MOISTURE GAIN AND ITS THERMAL CONSEQUENCE FOR COMMON ROOF INSULATIONS

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ABSTRACT

This paper describes a method for determining the rate of moisture gain and the decay in thermal resistance caused by moisture in common roof insulations. Information on the rate of moisture gain for various insulations is tabulated (Table III) and graphed (Figures 4 and 5). The rate of moisture gain varies significantly with insulation type and wetting test boundary conditions. Graphs are presented to define the decay in thermal resistance of insulation samples at increasing moisture contents (Figures 6-11). Moisture significantly reduces the thermal resistance of most roof insulations.

INTRODUCTION

The Corps of Engineers has recently studied nuclear, capacitance and infrared techniques to locate wet insulation in built-up roofs [Ref. 13 and 18]. In an overview of nondestructive moisture detecting techniques [Ref. 19], it is stated that no matter what technique is used, core samples are needed to verify results. Consequently, the moisture contents of hundreds of roof insulation cores have been determined over the past few years. Considered together, the core samples and a non-destructive survey can establish the variation in moisture content of insulation in a roof.

Now that we possess the ability to rapidly and cost effectively locate moisture in roofs, it has become important to define the thermal significance of various amounts of moisture in common roof insulations.

Some thermal measurements have been made in situ on roofs with wet and dry insulation [Ref. 17]. However, the results are not considered very accurate and have served only to show general trends.

Laboratory experiments on the rate of moisture absorption and concurrent decrease in thermal resistance of roof insulations have been conducted in Europe [Refs. 1, 9, 14 and 16], Canada [Refs. 6 and 7], and the U.S.A. [Refs. 4, 10, 12 and 15]. Empirical equations have been proposed [Refs. 5 and 12] to determine the thermal conductivity of various cellular plastic and glass fiber insulations as a function of their moisture content. The in-situ data mentioned above did not fit these equations well.

Prior moisture absorption studies of insulating materials at CRREL [Ref. 11] were conducted by immersing samples in water at room temperature and maintaining isothermal conditions. Hedlin [Ref. 7] has shown that foam plastic insulations gain much more moisture when subjected to thermally induced vapor pressure gradients than when soaked under isothermal conditions (e.g. 1-in-thick expanded bead polystyrene samples with an 11°C temperature differential across them gained moisture 100 times faster than similar samples in a wet but isothermal environment). For such insulations, moisture gain occurs by condensation of water vapor rather than by capillary flow in the liquid phase. Since there is often a significant temperature gradient through roof insulation, it seems appropriate to determine the rate of moisture gain under such conditions.

Since a comprehensive study of moisture in common roof insulations was lacking, a program was generated at CRREL to subject various roof insulations to combined temperature and moisture gradients and to monitor their rate of moisture gain and the thermal consequences of moisture. That program is not yet complete but from the tests conducted up to this time, some conclusions can be drawn.

WETTING APPARATUS

The availability of a Dynatech Rapid-k thermal conductivity instrument, capable of handling 12-in. x 12-in. samples of insulation, determined sample size. Since numerous samples were to be tested, a rather large area was needed for many months for the wetting tests. Since several coldrooms exist at CRREL, it was decided to make portable heated and insulated wetting boxes that could be placed in appropriate coldrooms. The inside of the box would represent the warm humid conditions within a building, while outside, in the coldroom, colder and drier conditions would exist. Tests to date have been conducted at temperatures above 32°F to eliminate questions relative to ice blockages and freeze-thaw deterioration. Tests with the freezing interface within the sample are envisioned for the future.

All wetting tests discussed in this report were conducted in a coldroom maintained at approximately 40°F. The relative humidity in the coldroom averaged 75%. A hygrothermograph was used to monitor the temperature and relative humidity in the room. A sling psychrometer was used periodically to calibrate the hygrothermograph.

Gravity forces must be considered in wetting porous and fibrous insulation. To properly represent the gravity conditions experienced by roof insulations, all samples were placed horizontally between partitions in the roof of the box. The partioned cover, made of redwood and extruded polystyrene, could accept 10 samples. Two such boxes are shown in Figure 1. Extruded polystyrene was used as a frame around each sample to minimize the creation of a thermal bridge at the perimeter. The sides and bottom of the box were sealed panels framed in redwood, filled with 2 in. of extruded polystyrene insulation and covered with skins of 3/8-in.-thick plastic-skinned plywood.

