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NATIONAL BUREAU OF STANDARDS REPORT

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HEAT TRANSFER AND SELF-DRYING CHARACTERISTICS OF FORMBOARD-TYPE INSULATED FLAT-ROOF CONSTRUCTIONS

by

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Heat Transfer Section
Building Research Division

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

U. S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS

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I. INTRODUCTION

The objective of this investigation, initially, was to develop data on the insulating value of certain typical flat-roof-deck constructions containing moisture. Of particular interest were those designs that utilized insulating materials over structural concrete decks with or without a vapor barrier beneath the insulations. First results were reported in National Bureau of Standards Report 6283 "The Effect of Moisture on Heat Transfer through Insulated Flat-Roof Constructions," which also described a method of measurement that utilized heat-flow meters for determining the insulating value of the constructions with and without moisture in them. It was learned from that work that exposure conditions were of primary importance in evaluating the effect of moisture on insulating value, and, for proper evaluation, temperatures that simulate in-service conditions, including daily simulated solar heating of the roofing, must be used especially under summer exposure conditions. It was found that wetted insulation above a 3-inch thick structural concrete deck, with or without a vapor barrier, and covered with a built-up roof, remained moist for long periods of time with serious impairment of its insulating value, especially under summer exposure conditions. It was also found that roof specimens whose undersurfaces were of a moderately vapor-permeable nature tended to dry out significantly during simulated summer exposure conditions and to recover nearly all of the insulating value expected of them in a dry condition, even if they had been excessively moist.

An insulated flat-roof construction that would dry in place, if wetted, was recognized as the most practical and economical solution to the many problems that result from moisture in insulations of flat roofs. Accordingly, the objective of the project was modified to include investigation of the factors affecting the ability of a wetted roof construction to dry by loss of moisture through the undersurface under conditions simulating natural exposures. Heat transfer and self-drying characteristics of eight insulated flat-roof constructions were determined and reported in National Bureau of Standards Report 7347, "Heat Transfer and Self-Drying Characteristics of Insulated Flat-Roof Constructions." For that study a new method of measurement and apparatus was needed. An apparatus that allowed simultaneous weight and heat transfer measurements of individual specimens to be made during their exposures was devised and a new calorimetric technique for measuring heat flux over the whole of the specimen area was incorporated in the new apparatus.

It was found that self-drying of three different wetted insulations without vapor barriers was inhibited and their insulating values impaired when they were placed over structural concrete roof decks 1-inch thick and of 100 pcf density. This result was similar to earlier findings observed when the same types of insulations were used over 3-inch thick, 145 pcf structural concrete decks. It was thought that the use of a lighter-density concrete deck of only one-third the thickness of previous constructions would allow the insulations to self-dry while providing sufficient structural strength. Other more encouraging results revealed that decks permeable to water vapor, such as gypsum concrete and glass fiber formboards, allowed the specimens to dry to the indoors after a few weeks' exposure to summer conditions, and to quickly recover their insulating values. Also of importance, it was observed that the quantities of moisture gained by these specimens during a winter exposure period were not great enough to seriously reduce their insulating value or prevent expulsion of accumulated moisture as water vapor through the deck during a subsequent summer exposure period. Brush painting of indoor surfaces of gypsum concrete decreased the gain of moisture under winter exposure conditions, but spray painting of glass fiber formboard showed little change when compared with the same surface unpainted. However, all painted specimens were able to expel winter-gained moisture in a reasonable length of time during a subsequent summer exposure period. Leaching of the upper surfaces of gypsum concrete decks occurred when these surfaces were in contact with moist insulations and the specimens were subjected to simulated summer exposure conditions. It was concluded that insulated flat-roof constructions having good self-drying characteristics are feasible and, realistically, are nearly essential if reliable insulating value is to be obtained in long-term service.

The ability of an insulated roof construction to self-dry in service when wetted appeared to be controlled by the exposure conditions, the arrangement and dimensions of the components of the construction, and physical properties such as moisture absorbency, thermal conductivity, and water vapor permeability.

The purpose of the work reported here was to determine the characteristics of additional constructions thought to be of a self-drying nature and to investigate the importance of the various physical properties, arrangement, and dimensions of components as factors controlling their self-drying and insulating performance. This report describes the specimens, the testing procedures and gives a summary of results and conclusions obtained from tests covering 22 to 64 weeks of exposure on 9 insulated flat-roof specimens, 22 by 23 inches in plan. Each specimen was exposed to successive periods of simulated summer and winter outdoor surface temperature conditions, each with daily solar heating of the outdoor surface. The tests included exposures of specimens initially at moisture contents commensurate with those found in practice when roofing is applied, and at moisture contents simulating those when a roofing leak occurs. At a suitable time in the program, the indoor surfaces of several specimens were spray painted to observe effects on the rate of moisture passage under winter and summer exposure conditions.

2. EXPERIMENTAL EXPOSURE CONDITIONS AND METHOD OF TEST

Experimentally feasible roof temperature conditions representative of those experienced by roofs in this country were used for the exposures reported here and for those reported in NBS Reports 6283 and 7347. For summer conditions it was assumed that the outdoor surface temperature of the specimens at night would be about 75°F on the average. During the day when the roof was subjected to solar heating, the top surface of the specimen was assumed to rise to about 138°F. For winter conditions, similar average temperatures were 38° and 75°F for night and day, respectively. These values are in good agreement with average values reported in NBS Report 7470 "The Effect of Insulation on the Durability of a Smooth-Surfaced Built-Up Roof" and those contained in several literature references reporting temperature measurements on roofs in this country and in Australia.

In the method of measurement used, a hollow metal calorimeter plate replaced roofing on a specimen. Water was pumped through passages in the plate at controlled temperatures in accordance with the daily cycles shown in Figure 1, to produce the simulated summer and winter roofing temperatures with solar heating. The calorimeter also served to measure the heat flux at the top surface of the specimen.

Also indicated in Figure 1 is the indoor air temperature used, 90°F. The indoor air condition beneath the specimens was 90°F and 30 percent relative humidity (0.43 in. Hg water vapor pressure and 54.5°F dewpoint), which corresponds in respect to water vapor pressure to an air conditioned environment of about 75°F and 49 percent relative humidity.

A detailed description of the calorimeter method of measurement, test apparatus, and the particulars for thermal guarding and moisture proofing of the specimen top and side surfaces is given in NBS Report 7347 "Heat Transfer and Self-Drying Characteristics of Insulated Flat-Roof Constructions."

3. SPECIMENS

A schematic drawing of each specimen is shown at the top of Figures 6-14. Details concerning the materials used in specimens are given in Table I. Each specimen was 22 by 23 inches in plan and, except for Specimen No. 17, contained two materials. Vapor barriers were not used between the materials in any specimen. The thicknesses of most of the materials were dimensioned to provide an overall calculated thermal transmittance, or U-value, of about 0.12 Btu/hr ft^2 °F on the basis of published thermal conductivity or thermal conductance values for dry materials.

Specimens were designed for the most part to represent practical constructions thought likely to possess in-service self-drying characteristics when installed containing initial construction moisture, or when wetted during their service life. Some specimens are probably not practical from the viewpoint of wet strength while being installed, such as No. 14 and 15, but were selected and dimensioned to meet the requirement of U=0.12, and at the same time to provide a range of thickness of these materials that normally contain considerable construction moisture. In general, all specimens were selected to be compatible with the construction technique of permanent formboards between subpurlins (bulb-tees). On the basis of previous measurements and published data, all materials were quite permeable to water vapor except the cement-asbestos board used in Specimen 16.

In addition to the thickness of the materials, the following physical properties were considered to be of primary importance in the design of a specimen: thermal conductivity; water vapor permeability; hygroscopicity; capillarity; and water absorbency. Materials were selected to provide amongst the specimens as wide a range as possible in these physical properties.

The concretes of Specimens 9-16 were cast in a mold directly on top of their formboards. The gypsum concrete of Specimens 9-11 was allowed to cure in its form for 1 day before fabrication into a specimen and installation in the apparatus. The perlite and vermiculite aggregate concretes were cured one day in the mold, three days in a damp room, and allowed to dry in laboratory air for three days out of the mold before fabrication into a specimen and installation in the apparatus. The factory-made board types of insulations used in all specimens were taken directly from their cartons after storage in the laboratory for several months.

Before assembly, a 1-inch square hole, 1/8-inch deep, was made in the center of the top surface of each specimen as a well for receiving water admitted through a drill-hole in the calorimeter plate that covered the top surface. Thermocouples were cemented or cast in place near the center of all horizontal surfaces of the component materials of each specimen. The specimen and calorimeter sides were moisture sealed with 1/32-inch thick neoprene rubber sheet bonded in place with a rubber adhesive. A thin soft blanket of glass fiber insulation was used as a gasket between sections of the board-type expanded polystyrene guard insulation. The guard insulation was held in place by steel-band strapping, tensioned by wedges, around the periphery of the specimen. All joints were mastic-sealed, tape-covered, and painted with a rubber-base paint paste. The water-feed hole through the center of the calorimeter plate was connected to plastic tubing that penetrated the top piece of guard insulation. Differential thermocouple wells at the inlet and outlet of the calorimeter plate were made from pipe nipples and tees which were insulated and vapor sealed. The assembled specimens were supported by slotted phenolic-plastic tubes on platform scales, and water connections to the calorimeter were made using flexible rubber tubing.

4. PROCEDURE

The investigation was conducted by subjecting specimens to alternations of periods of exposure simulating winter or summer temperature conditions. Each period consisted of repeated 24-hour cycles of the appropriate daily temperatures to simulate night-time and solar heating conditions, as indicated on Figure 1. Heat-flow, temperature, and weight measurements of each specimen were recorded on working days between 8 and 10 a.m., just prior to the start of the simulated solar heating part of the daily cycle. The seasonal periods were of several weeks' duration each, varying in length as necessary to observe apparent trends in the insulating value and weight change of a majority of the simultaneously exposed specimens.

The exposure periods were aimed at different objectives. The initial period for Specimens 11-17 (Fig. 8-14) was a summer exposure with specimens containing construction moisture. The objective for this exposure was to observe the insulating value and the ability of the specimens to self-dry by expelling construction moisture through the specimen undersurfaces. Specimens 9 and 10 (Fig. 6-7) were installed during a winter exposure condition which was followed shortly by a summer exposure condition. After the rate of self-drying had been established a known amount of water was added to selected specimens during summer exposure periods in simulation of a roofing leak. Specimens that contained much moisture and had not reached a moisture content equilibrium did not have water added to them until later when they had approached an equilibrium moisture content, as indicated by little change in weight with time. Winter test exposure periods were used to observe the effect on heat transfer of a change of exposure condition from summer to winter and to observe the rate at which the specimens gained weight as a result of moisture transfer from the room. Winter exposure periods were followed immediately by a summer exposure period to observe the time necessary to expel winter-gained moisture. At an appropriate time in the program, the interior or bottom surfaces of Specimens 9-13 and Specimen 17 were given two spray coats of rubber-base paint to observe the effect of painting on the rate of moisture gain during winter exposure and the rate of moisture loss during summer exposure. During a later summer exposure period water was added to the painted specimens in simulation of a roofing leak. About half-way through the program for Specimens 14 and 16, thin formboards of 1/2-inch thick gypsum board and 1/4-inch cement-asbestos board, respectively, were removed and the exposure continued. Also, at about this time, Specimen 15 was replaced by Specimen 17.

At the conclusion of its exposure, each specimen was dismantled, examined, photographed, and the moisture content of its component materials determined by drying to constant weight in an oven (see Table I).

Samples of the exposed materials, 8- by 8- by 1-inch thick were used for determining the thermal conductivity in an oven-dry condition, using the guarded hot plate method (ASTM C177-45), and additional samples, 4 1/4 inches in diameter and 1/2-inch thick, were used for measurement of water vapor permeance, using the dry cup method of ASTM E-96-53T, Procedure A.

5. RESULTS

Summarized results of the investigation are presented in Figures 2 through 15 and in Table I.

Figures 2 through 5 show for two specimens (9 and 10) temperatures and heat fluxes observed at 80-minute intervals throughout a typical 24-hour cycle of the imposed summer and winter exposure conditions.

Figures 6 through 14 show graphically heat transfer and moisture content results for Specimens 9 through 17, respectively. The heat transfer data are presented as thermal resistance values (reciprocal of thermal conductance) for the components of the specimen and the specimen as a whole. Thermal resistance is plotted against time in weeks for the duration of the tests. Also plotted against the same time scale is the moisture content in terms of pounds per square foot of roof area and percent of specimen dry weight. Each plotted value of resistance is the average of the daily values obtained during each week of the tests, usually five in number. In each of these figures, the thermal resistance of each specimen in a dry condition is indicated by a horizontal dashed line labeled "Design-R-Dry." This value of resistance was calculated using thermal conductivities determined by guarded hot plate tests on dry samples of the materials of each specimen obtained after their exposure in the apparatus. Thus, the figures show a comparison between the resistance of the dry specimen and that of the specimens at various moisture contents observed experimentally during several winter and summer exposure periods.

Table I lists the thickness and the results of density, thermal conductivity, and water vapor permeability determinations on the component materials of the specimens. Also given is the moisture content of each material as determined at the conclusion of its final exposure period. Table I also lists calculated values of thermal resistance (R) and permeance (P) for each specimen, formboard and top cover material. These values were obtained by using the determinations of thermal conductivity (k) and permeability (μ) in the relationship R = x (thickness)/k and P = μ/x and adding component resistances in series to obtain the specimen resistance. Also given, as a percentage, is the comparative insulating value for each specimen computed as the ratio of the average specimen thermal resistance (See 6.1 below) during their exposure history to the calculated thermal resistance of the specimen based on thermal conductivity determinations of its dry components. The ranges of the rates of drying during summer exposures and of moisture gain during winter exposures, as approximated by representative slopes of the moisture content curves on Figures 6-14, in terms of lb/sq ft (week), are also listed in Table I.

Figure 15 is a photograph of the top surface of those specimens containing gypsum concrete taken after their exposure in the apparatus. The photograph shows the surfaces that had been in contact with the calorimeter plate during exposure.

6. DISCUSSION OF RESULTS

Daily and weekly changes of thermal resistance were considered to be a measure of the effect of moisture on heat transfer through insulated flat-roof constructions. Daily determinations of thermal resistance of the specimens and their components were made just prior to the start of simulated solar heating. Figures 2 through 5 show, for the third winter and summer exposure periods, that all temperatures and heat flux through the upper surface of the specimens were nearly constant from 1:00 a.m., or earlier, to 10:00 a.m. Therefore, observations made between 8:00 and 10:00 a.m. yielded thermal resistance data for a condition approaching as nearly to an ideal steady-state condition as was possible within the restrictions of the imposed 24-hour periodic temperature cycle. Values of heat flux and temperature during the solar heating portion of the cycle, 10:00 a.m. to 4:00 p.m., and the cooling portion after 4:00 p.m., were clearly transient and would not have yielded a meaningful thermal resistance. The flow rates of water through the calorimeters of the specimens were changed from the normal 2.5 to about 0.5 lb/min from 1:00 a.m. to 10:00 a.m., in order to provide a larger, more easily measured temperature rise in the water as it passed through the calorimeter.

