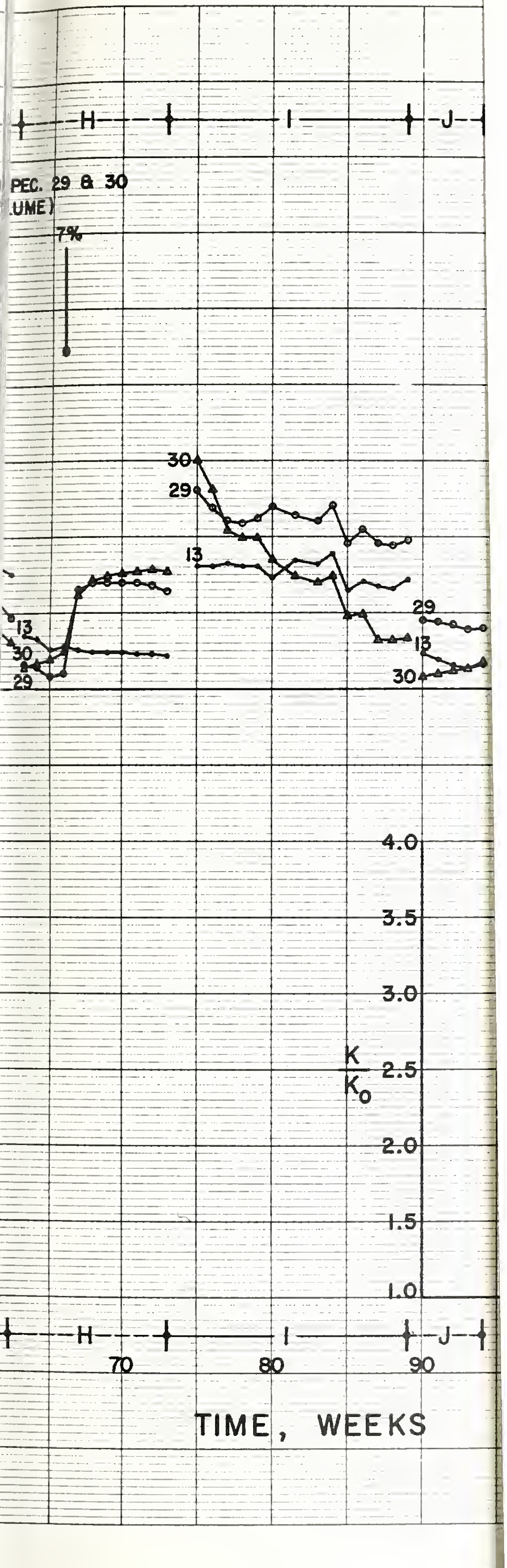


FIGURE 11.

FILL TYPE & BOARD TYPE INSULATIONS



A
B
C
D
E
F
G
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
K / K0
SUMMER TEST EXPOSURE
MILD WINTER TEST EXPOSURE
WINTER TEST EXPOSURE
WATER ADD
(%
1%
14
13
15
30
29
9
10
0
10
20
30
40
50