The two boxes shown in Figure 1 were built to maintain a relative humidity (RH) of 100% inside. A 5-in.-high galvanized steel pan, sized to fit the inside length and width of the box was filled with 3 in. of water which was kept at about 85% F (±2°F) using immersion heaters, with the box located in a 40°F (±2°F) cold room. Visible moisture on all interior surfaces of the box, including the bottoms of all samples, verified that the relative humidity was 100% on the warm side of all samples.

With 85°F, 100% RH conditions below the samples and 40°F, 75% RH (average) conditions above, an average vapor pressure difference of 1.03 in. of mercury was generated across them.

The visible moisture on the warm side of all samples would cause fibrous materials to absorb water by capillarity and thus gain moisture faster than if only vapor diffusion were causing moisture to enter them. In order to determine the significance of this difference, a double box (20 sample compartments) was made similar in construction to those described above but without the galvanized water pan and with higher walls. The extra height accomodated a humidifier, an electrical heating element and a fan. Internal temperatures were again maintained at 85°F but the relative humidity was set at 70%. A hygrothermograph was also placed within the box to maintain a continuous record of internal conditions.

With temperature and humidity at 85°F, 70% RH below these samples and 40°F, 75% RH (average) above, an average vapor pressure difference of 0.66 in. of mercury was generated across them.

Initially some samples were placed in the roof of the wetting apparatus with unsealed vertical edges. To close that path to moisture entry and to strengthen the samples against damage during handling, the vertical edges of most samples were painted with a vinyl vapor barrier paint.

Before insertion in the wetting apparatus each sample was dimensioned to the nearest 0.01 in. and weighted to the nearest 0.00002 lb. Weights were obtained before and after any vapor barrier paint was applied to the vertical edges. Except for trimming to the proper size and edge painting, samples were placed in the wetting apparatus as received from the manufacturer. Asphalt saturated papers and other types of skins were not removed. Where the insulation was meant to be used with a specific surface on top, it was so oriented in the wetting apparatus.

Common roof insulations included in the tests conducted to date are presented in Table I. The dry thermal resistance of each sample, as determined just prior to the wetting tests is also shown in Table I.

TABLE I.
THE TYPE, THICKNESS, DENSITY AND DRY THERMAL RESISTANCE OF ROOF INSULATIONS UNDER TEST.

Type	Thickness (in.)	Density (pcf)	Dry thermal resistance ($ft^2 \cdot hr \cdot °F/BTU$)
Cork	1	16	2.6
Fiberboard (crushed wood fibers)	1	18	2.6
	2	18	5.1
Perlite board	1	10	2.6
	2	10	5.1
Cellular glass	1.5	8	4.4
	2	9	5.8
Glass fiber board	1	14	3.6
	2	11	8.1
Expanded bead polystyrene	1	0.9	3.7
Extruded polystyrene	1	2.2	5.2
	2	2.2	10.8
Urethane with asphaltic skins	1	6.6*	5.5
	2	3.6*	15.1
Glass fiber reinforced urethane with asphaltic skins	1	6.3*	6.2
Glass fiber reinforced isocyanurate with asphaltic skins	1.2	5.2*	6.5
	2.25	3.7*	14.1
Composite of urethane with asphaltic skins and ¾ in. thick perlite board	1¾	7.5*	8.2

*Includes skins

The time of installation of each sample in the wetting apparatus was recorded. Periodically each sample was removed from the apparatus and a 12 x 12 x 1-in.-thick extruded polystyrene dummy sample was inserted in its place. The removed sample was carried into a 70°F laboratory, quickly surface dried with an absorbent laboratory paper towel, weighed, wrapped in a sheet of 0.0005-in.-thick plasticized PVC, weighed again, and placed in the Rapid-k thermal conductivity instrument which was maintained with its top plate at about 40°F and its bottom plate at about 85°F. It took 2 to 3 min. to accomplish this transfer. Once the 1 to 2 hr. thermal conductivity test was completed, the sample was again weighed, the PVC wrap was removed, the sample was reweighed and then returned to its original location in the wetting apparatus. This transfer also took two to three minutes. To minimize temperature and moisture changes, the sample was removed from the wetting apparatus for as short a time as possible.