In order to maintain reasonably high thermal insulating values in summer and winter, the proposed solution to the problems arising from moisture in insulated flat-roof constructions was to use a deck or formboard material that would allow self-drying of the wetted construction to the indoors as promoted by natural solar heating of the outdoor surface in summer. In winter the deck or formboard material must also inhibit the accumulation of moisture in the construction resulting from condensation of water vapor transferred from indoors. The results obtained indicate that the above-proposed solution can be considered feasible for several designs of practical insulated flat-roof decks provided the indoor vapor pressure is not excessive and is of the order of that found in normal-occupancy buildings (75°F, 50% RH). Shower rooms, kitchens, laundries and other high moisture and water vapor pressure areas are exceptions. These areas require special moisture resistant materials and designs.

6.1. Summary Discussion - All Specimens

An average insulating value for each specimen (See Table I) was determined by taking the arithmetic average of all weekly thermal resistance data points plotted, as shown in Figures 6-14. This average value covers a range of moisture contents for each specimen, involving the initial moisture content, and its changes during subsequent exposure conditions or as a result of experimental wetting. These moisture contents were not necessarily alike for all specimens.

The highest comparative insulating values (82 to 73 percent) were found for Specimens 13, 17 and 9, which were the thinnest specimens, and which had rapid rates of self-drying. These high comparative values were obtained even though the specimens were deliberately wetted one or more times during their exposures, with little effect on their average insulating value because of the rapidity of drying. The lowest comparative insulating values (36 to 46 percent) were found for Specimens 14, 15 and 16, which consisted of insulating concrete 6 to 7 inches thick placed on their formboards of gypsum or cement-asbestos. These specimens had initial moisture contents of about 8 to 11.5 lb/ft^2, which were reduced during the exposures to about 3.6 to 6.0 lb/ft^2, and might have been reduced further in longer time. It is thought that their thickness tended to reduce their rate, and ultimate degree, of drying under summer exposure conditions.

All specimens self-dried during summer exposure periods. The rate of drying varied for each specimen and from specimen to specimen. For all specimens the rate of drying was rapid initially when the specimens were moist, and for most decreased as the specimens dried.

The most rapid drying rate, 1.1 lb/ft^2(week), and the shortest drying time, 2 to 4 weeks, was observed for Specimen 9. Specimen 10 also dried rapidly. Both of these specimens were relatively thin and had relatively high overall permeances and formboard permeances. Specimens 11, 12 and 13, which were intermediate in thickness in the group tested, and had formboards of intermediate permeance in the group, had summer condition drying rates in the range 0.06 to 0.29 lb/ft^2(week). The relatively thick specimens, 14, 15 and 16, which had relatively low overall permeances and contained considerably more moisture, dried at a slow rate, approximately 0.1 to 0.3 lb/ft^2(week) which was increased when the specimens were at relatively high moisture contents and when the formboards were removed from Specimens 14 and 16. Specimens 9 through 13 reached equilibrium moisture contents, which appeared to be substantially their hygroscopic equilibrium moisture contents under the summer exposure conditions, in 25 or fewer weeks of summer exposure, even though they were quite moist initially. Specimens 14, 15 and 16 dried consistently under the summer condition, but because of their large initial moisture contents, and relatively slow drying rates, they did not reach substantial moisture equilibrium values in about 25 weeks of exposure. However, drying was continuing at that time, and presumably would have continued with prolonged, or a successive, summer exposure. The comparative insulating values for these specimens, for the period of observation, are probably considerably lower than the ultimate values corresponding to the final approximate equilibrium moisture contents which they would reach given sufficient time.

Moisture gain rates under winter exposure conditions for Specimens 9 to 16 were moderate, being generally less than 0.06 lb/ft^2(week). At such rates of gain, the accumulation of moisture over a period of twenty to thirty weeks of winter exposure would be considerably less than the moisture-holding capacity of the top layers of these specimens, and a succeeding summer exposure would rapidly expel the accumulated moisture. Thus, the essential requirement that winter moisture gain rates be noncritical was satisfied by these specimens, for the indoor condition maintained (dewpoint = 54.5°F).

In connection with moisture loss and gain rates, the plots of moisture content of Figures 7 to 13 show that for these specimens at high moisture contents the winter gain rate was less, and the summer loss rate was greater, relative to the rates at low moisture contents. For example, Specimens 10 to 16 lost or failed to gain moisture during the winter exposure condition when their moisture contents were high, although most of them gained moisture slowly during winter exposures when their moisture contents were relatively low. This behavior indicates that these specimens tend toward average equilibrium values of moisture content which will vary only slightly with alternations of the winter and summer exposures. This value would probably vary moderately with moderate changes of indoor dewpoint temperature.

The increases of moisture content resulting from winter exposures, for these specimens, caused little change in the overall insulating values of the specimens for either winter or summer conditions. Thus their insulating values tended to be stable, even if they were lower than those of oven-dry constructions. Such stability may be compared with the relatively much greater differences of insulating value in summer and winter exposure conditions recorded in Report No. 6283 for moisture-containing specimens having vapor barriers or dense concrete decks underneath. Even larger moisture contents, either initial or in simulation of a roofing leak, seriously affected the insulating values of the present specimens for only short periods, with the exceptions of Specimens 14 to 16.

Specimen 17, for which results are shown on Figure 14, consisted of a 3-inch layer of Tectum board, and thus differed from Specimen 10 (Figure 7), which had a top layer of 2 inches of gypsum concrete. Insulating values for the Tectum board were approximately alike for both specimens; winter condition rates of moisture gain were on the order of 0.05 lb/ft^2(week) for both, and were proportional to the vapor permeances of the respective Tectum board components (See Table I). Summer condition rates of moisture loss were greater for Specimen 10 when it contained considerable moisture, but for both specimens the rate approached zero at a moisture content of about 0.4 lb/ft^2, which apparently represented a hygroscopic moisture level for the material at a summer test condition. A comparison of the practical merits of the two constructions should take into account the safety factor afforded by the moisture-holding capacity of the gypsum concrete topping of Specimen 10. For example, in 20 weeks of the winter exposure condition, each specimen would gain about 1 lb/ft^2 of moisture. This amount might exceed that which could be held without dripping by Specimen 17 (when water was added at week 17, dripping occurred when the specimen moisture content was 0.9 lb/ft^2), but is much less than that (6 lb/ft^2) successfully held by Specimen 10. For under-ceiling dewpoints less severe than the value (54.5°F) used in the test winter condition, Specimen 17 might readily withstand 20 weeks of winter exposure.

6.2. Discussion - Gypsum Concrete Cover Specimens 9, 10 and 11

The constructions of Specimens 9, 10 and 11 (Figures 6, 7 and 8) were similar in that each contained a two-inch thickness of gypsum concrete over the formboard material, and a vapor barrier was not used between materials. The formboard deck material in each specimen provided the major share of insulating value, and all formboards were permeable to water vapor. The formboard materials differed in thickness, thermal conductivity and water vapor permeability as shown in Table I. Also, the formboards differed in their ability to absorb or retain liquid water and hygroscopic moisture. The variations of the thermal resistance and water vapor permeance of the formboards, gypsum concrete, and the specimens, as calculated from the thickness, thermal conductivity and water vapor permeability values, are also given in Table I.

At the start of the first summer exposure condition, these specimens contained evaporable moisture in amounts similar to that found when roll roofing would be applied to flat-roof constructions in the field. The moisture was well distributed as a result of the mixing and placing of the wet gypsum concrete. Initial moisture contents of the specimens were high: over 40 percent by weight. Rapid drying commenced immediately because of the comparatively low thermal resistance of the gypsum concrete top layer which allowed the entire volume of the moist gypsum concrete to be raised substantially in temperature during exposure to simulated solar heating. The concomitantly increased water vapor pressure in the moist permeable gypsum concrete promoted vapor escape through the permeable deck material, and thus affected rapid drying of the specimens. Specimen 9 (Figure 6) dried to a moisture equilibrium after five weeks of exposure. After 17 weeks Specimen 10 approached a moisture content equilibrium, but Specimen 11 was still losing weight at a uniform rate when the first summer exposure period was terminated. The average rates of drying during this period were about 1.1, 0.37, 0.22 lb moisture/(ft^2 of roof area) (week) for Specimens 9, 10 and 11, respectively. Shortly after the start of the first summer exposure period, water in the amount of ten percent by specimen volume was added to these specimens to simulate rain-wetting before roofing would be applied or to simulate an accidental puncture of the roll-roofing soon after it was applied. Specimen 9 expelled the added water in about two weeks, while Specimens 10 and 11 required five and nine weeks, respectively.

Specimen 9 showed the fastest drying rate because the permeance of its formboard was greatest (Table I) allowing rapid migration of water vapor from the moist gypsum concrete during summer exposure. The permeances of the formboards of Specimens 10 and 11 were approximately one-fourth that of the glass fiber board, as were their drying rates. The rapid expulsion of moisture from this type of construction, in service, after the roofing had been applied and the building closed in, could constitute a considerable short-term latent heat load to the room beneath, which could easily be dissipated by a ventilating or air-conditioning system. If a roof of this type of construction were installed in the spring construction season, it is estimated that most of the initial construction moisture would be dissipated by natural means before the fall heating season. These types of construction have a further advantage. If a leak in the roofing should occur in the service life of the building, it would be readily indicated by a wet spot on the ceiling or dripping of water indoors. Simple repair of the roofing would stop the leak and the roof would have the ability to self-dry to the indoors preventing the problem of costly replacement of large areas of insulation and roofing.

During the first summer exposure period when Specimen 9 was at a moisture equilibrium, its thermal resistance averaged about 70 percent of that calculated on the basis of the thermal conductivities determined on dry samples. When the specimen was drying rapidly, e.g., as during weeks 2-7 and 9-12, the observed temperature drop in the gypsum concrete becomes substantially zero, and the whole temperature drop at the time of observation occurred across the form-board. At the same time, the heat flow to the calorimeter through the specimen decreased to practically zero. Thus, the gypsum concrete appeared to have an indeterminate thermal resistance (calculated as $R = \Delta t/q$), and the form-board an apparent large resistance approaching infinity. These results results are indicated on Figure 6 by a broken line symbol, and can be explained in terms of the way the measurements were made and the latent heat transfer effect. During the early morning hours, when the near steady-state heat flow and temperature measurements were made, the moisture in the gypsum concrete was distributed in the specimen as a result of the daily reversals of the temperature gradient. The temperature at the interface of the materials was initially near the 75°F temperature of the calorimeter because of the lowered resistance of the wet gypsum concrete. Thus, initially, the gypsum concrete had a small temperature difference across it, while the glass fiber formboard had, initially, a higher temperature difference across it. Heat flowed from the undersurface of the specimen through the formboard to the underside of the gypsum concrete, which at that stage was relatively moist, and there most of the heat was used to evaporate moisture, which passed freely from the specimen through the permeable formboard to the indoor air, in a direction opposite to that of the heat flow. None, or only a small part, of the heat reaching the gypsum concrete remained to be conducted through it to the calorimeter plate and measured. The heat flow at the calorimeter increased as the vaporization and drying process progressed, causing the temperature at the interface of the materials to increase, yielding a gradual increase in the temperature difference and thermal resistance of the gypsum concrete, as indicated in Figure 6, weeks 7-9, 11-12, and 57-59. (A longer-term gradual rise in resistance of gypsum concrete is more clearly observed in Figure 7, weeks 15 to 25). The apparent thermal resistance of the glass fiber formboard decreased from near infinite to a measurable value as the heat flow reaching the calorimeter increased. The total temperature difference from the room to the calorimeter across the specimen remained relatively unchanged. Thus, the specimen was able to maintain its insulating integrity while expelling a considerable amount of moisture.

The summer drying rate of a specimen results primarily from evaporation of internal moisture and expulsion as vapor through its formboard undersurface during simulated daily solar heating of the top surface. Specimens 10 and 11 had lower summer drying rates than Specimen 9 (Table I) because of lower permeances of their formboards resulting in slower drying of their gypsum concrete covers as indicated by the slower recovery of thermal resistance (weeks 15-25, Figure 7 and weeks 31-45, Figure 8). Presumably, during the period of daily observation when heat was flowing toward the calorimeter, the lowered permeances of Specimens 10 and 11 as compared to Specimen 9 decreased the rate of evaporation from the underside of the moist gypsum concrete toward the room, so that the heat flow to the calorimeter did not approach zero, as in Specimen 9, and the thermal resistances of Specimens 10 and 11 remained measurable. Decreased thermal resistance shown during weeks 7-13, Figure 7 and weeks 5-11, Figure 8, after water was added in simulation of a roofing leak, was caused by a lowered thermal conductivity of the hygroscopic formboards whereas the thermal resistance of the gypsum at this time was already so low as to be negligible.

Specimens 9, 10 and 11 all gained weight and increased slightly or moderately in moisture content during winter exposure periods. The gain for Specimen 11 was very slight, and Specimen 10 showed a gain when its moisture content was low (0.6 lb/ft^2) but did not gain appreciably when its moisture content was high (2.5 lb/ft^2). Specimen 9 gained at an appreciable rate (0.06 lb/ft^2 week) during all winter exposure periods. The rate of moisture gain for these specimens apparently was controlled by their formboard material and perhaps also by the moisture content of the specimens.

At the rate of winter gain shown for Specimen 9 the increase in moisture content of the specimen could easily be accommodated during the longest winter period in the United States, and the accumulation of moisture would not severely reduce its insulating value and would speedily be expelled during a subsequent summer exposure period. This is important because the construction would not retain accumulated amounts of moisture winter after winter as it might do if a vapor barrier were used between components or there were a roofing leak. If the indoor vapor pressure were maintained at a higher value than used in the tests (54.5°F dewpoint), as in shower rooms and certain manufacturing processes, the quantity of moisture transferred into the construction over a winter period could become excessive.

The insulating value of the constructions during winter exposure periods remained stable. Under winter conditions, the moisture would tend to migrate toward the colder roof side. It will be noted that the thermal resistances of these specimens under winter exposure conditions was relatively higher when their moisture content was low (Specimen 9, first winter weeks 0-2, R = 4.5 and Moisture Content = 4.7 versus second and third winter weeks 26-31 and 48-57, R = 5.3 and Moisture Content = 0.3; similarly for Specimen 10, weeks 0-2 and 48-57 versus weeks 26-31; and for Specimen 11, weeks 24-29 versus weeks 45-55). Drying of the gypsum concrete cover during summer exposure periods was characterized by an increase in its thermal resistance. A similar trend may be noted for the insulating formboards of Specimens 10 and 11. Specimen 11 at week 38 exhibited a sudden change in the thermal resistance of its insulating formboard for which no explanation can be found.