H
I
J
PEC. 29 & 30
UME)
7%
30
29
13
13
30
29
29
13
30
4.0
3.5
3.0
2.5
2.0
1.5
1.0
$\frac{K}{K_0}$
70
80
90
TIME, WEEKS

Copy No. 1

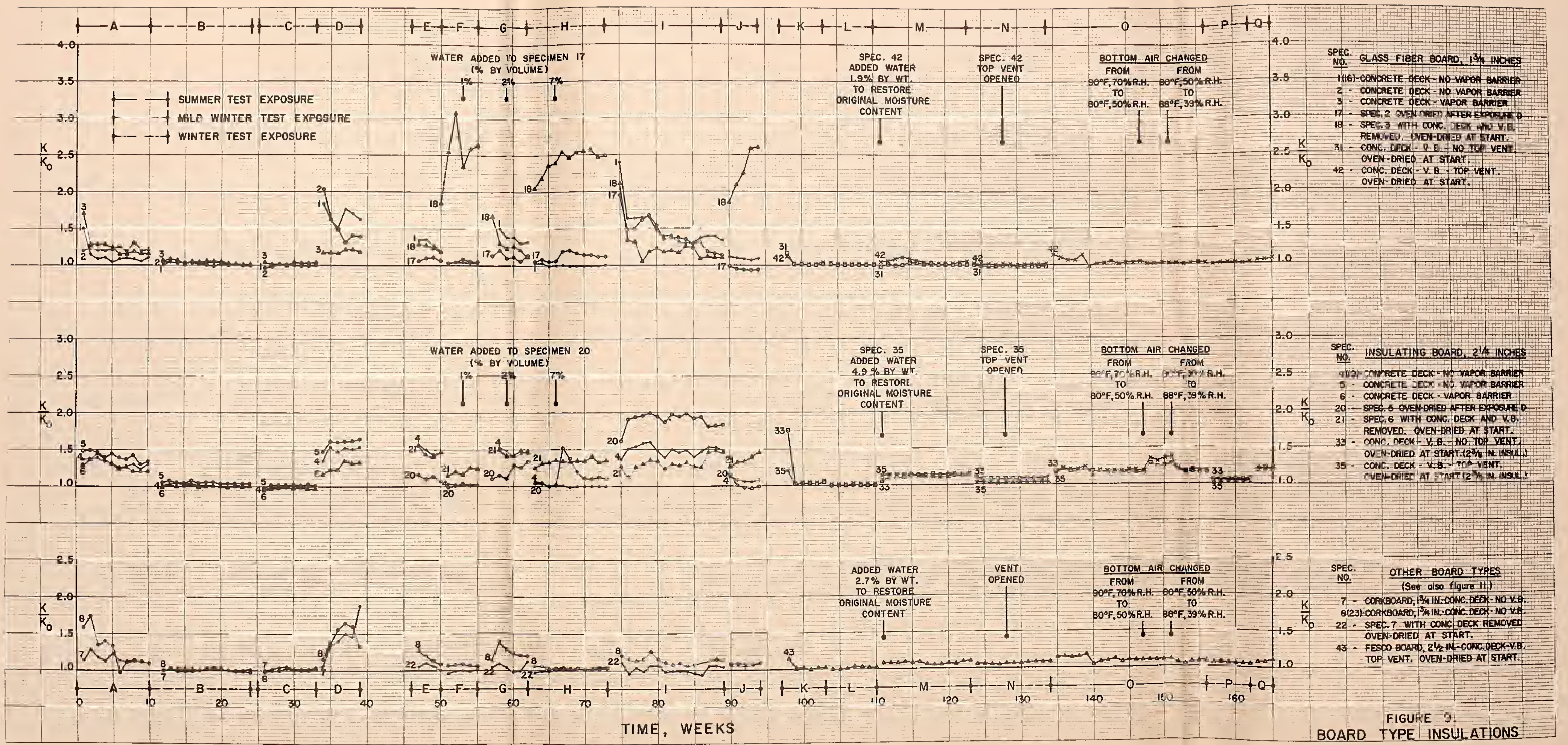


FIGURE 9.
BOARD TYPE INSULATIONS

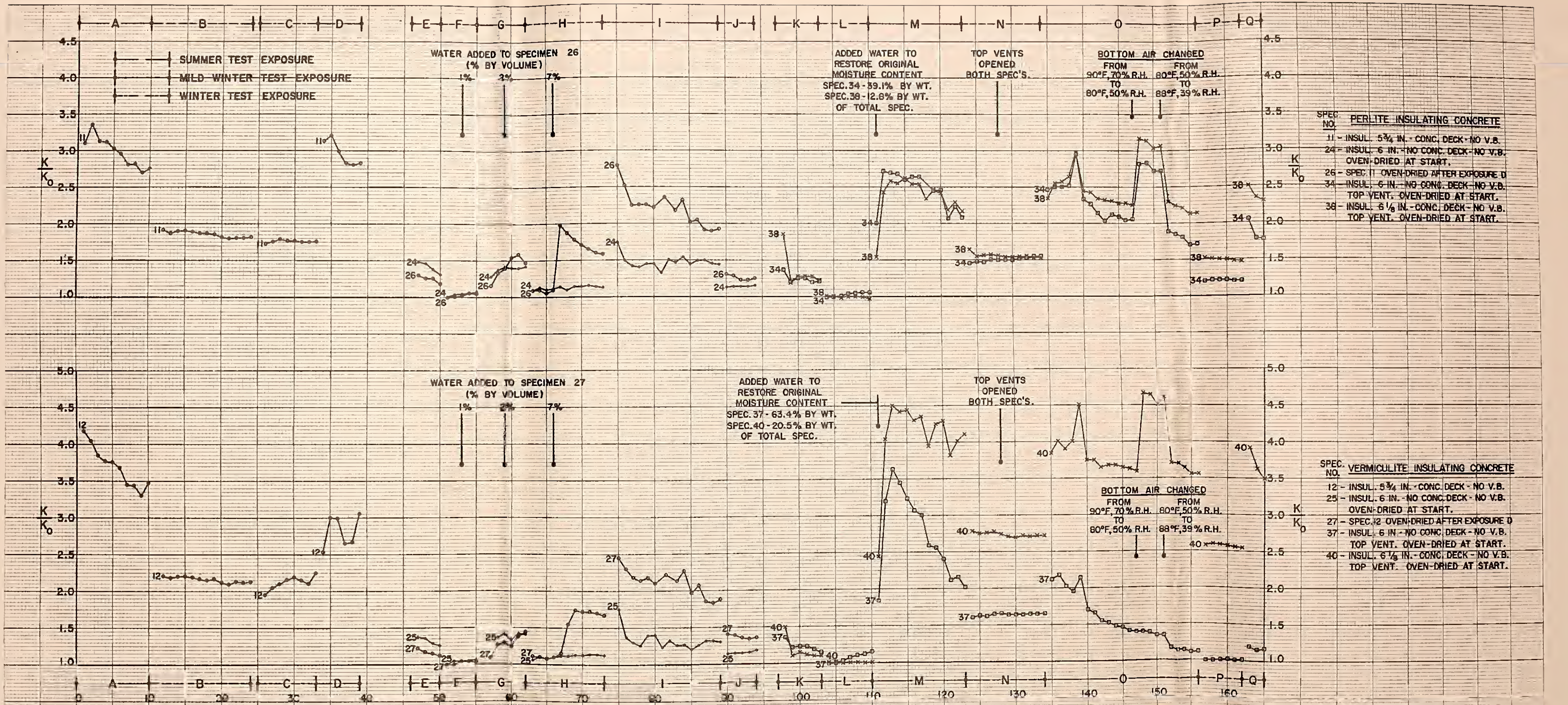


FIGURE 10.
FILL TYPE INSULATIONS

U. S. DEPARTMENT OF COMMERCE
Lewis L. Strauss, *Secretary*

NATIONAL BUREAU OF STANDARDS
A. V. Astin, *Director*

THE NATIONAL BUREAU OF STANDARDS

The scope of activities of the National Bureau of Standards at its headquarters in Washington, D. C., and its major laboratories in Boulder, Colo., is suggested in the following listing of the divisions and sections engaged in technical work. In general, each section carries out specialized research, development, and engineering in the field indicated by its title. A brief description of the activities, and of the resultant publications, appears on the inside front cover.

WASHINGTON, D. C.

Electricity and Electronics. Resistance and Reactance. Electron Devices. Electrical Instruments. Magnetic Measurements. Dielectrics. Engineering Electronics. Electronic Instrumentation. Electrochemistry.

Optics and Metrology. Photometry and Colorimetry. Optical Instruments. Photographic Technology. Length. Engineering Metrology.

Heat. Temperature Physics. Thermodynamics. Cryogenic Physics. Rheology. Engine Fuels. Free Radicals Research.

Atomic and Radiation Physics. Spectroscopy. Radiometry. Mass Spectrometry. Solid State Physics. Electron Physics. Atomic Physics. Neutron Physics. Radiation Theory. Radioactivity. X-rays. High Energy Radiation. Nucleonic Instrumentation. Radiological Equipment.

Chemistry. Organic Coatings. Surface Chemistry. Organic Chemistry. Analytical Chemistry. Inorganic Chemistry. Electrodeposition. Molecular Structure and Properties of Gases. Physical Chemistry. Thermochemistry. Spectrochemistry. Pure Substances.