MEASUREMENT OF THERMAL RESISTANCE

The Dynatech Rapid-k thermal conductivity instrument used in this study is shown in Figure 2. This instrument is designed to measure the thermal properties of dry homogenous insulating materials in accordance with ASTM Standard C518-76 "Test for Steady-state Thermal Transmission Properties by Means of the Heat Flow Meter" [Ref. 3]. Technical details of a similar but not identical device are presented in Reference 8. The 12-in. square sample is inserted horizontally between upper and lower plates maintained at specified temperatures by thermostatically controlled heating and cooling systems. For these tests the upper plate was maintained at approximately 40°F and the lower plate at about 85°F in order to reproduce the same top and bottom temperatures as in the wetting apparatus.

Mean sample temperature was about 63°F, only a few degrees below the temperature of the room in which the instrument is located. Large differences between room temperature and mean sample temperature introduce inaccuracies from later heat transfer into or out of the sample.

A 6-in.-square heat flow sensor is built into the lower plate of the thermal conductivity instrument and thermocouples are positioned to indicate the skin temperature of the upper and lower plates. Once steady-state heat flow conditions have been established across the sensor, the thermal resistance of the sample can be determined by using the linear heat flow equation:

$$R_a = \Delta T/Q \qquad (1)$$

where

R_a = apparent thermal resistance of the sample ($ft^2 \cdot hr \cdot °F/BTU$)

ΔT = temperature difference across sample (°F)

Q = heat flux ($BTU/ft^2 \cdot hr$).

The adjective "apparent" and the subscript "a" are used to emphasize that for these tests the R-value does not indicate the thermal resistivity of a homogenous material but only the thermal resistance of a particular sample having moisture distributed in it in an unknown fashion. This important distinction is discussed in the ASTM paper "What Property Do We Measure?" [Ref. 2].

When a test sample is inserted into the Rapid-k instrument, it replaces a calibration sample; with which the instrument has been operating for one to two hours to reach steady state heat flow conditions. Each day the instrument is used, measurements are first obtained with a calibration sample in place. The calibration sample is 12 x 12 x 1-in. thick, oven-dried, 6.6-pcf glass fiber insulation with a thermal resistance of 4.4 $ft^2 \cdot hr \cdot °F/BTU$ at room temperature.

In this study, the apparent thermal resistances of the wet and dry samples discussed ranged from 0.8 to 15.2 $ft^2 \cdot hr \cdot °F/BTU$. Because of this range, the heat flow rate changed significantly when the calibration sample was removed and the test sample inserted. When a test sample is inserted, the temperature controlling devices adjust to the new heat flow rate, but it takes some time for them to stabilize the system at the new rate and reestablish steady-state heat flow conditions. According to the manufacturer, stability is reached in approximately 10 minutes when dry room-temperature samples, having about the same total thermal resistance as the calibration sample, are placed in the instrument. When thermal resistances are different, up to 20 minutes is required for stability. The samples tested were not at room temperature when placed in the instrument but already subjected to the temperature gradient at which they would be tested: this factor shortened the time required for stability. Stabilization times increase for samples having a thermal resistance significantly different than that of the calibration sample and those containing appreciable moisture.

Stabilization times for two wet samples are shown in Figure 3. For samples of relatively low vapor permeability there is very little moisture migration during the test. A stable thermal resistance can be obtained 30 minutes after such a sample is placed in the instrument. For such samples, temperature and heat flow readings are taken about 30, 35, 40, 45, 50 and 55 minutes after they are placed in the thermal conductivity instrument and averaged to obtain the sample's apparent thermal resistance.

For some samples, such as the wet perlite board shown in Figure 3, the apparent thermal resistance still changes even after 30 minutes in the thermal conductivity instrument. Although this may be partially associated with migration of moisture within the sample, final readings are delayed until more stable conditions are present. For some samples this results in a test time as long as two hours.

Since all samples are sealed in a plastic film before insertion into the thermal conductivity instrument, moisture does not migrate out of the sample but rather moves upward through the sample toward the cold surface. Upward moisture migration also occurs while the sample is in the wetting apparatus but at this time, moisture may enter at the bottom and, for some samples, exit from the top. The moisture environment seen by the sample in the thermal conductivity instrument is, therefore, not identical to that encountered in the wetting apparatus. However, sealing of the wet samples in the thermal conductivity apparatus is essential since any free moisture condenses on cold portions of the instrument causing large measurement errors.

Tests of thermal resistance of dry insulations with and without the plastic sealing film showed that the film does not noticeably alter the values obtained.