Water was added to Specimens 9, 10 and 11 during summer exposure periods as shown in Figures 6, 7 and 8, respectively. During the first summer exposure period, the addition of water to the specimens was for the purpose of observing their performance at a time that would simulate the occurrence of a roofing leak soon after roll roofing would be applied to a new construction or a rain storm during application of the roofing. Later additions of water simulated a roofing leak after the construction had been subjected to one summer and winter exposure period with the exception of Specimen 11. The addition of water for this specimen was deferred until its third summer exposure because it did not reach a moisture content equilibrium during its first summer exposure period. The quantities of water added were 10 to 20 percent by specimen volume except during the third summer exposure condition. In the latter case water was continuously added to each specimen until the bottom surface of each specimen was wetted to the point where it barely had begun to drip. The quantities of water added are indicated on Figures 6, 7 and 8. Each specimen dried rapidly after an addition of water, and the added water did not seriously affect the overall thermal resistance of the specimens for long periods of time. Adding water to the gypsum concrete cover caused an immediate decrease in its thermal resistance as is apparent in the figures.

During the third winter exposure period, two spray coats of latex-base paint were applied to bottom or indoor surfaces of Specimens 9, 10 and 11. Coverage was only that needed to change the color and the coating did not dry as a continuous film. Changes in average permeability because of painting are indicated in Table I. Painting did not appear to seriously affect the rate of moisture gain to the specimens as evidenced by a comparison of the curves for the third winter exposure period with those of the second winter exposure period when the surfaces were not painted. When the exposure conditions were changed from the third winter to the third summer period, the specimens rapidly lost the moisture accumulated during the third winter exposure period, indicating that the painting procedure used offered no appreciable restriction to expulsion of moisture under summer exposure conditions.

Each specimen was examined when removed from the apparatus. The insulating formboards appeared as when installed. Leaching of the gypsum concretes had occurred at their upper surfaces, especially in an area directly beneath the hole in the calorimeter plate that was used for adding water to the specimens in simulation of a roofing leak. Figure 15 is a photograph showing the condition of the upper surface of the gypsum concretes of Specimens 9, 10 and 11 just after removal from the apparatus. During the tests water penetrated the central area of the specimens and was absorbed over the full volume of the gypsum concrete. Specimens 10 and 11 were in a much more wetted condition when removed from the apparatus as compared to Specimen 9. (Moisture contents for Specimens 9, 10 and 11 at this time were about 1.4, 6.2, and 4.5 lb/ft^2 roof area, respectively). This difference is discernible by the lighter shade of Specimen 9 in Figure 15. In the drying process the gypsum concrete remained wet for several weeks while being subjected to daily simulated solar heating. The combination of heat and moisture caused leaching of the upper surface of the gypsum concrete. It is probable that the cavities were formed by the solution of gypsum and its deposition elsewhere in the pore space of the specimens. The summer cycle of the specimens probably carried the temperature of the gypsum above the point at which gypsum is in its stable phase, and under these conditions it could be expected to dissolve and reprecipitate as anhydrite, with a higher density and hence a smaller specific volume.

6.3. Discussion - Perlite and Vermiculite Concrete Cover Specimens 12 and 13

Specimens 12 and 13, Figures 9 and 10, were made with wood-fiber insulating formboards which were permeable to water vapor and which constituted about six-tenths of the thermal resistance of the specimens, when calculated on the basis of thermal conductivity values determined on oven-dry samples. The top layers of these specimens were insulating concretes made with perlite and vermiculite aggregates, respectively. The permeances of the insulating concrete layers were lower than those of the formboards but their thermal conductivities, thicknesses, and water-holding capacities were higher.

The average comparative insulating values of Specimens 12 and 13 were 65 and 82 percent, respectively. Thermal resistances, as plotted in Figures 9 and 10, changed relatively little with changes of exposure conditions from winter to summer or with large changes in specimen moisture content, when compared with other specimens tested. In view of the greatly reduced insulating values observed over long periods of time for previously-tested specimens that contained wetted insulation over relatively impermeable concrete decks, the stability of the insulating performance of Specimens 12 and 13 shown here is a definite practical improvement. These specimens self-dry in place if wetted and at the same time provide fair insulating value, although not as much as expected for dry materials. Insulating values observed were lower than dry values because the specimens contained moisture throughout the tests. A sudden increase in moisture content, when water was added at week number 42 to simulate a roofing leak, caused a decrease in the thermal resistance of the insulating concretes but little change in the resistance of the formboards. The performances of the wetted specimens, from week 43 onward, appeared substantially similar to their performances during weeks 1 to 4 when their moisture contents were the same.

The drying rates for Specimens 12 and 13 were less than for Specimens 9, 10 and 11. Their moisture contents decreased from initial high values of 4 or 5 lb/ft^2 to about 1 lb/ft^2 in 23 weeks of exposure to the summer conditions. The moisture content of 1 lb/ft^2 appears to be approximately an equilibrium value for these constructions under the summer conditions and, in service, presumably would be substantially reached in five months of spring and summer weather. The rate of moisture gain during the winter condition of the tests was small, even when the specimen moisture content was near the summer equilibrium value, and the moisture gained in several months of winter would be expelled in a few weeks of the summer exposure conditions.

At week 42, Figures 9 and 10, water was added to the specimens in simulation of a roofing leak. It was much more difficult to add water to the perlite and vermiculite concrete top covers than to the gypsum concretes of Specimens 9, 10 and 11. Water was added slowly to these specimens for about 4 days. The undersurface of the insulating board formboard did not get wet and, when the quantity added approached that of the initial construction moisture content, water addition was terminated. The quantities added were 14.5 and 17.2 percent of specimen volume for Specimens 12 and 13, respectively.

Each specimen was examined when removed from the apparatus. The materials appeared substantially as when installed. The insulating board formboard was moist and had increased in length by approximately 1/8 inch in 23 inches, and in thickness by about 1/16 inch in 1 1/2 inches.

6.4. Discussion - Perlite and Vermiculite Cover Over Thin Formboards - Specimens 14, 15 and 16

The constructions of Specimens 14 to 16, Figures 11 through 13, consisted of a 6- to 7-inch thickness of perlite or vermiculite aggregate concrete placed over a formboard of 1/2-inch thick gypsum or 1/4-inch thick cement-asbestos board. Previous work (NBS Report 6283), with about 6-inch thick specimens of perlite, vermiculite, and cellular concrete with no formboard, had indicated that these materials had self-drying characteristics, with increasing insulating values as the specimens approached their equilibrium moisture contents. Since it may not be practical to place these materials on the job without using a permanent type of formboard, Specimens 14 to 16 were designed to include two possible types of formboards. The gypsum formboard had a permeance of about 28 perms (Table I), and the cement-asbestos board permeance was about 0.8. The formboards contributed very little thermal resistance to the specimens. The calculated overall permeances of the specimens were low (about 0.33 to 1.7), as compared to other specimens. The dry thermal conductivity of the vermiculite concrete was about twice that of the perlite concrete (See Table I) because of its greater density, which was selected to provide different conductivity and compressive strengths, for the two concretes.

The comparative average insulating values of Specimens 14, 15 and 16 were 36, 46 and 42 percent, respectively. These values are low, compared to those for other specimens, because of the relatively high moisture contents maintained throughout the exposure tests. Appreciable drying did occur during summer exposure conditions, but because of the high initial moisture contents, the specimens did not reach their presumable low moisture equilibriums during the total test duration. It is estimated that to reach substantial summer equilibrium values, about two summer seasons would be needed in service. Moisture gain rates during winter exposure conditions were very small, at the existing specimen moisture contents. Specimen 16 actually lost weight during the winter exposure conditions (weeks 7-13 and 29-39), but a small gain rather than a loss would probably occur in winter when the specimens had been dried to a summer equilibrium moisture content.

The insulating values of the specimens, which were very largely those of the insulating concrete layers, increased as their moisture contents decreased. The formboards of Specimens 14 and 15 were of moderately high permeance, and did not materially decrease their drying rates, as indicated by the slight change in the summer drying rate of Specimen 14 when its formboard was removed (week 26). The formboard of Specimen 16, however, was of low permeance and impeded drying, as is indicated by the substantial increase in drying rate when the formboard was removed (week 26).

Winter thermal resistance values were higher than summer values for these specimens, because of their appreciable moisture contents during the period of observation. The higher winter values are due to concentration of moisture in the upper (continuously colder) parts of the insulating concrete, which caused the lower parts to be dryer, and reduced latent heat transfer. In the summer exposure conditions, the moisture content of the specimen was kept more uniformly distributed by the daily reversals of temperature difference in the specimen, and latent heat transfer contributed to heat flow.

Water was added to Specimens 14 and 16 at week 42, the amounts added being the maximum accepted by the specimens in one or two weeks, as shown on Figures 11 and 13. In neither case did dripping of water from the undersurface of the specimen occur. In service, such resistance to acceptance or penetration of water entering through a roof leak might be of value, but it would also provide little evidence visible from the interior that a roof leak was in need of repair.

7. SUMMARY

1) Heat transfer and self-drying characteristics are reported for nine formboard-type insulated flat-roof specimens containing moisture, as determined in the laboratory with their indoor surfaces exposed to a constant room environment of 90°F and 30 percent relative humidity (54.5°F dewpoint) and their exterior surfaces subjected to successive periods of simulated summer and winter temperature conditions, each with daily simulated solar heating.

2) Average insulating values of six of the nine specimens, each of which initially contained construction moisture and later was deliberately wetted at least once during the tests, ranged from 63-82 percent of that expected for dry materials. These specimens were in general the thinner ones of the group (all were designed on the basis of $U = 0.12$ Btu/hr ft^{2}°F when dry) and all showed self-drying characteristics during summer exposure periods. The more rapid drying rates were observed for the specimens having greater overall permeance to water vapor. In service, it was estimated that all of these specimens would dry to a substantial moisture content equilibrium during a normal spring-summer-fall season. Moisture gained during a winter exposure period was moderate and the accumulated moisture was easily held by the specimens, with rapid expulsion during the subsequent summer exposure. Drying of these specimens when wetted as a result of a roofing leak could be accomplished by their normal solar heating in summer without removing the materials from the roof.

   Insulating values for the three remaining specimens, which were the thickest of the group (6-7 inches), and which contained relatively large quantities of moisture, ranged from 36 to 48 percent of dry values. It was estimated that perhaps 2 or 3 summer seasons of drying would be required to improve their insulating values materially.

3) Results show that the formboard constructions tested may be lightly spray-painted for decorative purposes on their indoor exposed surfaces without seriously affecting their ability to dry when moist. Leaching was observed in gypsum concrete when wetted by simulating a roofing leak as was some expansion of wood-fiber insulating board.

4) In review of the results obtained in this and previous reports, it is concluded in general that a practical engineering solution for coping with moisture in insulated roof decks over normal occupancy (maximum dewpoint 54.5°F) is to use an insulating formboard permeable to water vapor and cover it with a not-too-thick lightweight water absorbent concrete without a vapor barrier between components.

The factors that control the heat and moisture transfer performance of such a construction have been identified in this report as exposure conditions, thickness and arrangement of component materials, and materials properties of thermal conductivity, water vapor permeability, water absorbency, and hygroscopicity. However, a design rule relating these factors in a manner suitable for predicting performance of constructions composed of any combination of insulation and building material was not obtained. Further research is needed to develop simpler and more rapid methods of measurement and a general relationship for the several variables involved in simultaneous heat and moisture transfer.

8. COMPARATIVE EVALUATION OF SPECIMENS

Comparison of various insulated flat-roof constructions in respect to insulating value and moisture content cannot be made on the basis of the performance of the insulating materials alone, except in the case of insulating materials completely impermeable to water and water vapor. Superiority of one construction over another depends upon relative ability to keep the construction dry, or to effect self-drying if it should become moist. Important factors involved are the dewpoint temperature of the indoor air and its variation with time or season; the vapor and thermal resistance; absorbency, and moisture content of the deck and insulating materials; the use of a vapor barrier beneath the insulation; the arrangement and thicknesses of the components of the construction; the temperature variations imposed on the built-up roofing; the long-term susceptibility of the roofing for leakage; and damage to materials immediately below the roofing from freeze-thaw effects.

The moisture content of the roof construction when first completed determines its immediate insulating effectiveness, but the other factors listed, in the long run, ultimately control its moisture content and insulating performance. To classify the roof constructions discussed in this report, in terms of their relative freedom from impairment of insulating effectiveness due to moisture, requires an estimate, good for long periods, of the probability of moisture entry into the construction, as it may be affected by initial conditions, continued service, and roof leaks. The classification and discussion below pertain only to the constructions listed, and for the exposure conditions used.

In NBS Report 6283, which dealt chiefly with tests of insulated roof constructions having dense concrete decks, and their insulating performance when they contained moisture, under summer and winter exposure conditions with simulated daily solar heating, it was shown that the dense concrete decks had effective resistances to the passage of moisture or vapor approaching those of vapor barriers. Thus, if a construction contained moisture, the deck, with or without an applied vapor barrier, greatly impeded its expulsion, and wet insulation in the construction dried little with continued exposure, even to summer conditions, and therefore the construction was seriously impaired in insulating performance. If the insulation were dry, the deck protected it against vapor entry from the under-roof space. However, this advantage is slight in consideration of probable initial moisture in many roof constructions and the wetting possible as a result of accidental or eventual roof leaks. In the same report, data were presented for a few 6-inch thick monolithic insulating concrete roof specimens, which were found to exhibit self-drying characteristics, under the test summer exposure conditions, which resulted in substantial drying of contained moisture through the undersurface of the specimen. Regain of moisture during the test winter exposure conditions was low and of relatively minor importance. These findings suggested the possibility, and value, of developing insulated roof constructions having satisfactory self-drying characteristics, with improved recovery of insulating value following accidental or other wetting of the roof construction.

NBS Report 7347 dealt chiefly with tests of some practical insulated roof constructions having permeable under-decks that would allow self-drying of the wetted construction to the room beneath with a resultant increase in insulating value. Exposure conditions were made to simulate natural exposure, and it was shown that decks permeable to water vapor, such as gypsum concrete and glass fiber formboards, allowed wetted specimens to dry to the indoors after a few weeks' exposure to summer conditions and to quickly recover their insulating values. Also, the quantity of moisture gained during winter exposure was relatively low and was easily expelled during a subsequent summer exposure. It was also shown that a 100 pcf, 1-inch thick concrete deck, such as used for the web section of prefabricated concrete building panels, inhibited the drying of wet insulations placed over it, and prevented recovery of their insulating value during long periods of summer exposure.