Mechanics. Sound. Mechanical Instruments. Fluid Mechanics. Engineering Mechanics. Mass and Scale. Capacity, Density, and Fluid Meters. Combustion Controls.

Organic and Fibrous Materials. Rubber. Textiles. Paper. Leather. Testing and Specifications. Polymer Structure. Plastics. Dental Research.

Metallurgy. Thermal Metallurgy. Chemical Metallurgy. Mechanical Metallurgy. Corrosion. Metal Physics.

Mineral Products. Engineering Ceramics. Glass. Refractories. Enameled Metals. Concreting Materials. Constitution and Microstructure.

Building Technology. Structural Engineering. Fire Protection. Air Conditioning, Heating, and Refrigeration. Floor, Roof, and Wall Coverings. Codes and Safety Standards. Heat Transfer.

Applied Mathematics. Numerical Analysis. Computation. Statistical Engineering. Mathematical Physics.

Data Processing Systems. SEAC Engineering Group. Components and Techniques. Digital Circuitry. Digital Systems. Anolog Systems. Application Engineering.

- Office of Basic Instrumentation.
- Office of Weights and Measures.

BOULDER, COLORADO

Cryogenic Engineering. Cryogenic Equipment. Cryogenic Processes. Properties of Materials. Gas Liquefaction.

Radio Propagation Physics. Upper Atmosphere Research. Ionospheric Research. Regular Propagation Services. Sun-Earth Relationships. VHF Research. Ionospheric Communication Systems.

Radio Propagation Engineering. Data Reduction Instrumentation. Modulation Systems. Navigation Systems. Radio Noise. Tropospheric Measurements. Tropospheric Analysis. Radio Systems Application Engineering. Radio-Meteorology.

Radio Standards. High Frequency Electrical Standards. Radio Broadcast Service. High Frequency Impedance Standards. Electronic Calibration Center. Microwave Physics. Microwave Circuit Standards.

NBS