The requirements of ASTM C518-76 [Ref. 3] necessary to determine the thermal resistance of the samples are met except that:

1. Many samples contained free water since that was the purpose of the study.
2. Six successive readings for all wet samples tested did not always yield thermal resistance values agreeing within 1%.
3. The 45°F temperature difference across samples was less than that recommended for good insulators greater than 1 in. thick. However, the minimum temperature difference specified in the test method was always met.

RATE OF MOISTURE GAIN

Tests to establish the rate of moisture gain for various insulations have been conducted under the moisture boundary conditions presented in Table II.

TABLE II. MOISTURE BOUNDARY CONDITIONS.

Condition	Cold side vapor seal	Dew point on warm side	Vapor pressure difference across sample (in. Hg)
A	No	No (70% RH there)	0.66
B	No	Yes	1.03
C	Yes	Yes	1.21 max
D	Yes	No (70% RH there)	0.85 max

All of the above situations can exist on a roof depending on the relative vapor permeabilities of the membrane and vapor barrier and the amount of ventilation available between the two.

The rate of moisture gain of an insulation is strongly dependent on the moisture boundary conditions present. (See Figure 4 for the rates of moisture gain of 1-in.-thick perlite board insulation under moisture boundary conditions A, B and C.)

The significant differences in moisture gain after 100 days in the wetting apparatus for various roof insulations under moisture boundary conditions A and B are shown in Table III. Tests have not yet been conducted for most insulations under moisture boundary conditions C and D.

The large differences between condition A and condition B attest to 1) the ability of many insulations to remain relatively dry even when significant amounts of water vapor are passing through them (condition A), and 2) to the rapid wetting that can occur when the dew point occurs within an insulation and water vapor is available for condensation (condition B for all samples and condition A for the urethane-perlite composite sample). Once the dew point is reached, the rate of moisture gain is dependent on the vapor permeability and the ease of water movement within the insulation by capillary attraction.

TABLE III.
INFLUENCE OF MOISTURE BOUNDARY CONDITIONS ON THE 100-DAY MOISTURE GAIN OF VARIOUS INSULATIONS.

Insulation	100 day moisture gain (% of dry weight) Condition A	Condition B
Fiberboard (1-in.)	5.5	140.0
Perlite board (1-in.)	2.0	90.0
Cellular glass (1-in.)	0.7	11.0
Expanded bead polystyrene (1-in.)	0.2	1000.0
Extruded polystyrene (1-in.)	2.5	5.5
Urethane with asphaltic skins (1-in.)	4.0	160.0
Composite of 1-in. urethane with asphaltic skins and ¾ in. perlite board below	45.*	340.0

*The relatively low vapor permeability of the skins causes the dew point to occur within the sample.

Cellular glass and extruded polystyrene have a very low vapor permeability and they gain moisture very slowly. The other materials in Table III take on water much more rapidly. Tremendous differences exist in the amount of moisture gained by the two types of polystyrene.

Various wetting situations for extruded polystyrene samples are presented in Figure 5. By comparing curves in that figure it is seen that:

(1) Less moisture is gained when edges are vapor sealed (compare curves b and d).
(2) More moisture is gained when the integral skins are removed (compare curves b and e).
(3) Moisture gain is reduced for thicker samples (compare curves c and d).
(4) Moisture gain is very low when the dew point is not present on or in the sample (compare curves a and b).

Additional tests are needed before a comprehensive statement can be made on the rate of moisture gain under various moisture boundary conditions for common roof insulations. The intent of this brief overview is to introduce important variables and to alert the reader to the difficulties associated with generating a simple laboratory test to represent the various moisture conditions that can exist on roofs.

THERMAL RESISTANCE OF WET INSULATION

The dry thermal resistance of the 11 types of insulation tested are presented in Table I as previously mentioned. As a sample takes on water its thermal resistance decreases. The ratio of its wet thermal resistance to its dry thermal resistance is a measure of its thermal efficiency. In this report, this efficiency ratio, expressed as a percentage, is called the Thermal Resistance Ratio. It is used in the graphs that follow to present the results of these tests.

The letters A, B and C, which appear in these graphs, refer to the moisture boundary conditions described in Table II. No tests have yet been completed using moisture boundary condition D.

All samples were tested with sealed edges except those designated by an asterisk, which appears after the moisture boundary condition letter in the graph.