In the present report, results are given for nine insulating roof specimens of designs selected with a view to their self-drying characteristics and moisture-holding capacity. Most designs chosen were thought practical for construction on buildings, but were also selected to cover a wide range of components and component properties to enable investigation, in some measure, of the factors involved in good self-drying and insulating characteristics. Thus, they were constructed with several kinds of commercially available formboards and covered with three different concretes, yielding a range of water vapor permeance and thermal conductance values. Details of the nine constructions are given in Section 3 and Table I of this report.

As given below, these nine specimens are listed in decreasing order of merit, as judged on the basis of their insulating and self-drying performances and as to their overall suitability as practical insulated flat-roof-deck constructions. The order given is estimated on the basis of the results in this report, and it is not to be inferred that the results can be extrapolated for more severe moisture or temperature conditions than those to which the specimens were subjected in the tests, i.e., an under-roof dewpoint temperature of 55°F, and a concomitant minimum roof-top surface (long-term) temperature of 38°F. After each listing, qualifying remarks are made to assist in judging the feasibility or limitations of the constructions for various types of applications.

1. Specimen No. 12 (Figure 9) - 1 5/8-inch wood-fiber formboard; 3-inch perlite insulating concrete.

2. Specimen No. 13 (Figure 10) - 1 1/2-inch wood-fiber formboard; 3-inch vermiculite insulating concrete.

These specimens are listed first because of their stable insulating value year-round, regardless of large changes of moisture content and seasonal temperature conditions. They have the ability to self-dry in summer and gain only moderate accumulations of moisture in the concretes over a winter, which are soon expelled from the construction during the following summer. They have sufficient moisture-holding capacity to hold a considerable quantity of moisture without dripping. The concretes contain considerable free moisture when placed, and it is recommended that they be dried as much as is practical before the built-up roofing is applied. The insulating concrete cover on the top side would help to restrict the ingress of water should the roofing leak. Evidence of a large roof leak would show as a wet spot on the interior face of the formboard, or as a slow drip from its surface. After the roof leak was sealed, the construction would tend to dry rapidly in summer, and if very wet possibly rather slowly in winter, by expulsion of moisture through its undersurface. For a not-excessive or neglected leak, it is believed the roof components would not need replacement. If dried to a moisture equilibrium with the interior in summer, the concrete becomes dry enough to serve as a moisture sink in winter and to an appreciable degree it resists rapid absorption of water, thus backstopping the roofing. The insulating formboard provides the major share of the insulating value of the construction, and is permeable enough to allow vapor passage for self-drying, and at the same time is absorptive enough for liquid water to prevent immediate excessive dripping. The indoor face can be spray painted for decoration without seriously interfering with the expulsion of moisture in summer. It is believed that this construction could serve open to the room as a ceiling or, with a hung ceiling provided there is free communication of plenum air with indoor air to dissipate moisture vapor that might be expelled from the roof construction in summer. Alternatively, the hung ceiling could form an air plenum for a heating, ventilating, or air conditioning system, which would assure dissipation of accumulations of water vapor from the plenum.

These specimens did not exhibit the insulating values to be expected for the dry constructions, primarily because they always contained some moisture in these tests. The hygroscopic component materials would always contain some equilibrium amount of moisture, but under the simulated service exposure conditions they exhibited ability to dry to this equilibrium moisture content. The ability to dry in place when wetted while maintaining a stable insulating value was considered to be of primary importance. Expansion of wood-fiber insulating board when wetted was observed during the tests. The importance of this, and accommodation for it in the design of an insulated flat-roof-deck construction, was not within the scope of this investigation.

3. Specimen No. 9 (Figure 6) - 1 1/2-inch glass fiber formboard; 2-inch gypsum concrete cover.

4. Specimen No. 11 (Figure 8) - 2 3/4-inch wood-fiber formboard; 2-inch gypsum concrete cover.

5. Specimen No. 10 (Figure 7) - 3-inch Tectum board formboard; 2-inch gypsum concrete cover.

These constructions have the ability to self-dry under summer exposure conditions, if wet (Specimens 9 and 10 quite rapidly), and do not accumulate moisture in winter exposure conditions to a degree that seriously affects their insulating value. Their year-round insulating value was good, but subject to a greater variation with changes of season and moisture content as compared with Specimens 12 and 13. Increasing the formboard thickness to 2 3/4 inches for Specimen 11 versus 1 1/2 inches for Specimen 13 did not produce a proportional increase in insulating value and therefore use of this formboard in thicknesses greater than about 2 inches does not appear warranted. The insulating values of these specimens were lower than expected for dry specimens, but were fairly stable year-round, even when the specimens were subjected to large changes in moisture content.

These constructions are rated a little lower than those of the first group, although their test performance was approximately as good, for two reasons. The first is that Specimens 9 and 10 containing quite porous formboards under a very absorptive concrete may allow a greater ingress of water through a roofing leak than the insulating concrete of the first group. This possibility must be weighed against the desirable characteristic of a more rapid drying rate in the event of wetting. The second reason is that with an excessive amount of water in the gypsum concrete (as might occur with a roof leak), there is a tendency for the water to dissolve holes locally in the gypsum (leaching, see Figure 15). If the latter process went to extremes, a perforation of the gypsum deck could occur in some cases and deluge a local area below the roof. Once a roof leak had been stopped, the self-drying and recovery of insulating value with these constructions would probably be faster than with those of the first group, and corrective maintenance would be about equal and rather easy. Specimen 11 would have the advantage of preventing a deluge of water in the event of gypsum leaching, but probably would drip copiously when saturated.

6. Specimen 17 (Figure 14) - 3-inch Tectum formboard.

This construction exhibited good self-drying and insulating characteristics. However, it is relatively low in water-holding capacity, and with an air dewpoint as high as 54°F underneath, the moisture gain under winter conditions might exceed this capacity, allowing dripping of condensed water. In the tests, the asphalted-felt factory-applied to the top surface was removed to allow water input in simulation of a roof-leak. Water added began to drip from the undersurface when the amount reached about 0.9 lb/ft^2; if the asphalted-felt had not been removed, unsealed joints between boards would have allowed a similar passage of water. It is considered that this construction is suitable for use in moderate climates with severe cold spells of only moderate duration, and preferably with relatively low indoor dewpoints. For more extreme conditions, caution may be necessary because of the relatively small moisture-holding capacity of the construction, and a construction like that of Specimen 10 would be preferable.

7. Specimen 14 (Figure 11) - 1/2-inch gypsum formboard; 6-inch perlite insulating concrete.

8. Specimen 15 (Figure 12) - 1/2-inch gypsum formboard; 6 3/4-inch vermiculite insulating concrete.

9. Specimen 16 (Figure 13) - 1/4-inch cement-asbestos formboard; 7-inch vermiculite insulating concrete.

These constructions are considered much less desirable than those preceding, because of the quantity of moisture that must be removed by self-drying, the long time required for its removal, and their seriously impaired insulating value when wet. The low permeance of the cement-asbestos board is particularly disadvantageous. These constructions are more resistive to water penetration due to roof leaks as compared to others, but if a leak should occur in the roofing they would give less or no immediate indication, on their undersurfaces, of its existence, or location. Some difficulty in supporting a wet mix of insulating concrete 6-7 inches in thickness during initial placement would be anticipated, but possibly could be overcome with a steel reinforcing mesh and placement in stages of two or more thicknesses. Another possible difficulty during the first winter would be the concentration and subsequent freezing of moisture in a layer at the top cold outdoor side of the concrete which may cause freeze-thaw damage to this layer. This would be more probable if the concrete were placed in late fall with little time for self-drying of the construction. However, deterioration was not observed during the tests, in which freezing conditions were not used.

Table I. Details of Specimens

Spec. No.	Materials	Thickness in.	Properties, oven-dry: Density lb/ft³	Properties, oven-dry: Th. Cond. at 75°F MT Btu/hr ft²(°F/in.)	Final Moisture content[a] % above dry wt	Water vapor permeability[b] Grains/hr ft²(in. Hg/in.): Unpainted	Water vapor permeability[b] Grains/hr ft²(in. Hg/in.): Spray painted	Calculated values[o] Thermal Resistance, °F/(Btu/hr ft²): Specimen (Design R-Dry)	Calculated values[o] Thermal Resistance, °F/(Btu/hr ft²): Formboard	Calculated values[o] Thermal Resistance, °F/(Btu/hr ft²): Top Cover	Calculated values[o] Permeance, grains/hr ft² in. Hg: Specimen	Calculated values[o] Permeance, grains/hr ft² in. Hg: Formboard	Calculated values[o] Permeance, grains/hr ft² in. Hg: Top cover	Average summer-winter comparative insulating value, test/dry specimens, percent	Averaged ranges: Summer drying rate lb/ft² week	Averaged ranges: Winter regain rate lb/ft² week
9	Gypsum concrete[c] Glass fiber formboard	2 1 1/2	56.7 11.6	1.95 0.26	6.8 1.4	26.7 44.7[d]	--- 39.4[d]	6.84	5.81	1.03	9.2	29.8	13.4	73	0.13- 1.1	0.05- 0.06
10	Gypsum concrete[c] Tectum board[n]	2 3	56.7 24.0	1.95 0.60	37.5[e]	24.7 26.0[d,f]	--- 27.5[d,f]	6.06	5.03	1.03	5.1	8.7	12.4	66	0.08- 0.37	0- 0.05
11	Gypsum concrete[c] Insul board (plain)[g]	2 2 3/4	56.7 18.1	1.95 0.39	34.8[e]	26.0 22.6[d]	--- 20.2[d]	8.01	6.98	1.03	5.0	8.2	13.0	63	0- 0.22	0
12	Perlite concrete[h] Insul bd(asphalt & plain)[i]	3 1 5/8	31.6 18.9	0.78 0.39	31.8 13.4	11.9 20.0[d](14.9)[j]	--- 5.3[d]	7.99	4.15	3.84	3.0	12.3	3.97	65	0.06- 0.2	0.02- 0.05
13	Vermiculite concrete[k] Insul bd(asphalt & plain)[i]	3 1 1/2	41.1 18.9	1.47 0.39	32.5 13.4	5.4 20.8[d](19.5)[j]	--- 16.2[d]	5.87	3.83	2.04	1.6	13.9	1.8	82	0.06- 0.29	0- 0.04
14	Perlite concrete[h] Gypsum formboard[l]	6 1/2	31.6 50.4	0.78 1.04	26.0 ---	11.1 14.7	--- ---	8.16	0.48	7.68	1.74	29.4	1.85	36	0.09- 0.39	0
15	Vermiculite concrete[k] Gypsum formboard[l]	6 3/4 1/2	40.1 50.4	1.50 1.04	24.8 15.5	6.3 13.5	--- ---	4.98	0.48	4.50	0.9	27.0	0.93	46	0.17- 0.9	0
16	Vermiculite concrete[k] Cement-asbestos board	7 1/4	40.1 109.8	1.50 4.13	29.1 ---	4.0 0.2(0.125)[m]	--- ---	4.73	0.061	4.67	0.33	0.8	0.57	42	0.08- 0.16	0
17	Tectum board[n]	3	24.0	0.60	9.3	40.2[d,f]	46.2[d,f]	5.03	5.03	---	13.4	13.4	---	76	0.01- 0.12	0.003- 0.044

a. Gypsum concrete was oven dried to constant weight at 110-115°F; all other materials at 215°F.
b. Specimens were 4 1/4-in. diameter and 1/2-in. thick, except cement-asbestos board (No. 16) which was 1/4-in. thick. The method of test was ASTM E96-53T, Procedure A.
c. Mix: 8 gal. water per 80 lb sack; compressive strength 565 psi on a 2-in. cube after 7 days at 70°F, 30% RH and 24 hours in a desiccator.
d. Specimens were measured with normal factory finish and with two light spray coatings of latex base paint, which covered only enough to change color and did not set as a film coating.
e. Value is for combined materials.
f. Rough interior surface factory finished with sprayed white paint.
g. Insulating board made of 5 plies, each about 9/16-in. thick laminated together with a glue reported to be vapor permeable.
h. Mix: 1 to 6 by volume; water content 102 lb/sack of portland cement; 28 day compressive strength 365 psi on 3-in. by 6-in. air dry cylinders.
i. Insulating board made of three, approximately 1/2-in. thick plies laminated together with a glue reported to be vapor permeable. The two upper plies had an asphaltic binder and the indoor ply had the normal binder.
j. Value in parenthesis is for asphalt impregnated board.
k. Mix: 1 to 4 by volume; water content 92 lb/sack of portland cement; 28 day compressive strength 860 psi on 3-in. cubes oven-dried.
l. Gypsum formboard made from gypsum enclosed by heavy kraft paper and is produced especially for roof decks.
m. Value in parenthesis is for smooth surface of the specimen exposed on the top of the dry-cup during permeance tests. Value of 0.2 is for rough side of specimen exposed.
n. Asphalted felt top surfacing of insulation removed before fabrication into a specimen.
o. Values given were calculated from thermal conductivity and permeability data listed here, using the relationships $R=x(\text{thickness})/k$ and $P=\mu/x$, respectively. Component resistances were added in series to obtain the specimen resistance.

CALORIMETER TEMPERATURE VARIATIONS TO SIMULATE SOLAR EFFECT

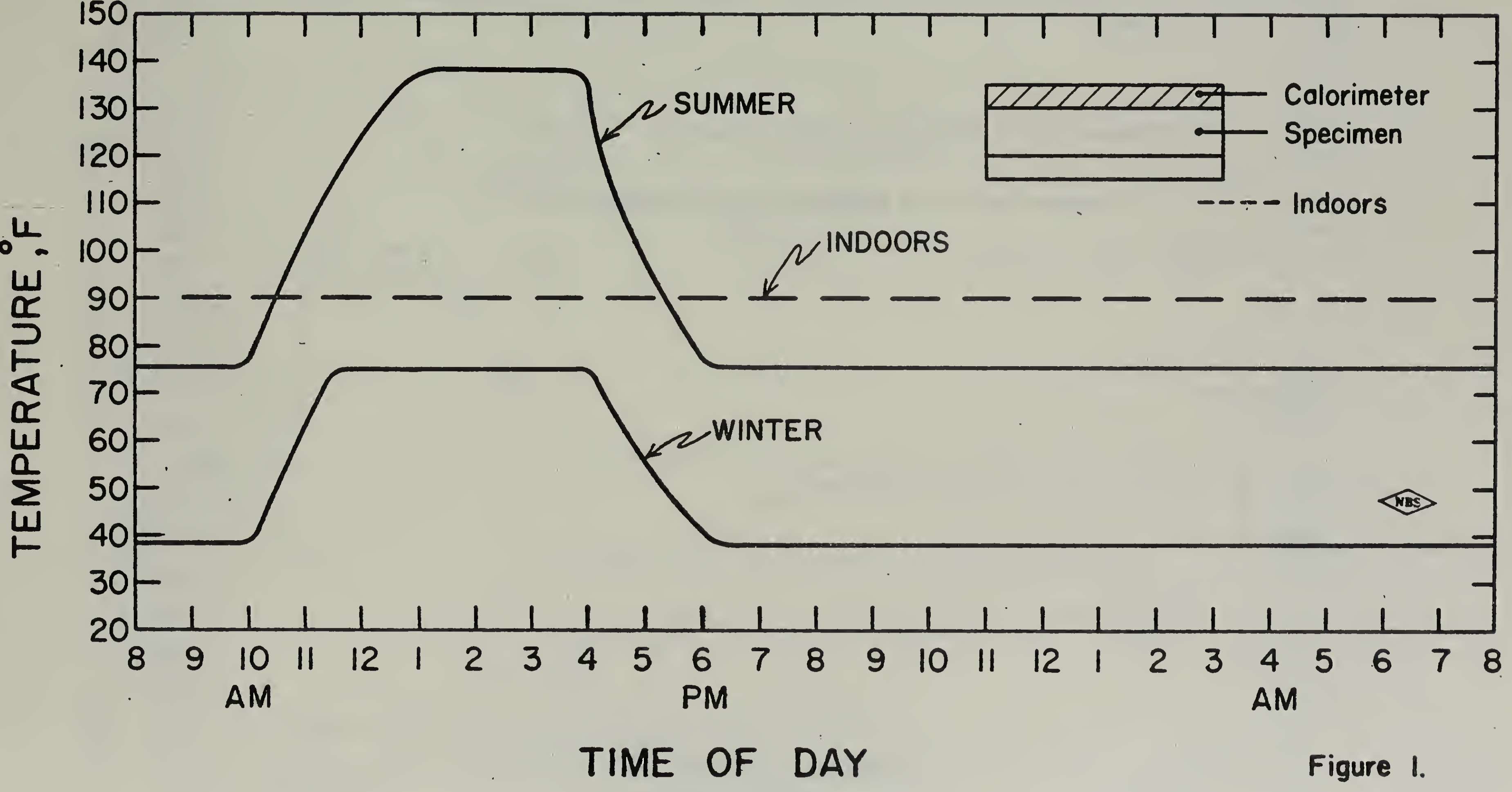


Figure I.

USCOMM-NBS-DC

SPECIMEN 9

TEMPERATURES AND TOP SURFACE HEAT FLUX-SUMMER EXPOSURE

2" GYPSUM CONCRETE
NO VAPOR BARRIER
1.5" GLASS FIBER FORMBOARD

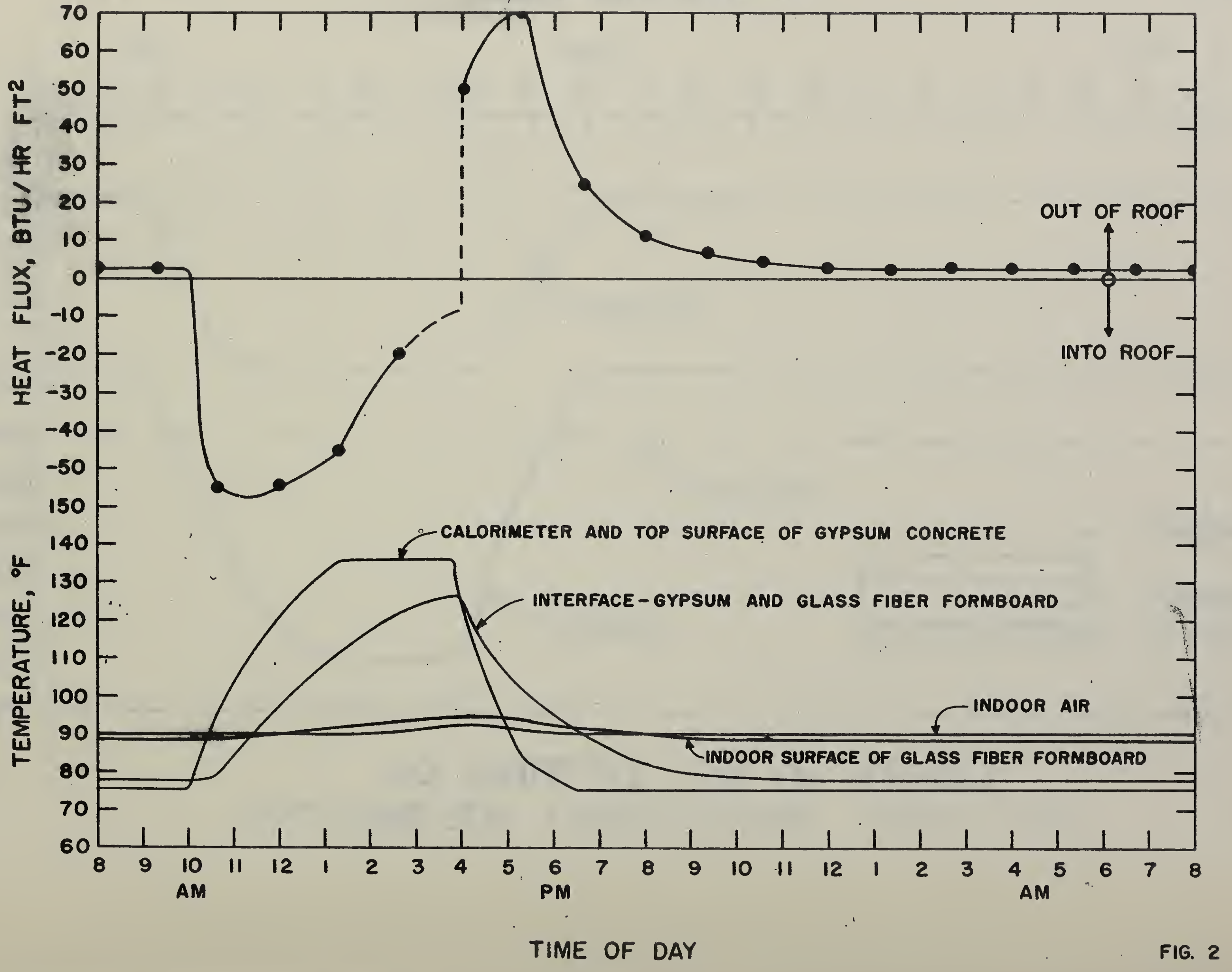


FIG. 2

TEMPERATURES AND TOP SURFACE HEAT FLUX-SUMMER EXPOSURE

2" GYPSUM CONCRETE
NO VAPOR BARRIER
3" TECTUM BOARD

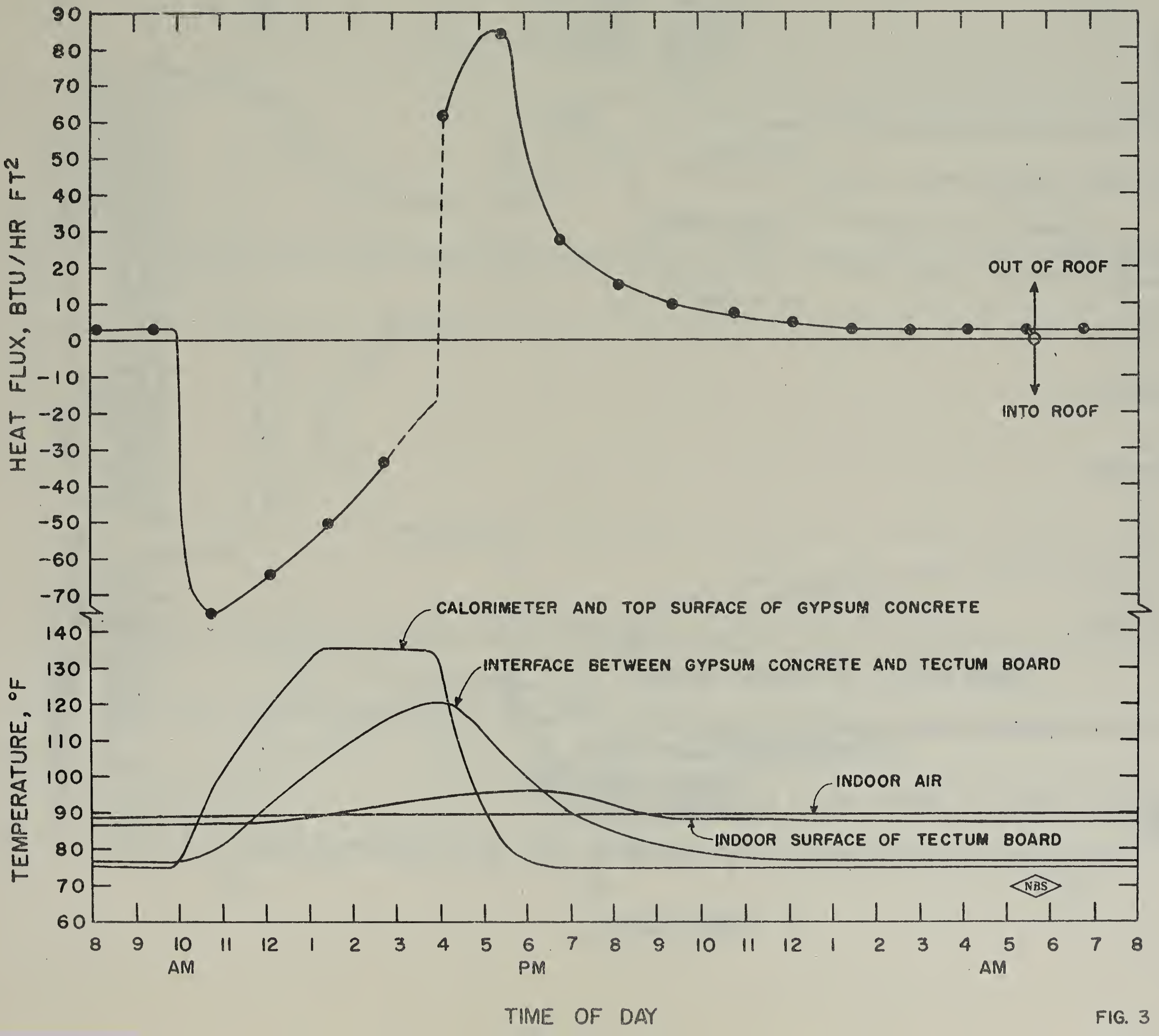


FIG. 3

SPECIMEN 9

TEMPERATURES AND TOP SURFACE HEAT FLUX-WINTER EXPOSURE

2" GYPSUM CONCRETE
NO VAPOR BARRIER
1.5" GLASS FIBER FORMBOARD

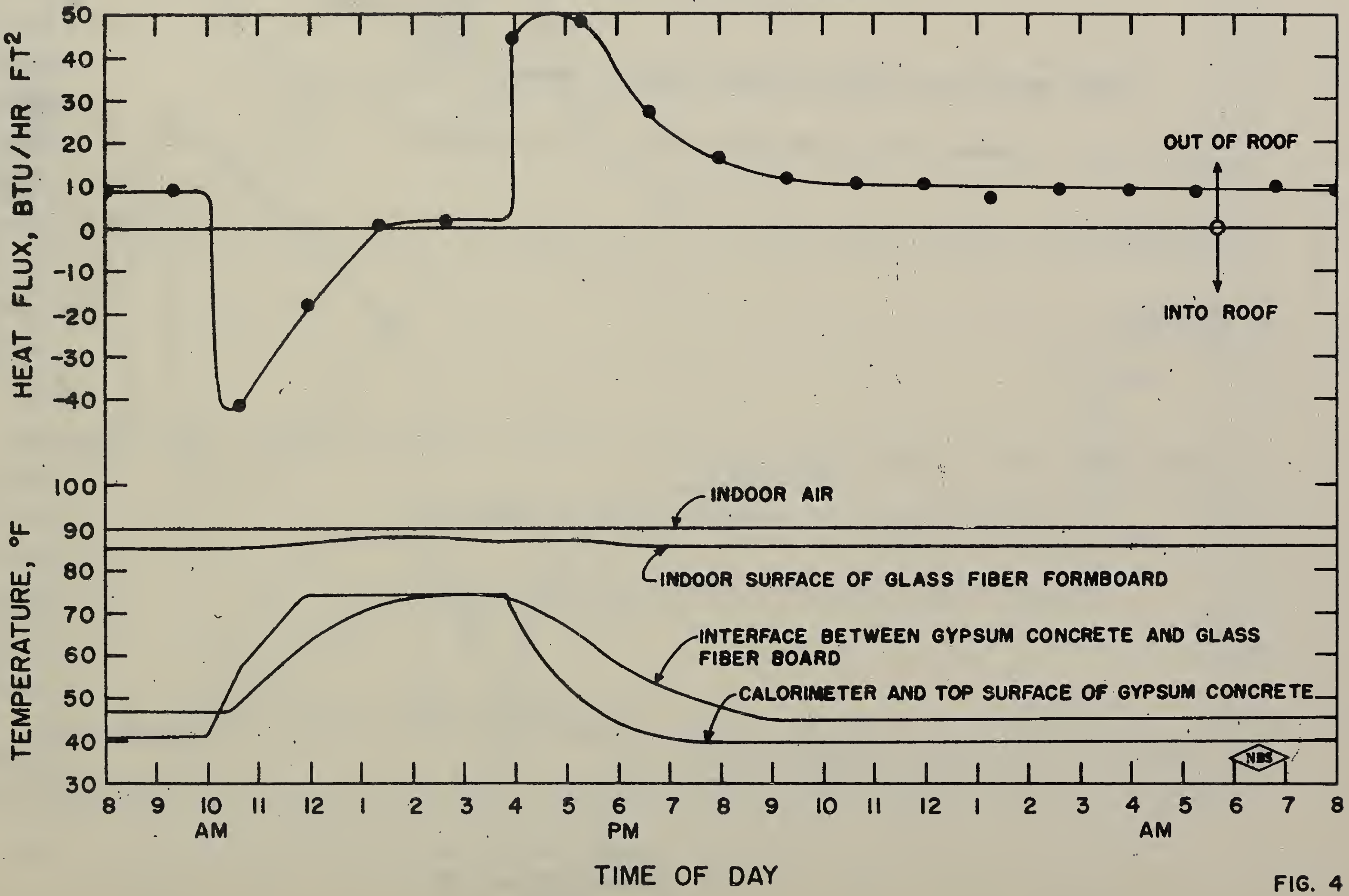


FIG. 4

SPECIMEN 10

TEMPERATURES AND TOP SURFACE HEAT FLUX-WINTER EXPOSURE

2" GYPSUM CONCRETE
NO VAPOR BARRIER
3" TECTUM BOARD

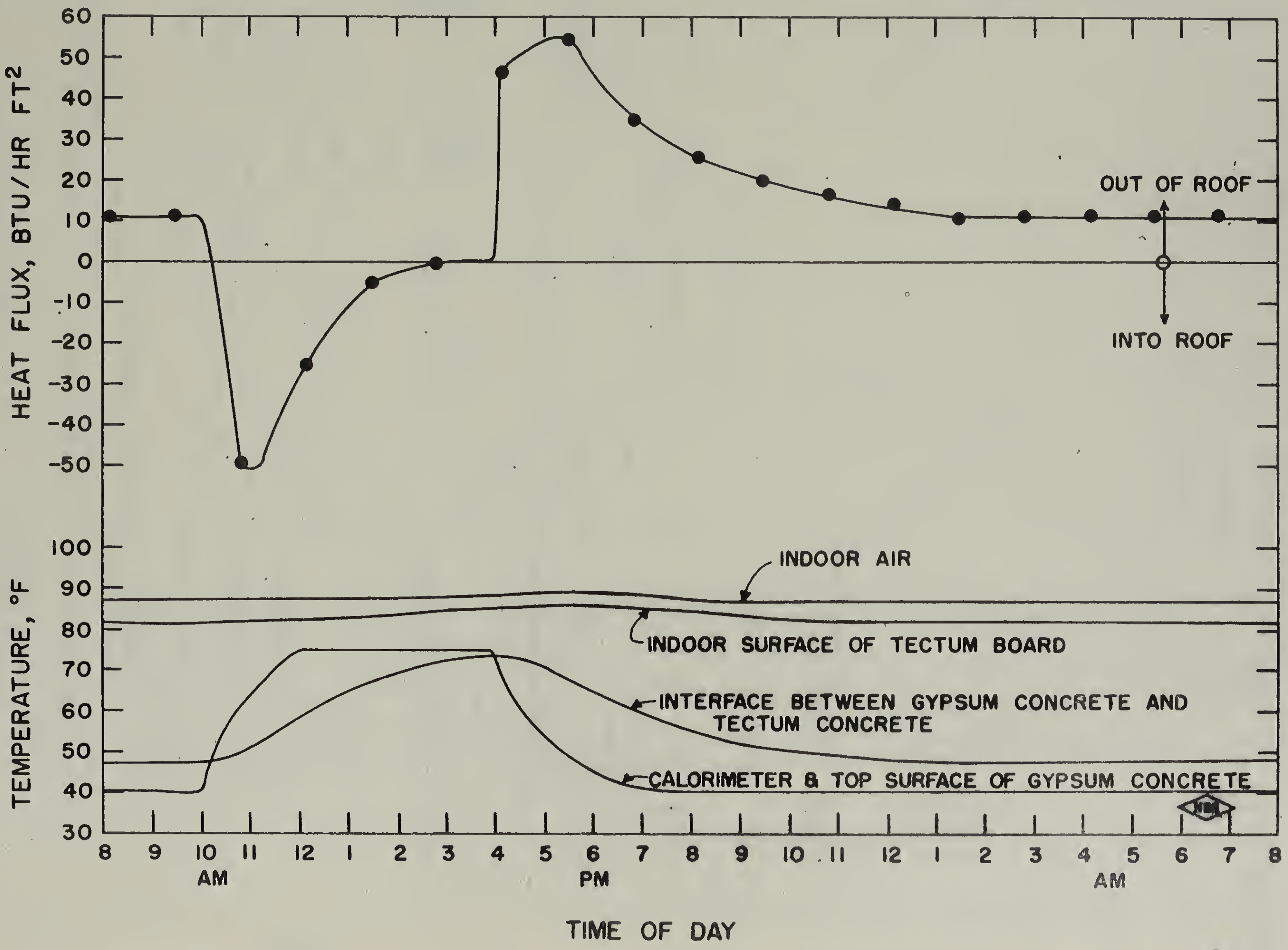


FIG. 5

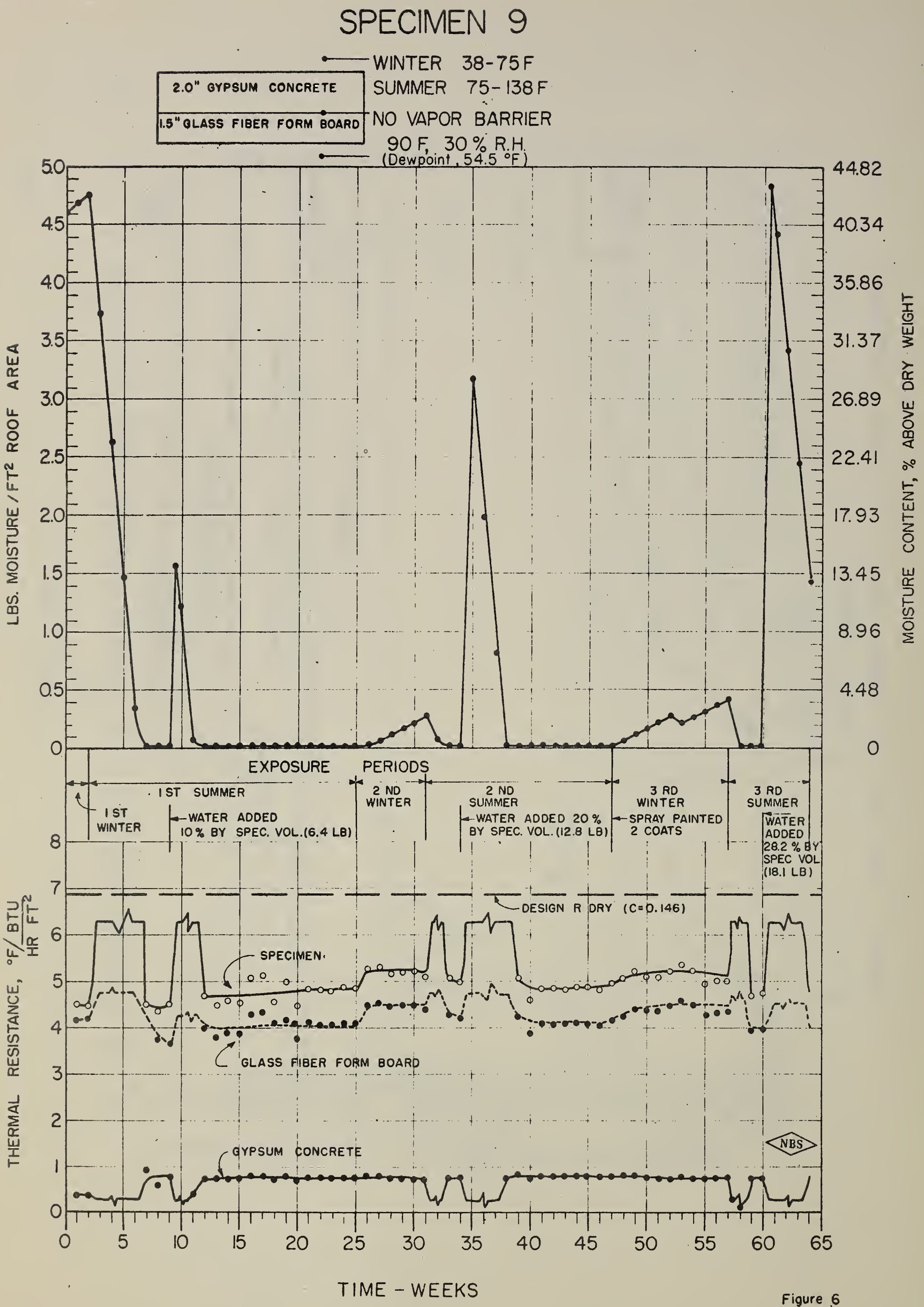

SPECIMEN 9
2.0" GYPSUM CONCRETE
1.5" GLASS FIBER FORM BOARD
WINTER 38-75F
SUMMER 75-138F
NO VAPOR BARRIER
90 F, 30 % R.H.
(Dewpoint, 54.5 °F)
LBS. MOISTURE / FT² ROOF AREA
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0
MOISTURE CONTENT, % ABOVE DRY WEIGHT
44.82
40.34
35.86
31.37
26.89
22.41
17.93
13.45
8.96
4.48
0
EXPOSURE PERIODS
1 ST WINTER
1 ST SUMMER
WATER ADDED 10 % BY SPEC. VOL. (6.4 LB)
2 ND WINTER
2 ND SUMMER
WATER ADDED 20 % BY SPEC. VOL. (12.8 LB)
3 RD WINTER
SPRAY PAINTED 2 COATS
3 RD SUMMER
WATER ADDED 28.2 % BY SPEC VOL (18.1 LB)
DESIGN R DRY (C=0.146)
SPECIMEN
GLASS FIBER FORM BOARD
GYPSUM CONCRETE
THERMAL RESISTANCE, °F/(BTU/HR FT²)
8
7
6
5
4
3
2
1
0
NBS
0
5
10
15
20
25
30
35
40
45
50
55
60
65
TIME - WEEKS

Figure 6

SPECIMEN 10

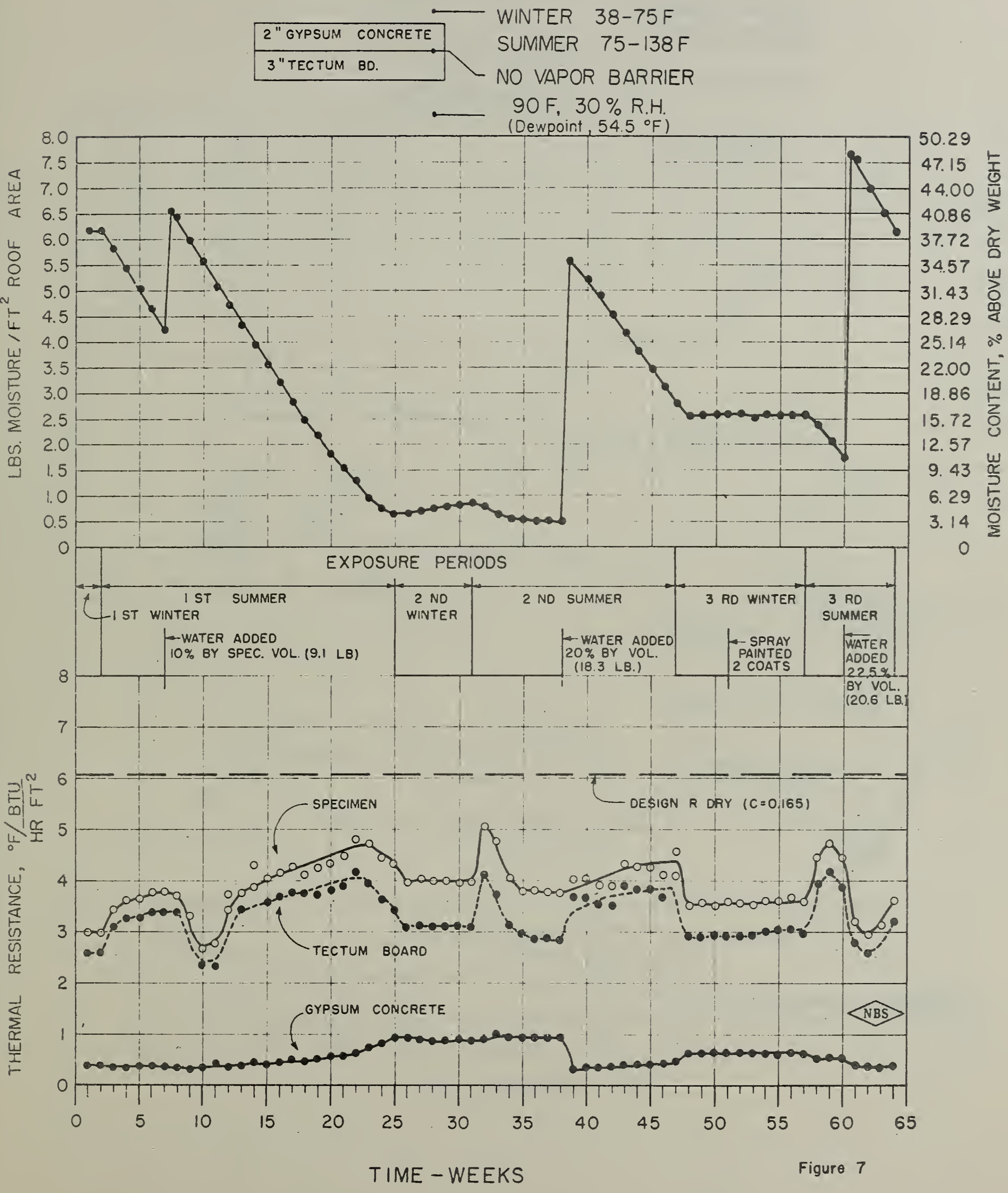


Figure 7

SPECIMEN II

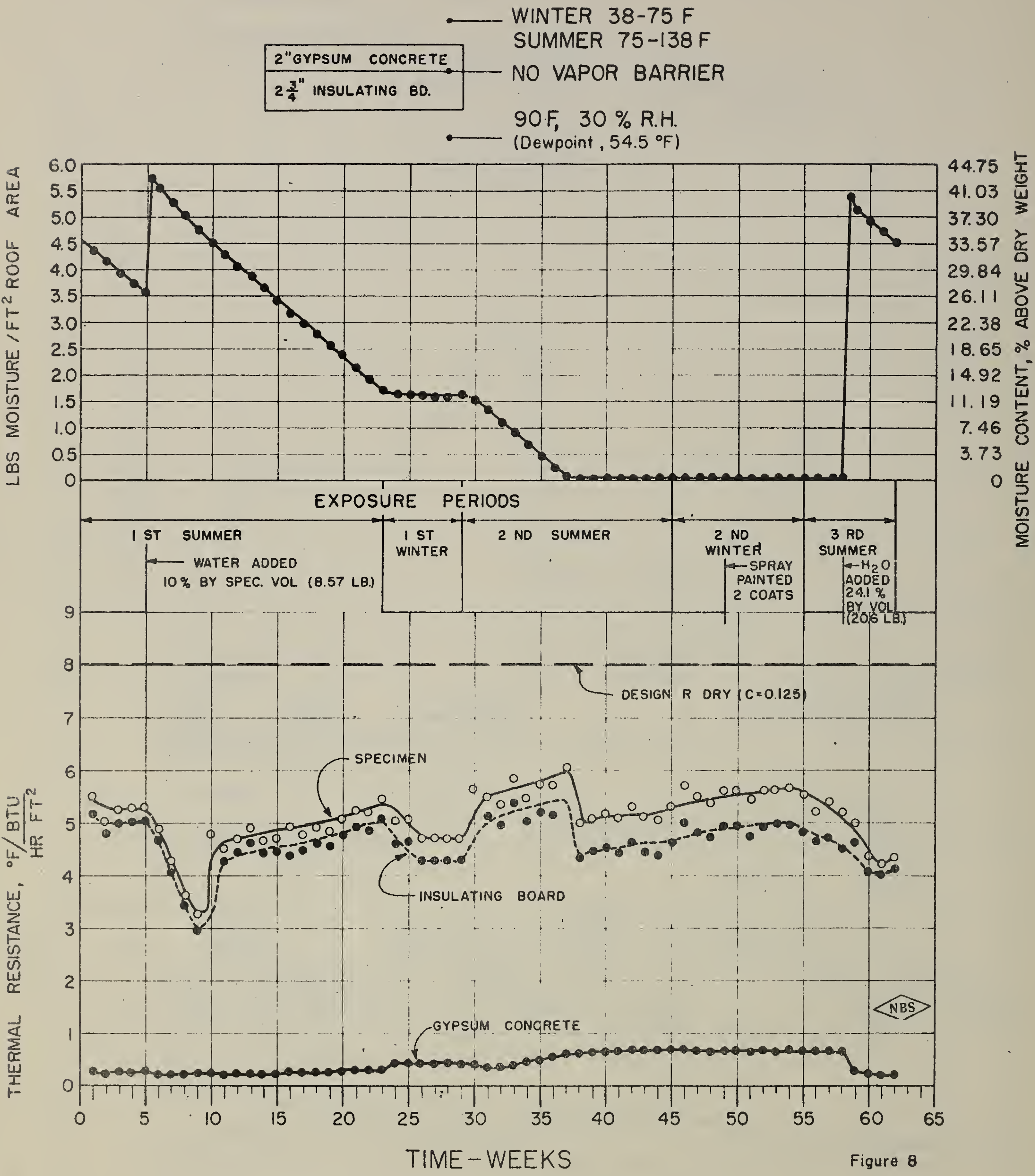
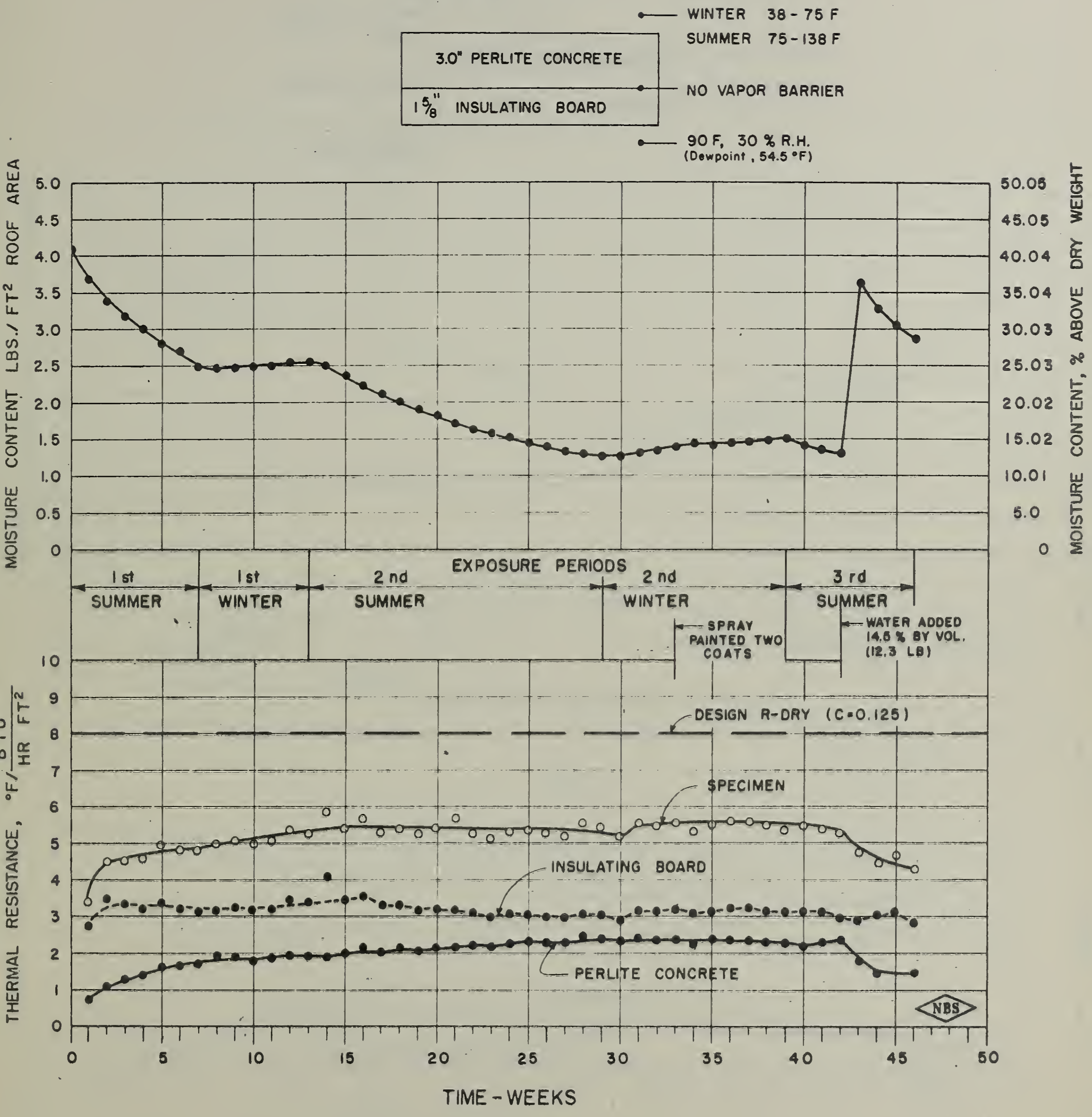


Figure 8

SPEC. 12



3.0" PERLITE CONCRETE
$1\frac{5}{8}$" INSULATING BOARD
WINTER 38 - 75 F
SUMMER 75 - 138 F
NO VAPOR BARRIER
90 F, 30 % R.H.
(Dewpoint , 54.5 °F)
MOISTURE CONTENT LBS./ FT² ROOF AREA
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0
50.05
45.05
40.04
35.04
30.03
25.03
20.02
15.02
10.01
5.0
0
MOISTURE CONTENT, % ABOVE DRY WEIGHT
EXPOSURE PERIODS
1 st SUMMER
1 st WINTER
2 nd SUMMER
2 nd WINTER
3 rd SUMMER
SPRAY PAINTED TWO COATS
WATER ADDED 14.5 % BY VOL. (12.3 LB)
THERMAL RESISTANCE, °F/ BTU/HR FT²
10
9
8
7
6
5
4
3
2
1
0
DESIGN R-DRY (C=0.125)
SPECIMEN
INSULATING BOARD
PERLITE CONCRETE
NBS
0
5
10
15
20
25
30
35
40
45
50
TIME - WEEKS

FIG. 9

SPEC. 13

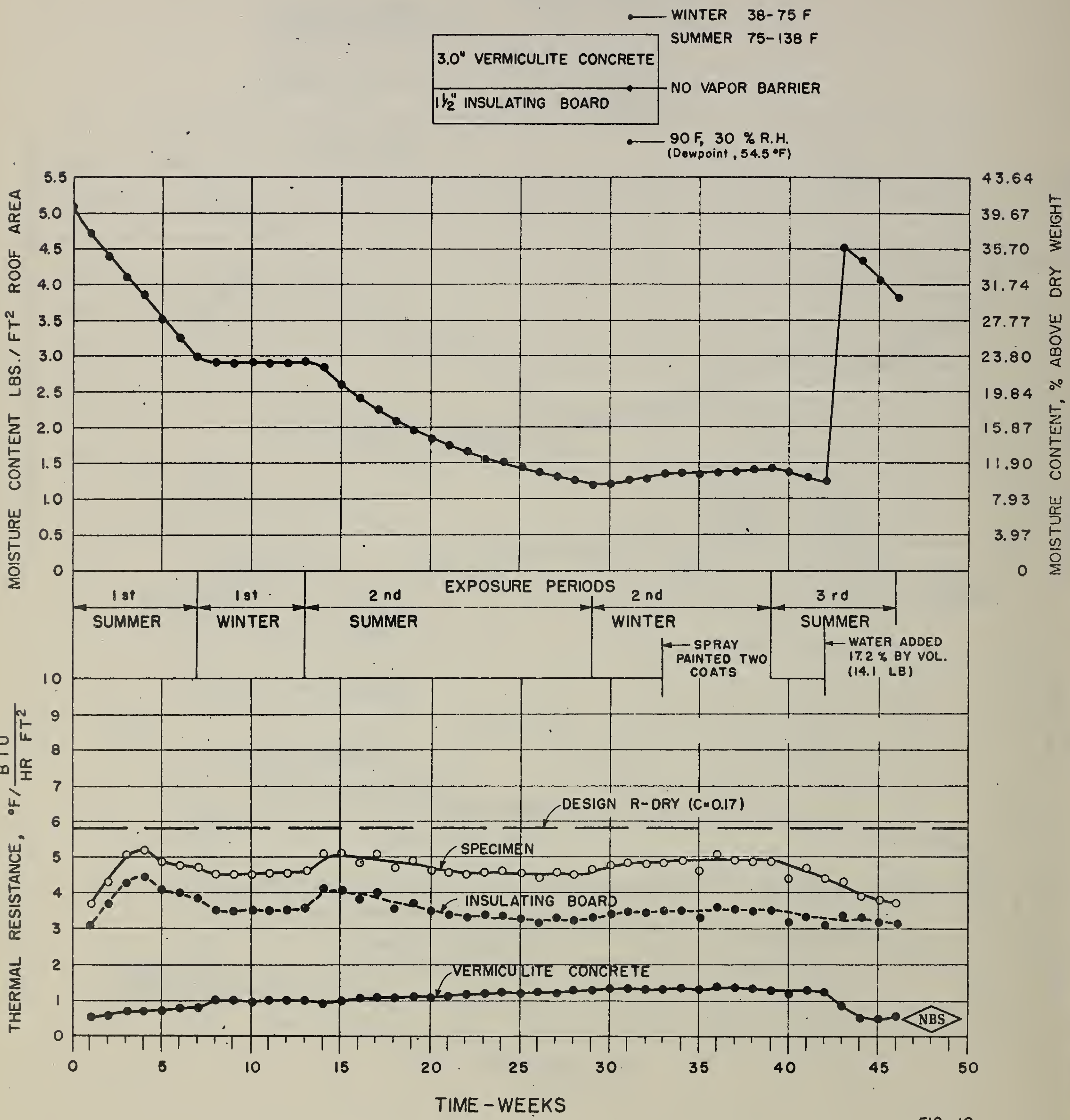


FIG. 10

SPEC. 14

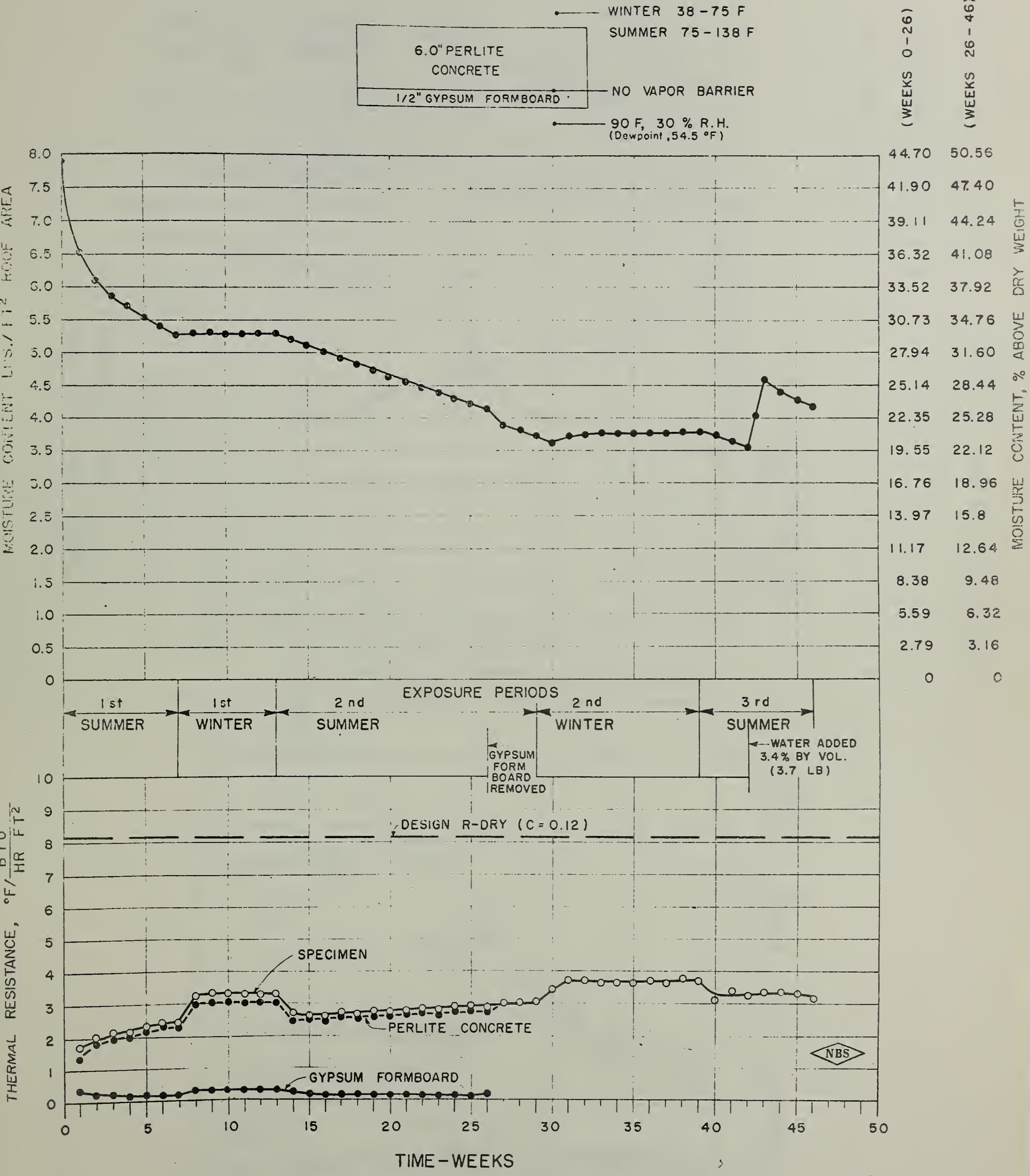


FIG. 11

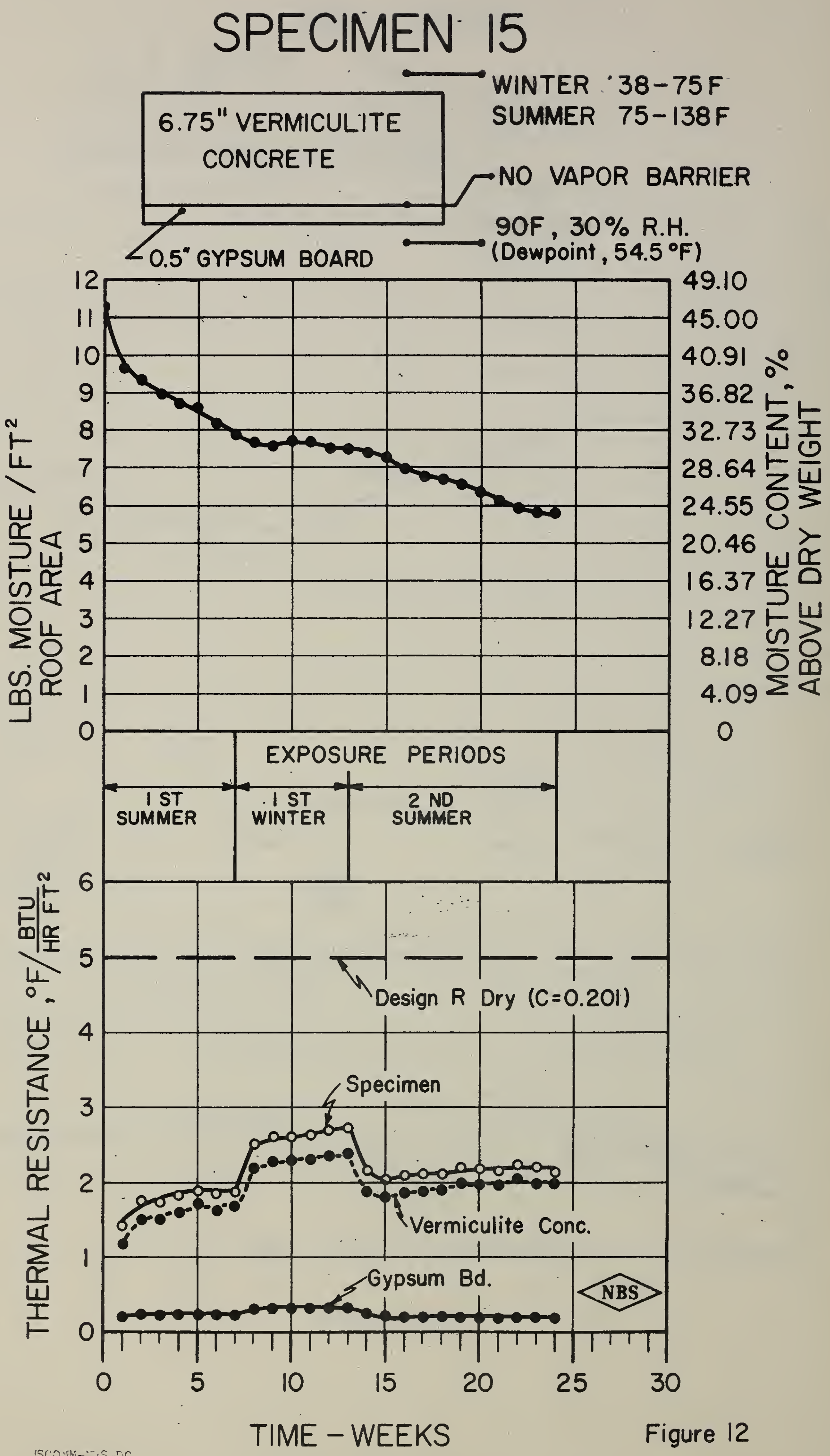


Figure 12

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SPEC. 16

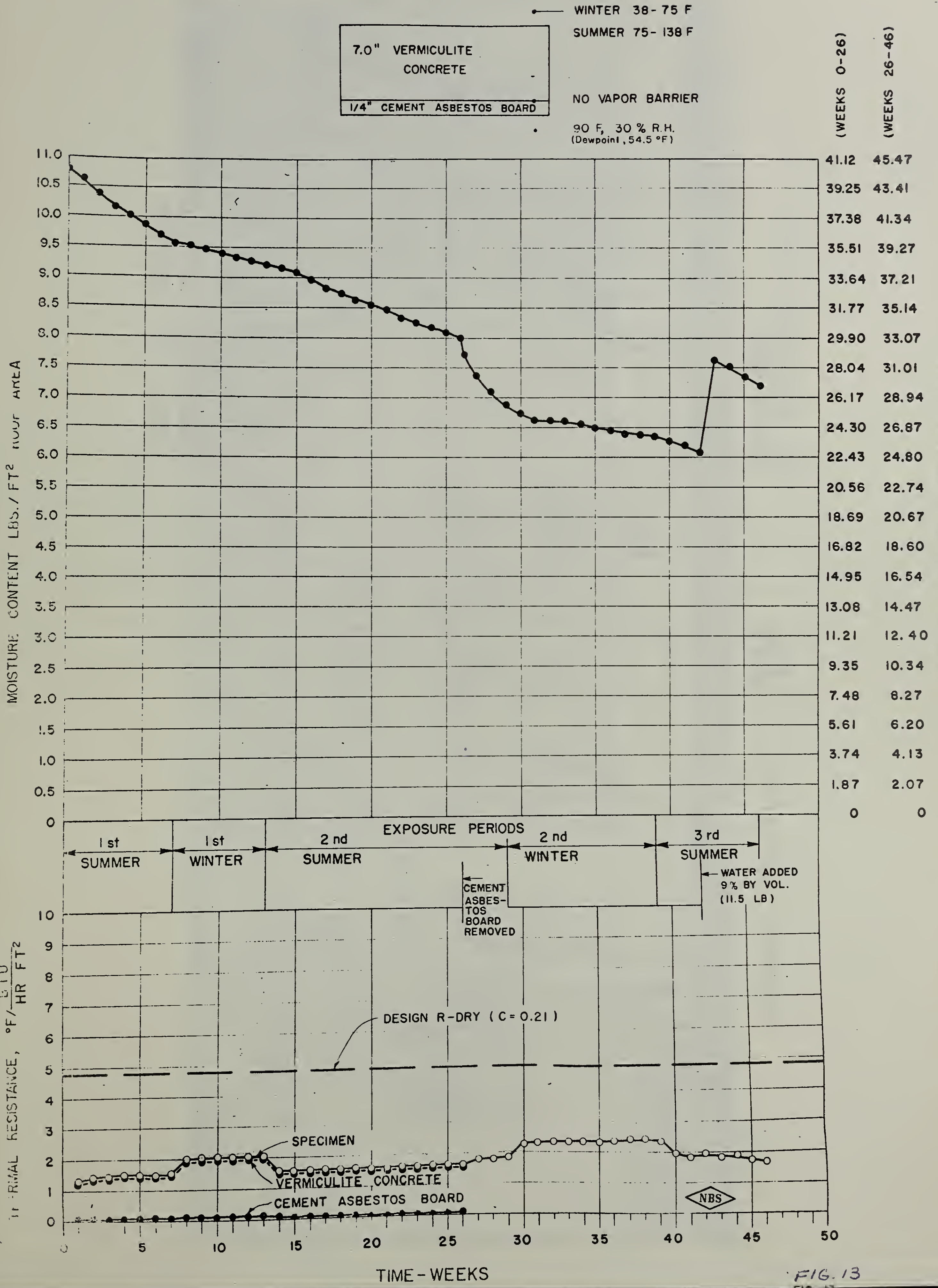

FIG. 13

SPECIMEN 17

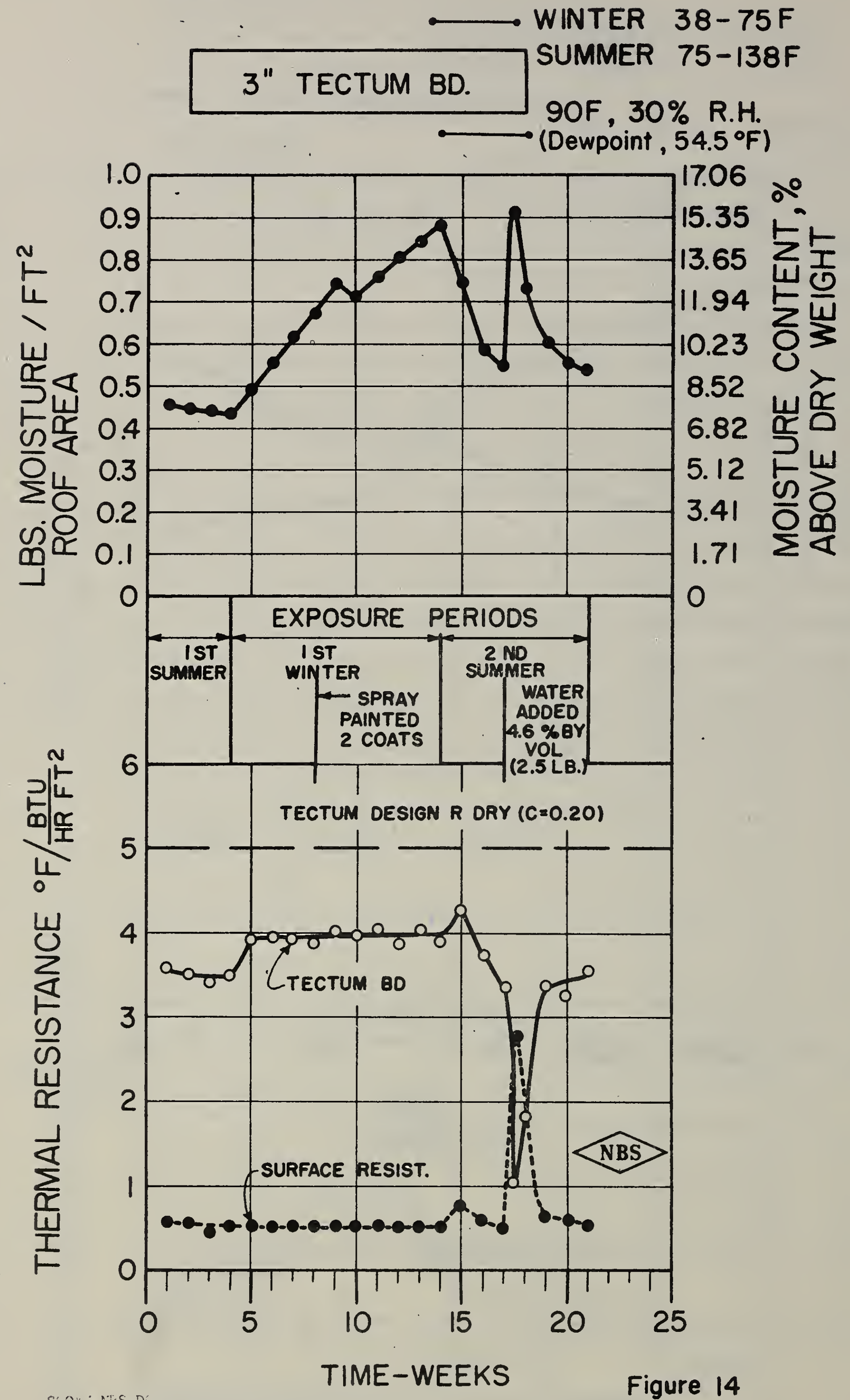

Figure 14

Fig. 15

U. S. DEPARTMENT OF COMMERCE
Luther H. Hodges, *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 major laboratories in Washington, D.C., and Boulder, Colorado, 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 of the front cover.

WASHINGTON, D. C.

Electricity. Resistance and Reactance. Electrochemistry. Electrical Instruments. Magnetic Measurements. Dielectrics. High Voltage.

Metrology. Photometry and Colorimetry. Refractometry. Photographic Research. Length. Engineering Metrology. Mass and Scale. Volumetry and Densimetry.

Heat. Temperature Physics. Heat Measurements. Cryogenic Physics. Equation of State. Statistical Physics.

Radiation Physics. X-ray. Radioactivity. Radiation Theory. High Energy Radiation. Radiological Equipment. Nucleonic Instrumentation. Neutron Physics.

Analytical and Inorganic Chemistry. Pure Substances. Spectrochemistry. Solution Chemistry. Standard Reference Materials. Applied Analytical Research. Crystal Chemistry.

Mechanics. Sound. Pressure and Vacuum. Fluid Mechanics. Engineering Mechanics. Rheology. Combustion Controls.

Polymers. Macromolecules: Synthesis and Structure. Polymer Chemistry. Polymer Physics. Polymer Characterization. Polymer Evaluation and Testing. Applied Polymer Standards and Research. Dental Research.

Metallurgy. Engineering Metallurgy. Microscopy and Diffraction. Metal Reactions. Metal Physics. Electrolysis and Metal Deposition.

Inorganic Solids. Engineering Ceramics. Glass. Solid State Chemistry. Crystal Growth. Physical Properties. Crystallography.

Building Research. Structural Engineering. Fire Research. Mechanical Systems. Organic Building Materials. Codes and Safety Standards. Heat Transfer. Inorganic Building Materials. Metallic Building Materials.

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

Data Processing Systems. Components and Techniques. Computer Technology. Measurements Automation. Engineering Applications. Systems Analysis.

Atomic Physics. Spectroscopy. Infrared Spectroscopy. Far Ultraviolet Physics. Solid State Physics. Electron Physics. Atomic Physics. Plasma Spectroscopy.

Instrumentation. Engineering Electronics. Electron Devices. Electronic Instrumentation. Mechanical Instruments. Basic Instrumentation.

Physical Chemistry. Thermochemistry. Surface Chemistry. Organic Chemistry. Molecular Spectroscopy. Elementary Processes. Mass Spectrometry. Photochemistry and Radiation Chemistry.

Office of Weights and Measures.

BOULDER, COLO.

Cryogenic Engineering Laboratory. Cryogenic Equipment. Cryogenic Processes. Properties of Materials. Cryogenic Technical Services.

CENTRAL RADIO PROPAGATION LABORATORY

Ionosphere Research and Propagation. Low Frequency and Very Low Frequency Research. Ionosphere Research. Prediction Services. Sun-Earth Relationships. Field Engineering. Radio Warning Services. Vertical Soundings Research.

Radio Propagation Engineering. Data Reduction Instrumentation. Radio Noise. Tropospheric Measurements. Tropospheric Analysis. Propagation-Terrain Effects. Radio-Meteorology. Lower Atmosphere Physics.

Radio Systems. Applied Electromagnetic Theory. High Frequency and Very High Frequency Research. Frequency Utilization. Modulation Research. Antenna Research. Radiodetermination.

Upper Atmosphere and Space Physics. Upper Atmosphere and Plasma Physics. High Latitude Ionosphere Physics. Ionosphere and Exosphere Scatter. Airglow and Aurora. Ionospheric Radio Astronomy.

RADIO STANDARDS LABORATORY

Radio Physics. Radio Broadcast Service. Radio and Microwave Materials. Atomic Frequency and Time-Interval Standards. Radio Plasma. Millimeter-Wave Research.

Circuit Standards. High Frequency Electrical Standards. High Frequency Calibration Services. High Frequency Impedance Standards. Microwave Calibration Services. Microwave Circuit Standards. Low Frequency Calibration Services.

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