All samples are 1-in.-thick unless otherwise noted.

The relationships between the Thermal Resistance Ratio and moisture content for fiberboard, cork and glass fiber samples are presented in Figure 6. A significant decrease in insulating ability with increasing moisture content occurs for each material.

The thermal resistance-moisture content relationship for perlite board insulation is shown in Figure 7 for moisture boundary conditions B and C. The similarity of the B and C curves for perlite board suggests that the moisture boundary condition may not be of major importance in defining the thermal resistance-moisture content relationship for this type of insulation.

Moisture boundary conditions are expected to influence the thermal resistance-moisture content relationship for other insulations. Although tests to answer this question have not yet been conducted for most insulations, some insight into potential effects is available from tests of a urethane-perlite board composite insulation under moisture boundary conditions A and B (Figure 8). Under condition A, the dew point is not in the perlite but in the urethane because of the relative vapor permeabilities of the urethane and perlite components and the asphaltic skins. Under condition B the dew point is initially in the perlite and it accumulates moisture. Since most of the insulating ability of the composite is in the urethane, moisture in the perlite is thermally less detrimental than moisture in the urethane. This explains why the thermal resistance ratio at a water content of, say, 120% is significantly greater for condition B than for condition A.

Thermal resistance-moisture content relationships for one isocyanurate and two urethane samples are presented in Figure 9. The two urethanes, although from different sources, behave almost identically. The 1.2-in.-thick isocyanurate has a similar thermal resistance-moisture content relationship but the 2.25-in.-thick isocyanurate sample retains more of its insulating ability at similar moisture contents, a difference probably explained by different distributions of moisture within the thick and thin samples at the same overall moisture content.

The thermal resistance-moisture content relationship for expanded bead polystyrene is shown in Figure 10. Since this material has a very low density (0.9 pcf; from Table I), water contents expressed as a percentage of its dry weight are quite high. Nevertheless, expanded bead polystyrene can accumulate a significant amount of water.

Extruded polystyrene behaves in an entirely different manner. It and cellular glass insulation are considerably more resistant to moisture gain (see Table III). Because of their resistance to moisture gain, little thermal resistance-moisture content information has been obtained to date for these two materials. That which has been collected is for low moisture contents only and is shown in Figure 11. Because of the difficulty of measuring small amounts of moisture in these samples, the information in Figure 11 is of questionable accuracy.

THERMAL RESISTANCE OF A ROOF

The thermal resistance-moisture content information presented in Figures 6-11 is incomplete since all moisture boundary conditions have not yet been studied. However, it can serve as a useful guide for determining the in-situ thermal resistance of some roof insulations.

For example, suppose a roof moisture survey and core samples establish that 15% of the 1-in.-thick perlite board insulation on a roof has a moisture content of 130% (dry weight basis) and the remainder has a moisture content of 10%. Averaging values obtained from the B and C curves for 1-in.-thick perlite board insulation in Figure 7, the "wet" and "dry" portions of this roof would have thermal resistance ratios of 52% and 83% respectively. Prorating this over the areas involved, the roof would be found to have only 81% of its expected thermal efficiency. This is to say that moisture in this roof has increased heat losses through it by 19%. Having this information, it is relatively easy to assess the economic consequences of the moisture in this roof. Technical and economic aspects of alternative remedies can then be developed and evaluated.

SUMMARY

A method has been developed to subject common roof insulation samples to combined temperature and moisture flow, to monitor the amount of moisture in the samples and to measure the thermal implications of this moisture. The rate of moisture gain varies considerably among the insulations studied (Table III) and also depends on the moisture boundary conditions to which the samples are subjected. Most insulations possess the ability to remain relatively dry even when significant amounts of water vapor are passing through them. However, when the dew point occurs within them, most gain moisture rapidly. Cellular glass and extruded polystyrene are quite resistant to wetting even when free water is available at their base. The presence of exposed edges and skins affects the rate of wetting.

Thermal resistance-moisture content relationships have been generated for samples of cork, fiberboard, perlite board, cellular glass, expanded bead polystyrene, extruded polystyrene, urethane, isocyanurate and urethane-perlite board insulations for various moisture boundary conditons (Figures 6-11). Although the study is not yet complete, the information presented in this report can be used in conjunction with roof moisture surveys and core samples to establish the thermal efficiency of existing roofs.

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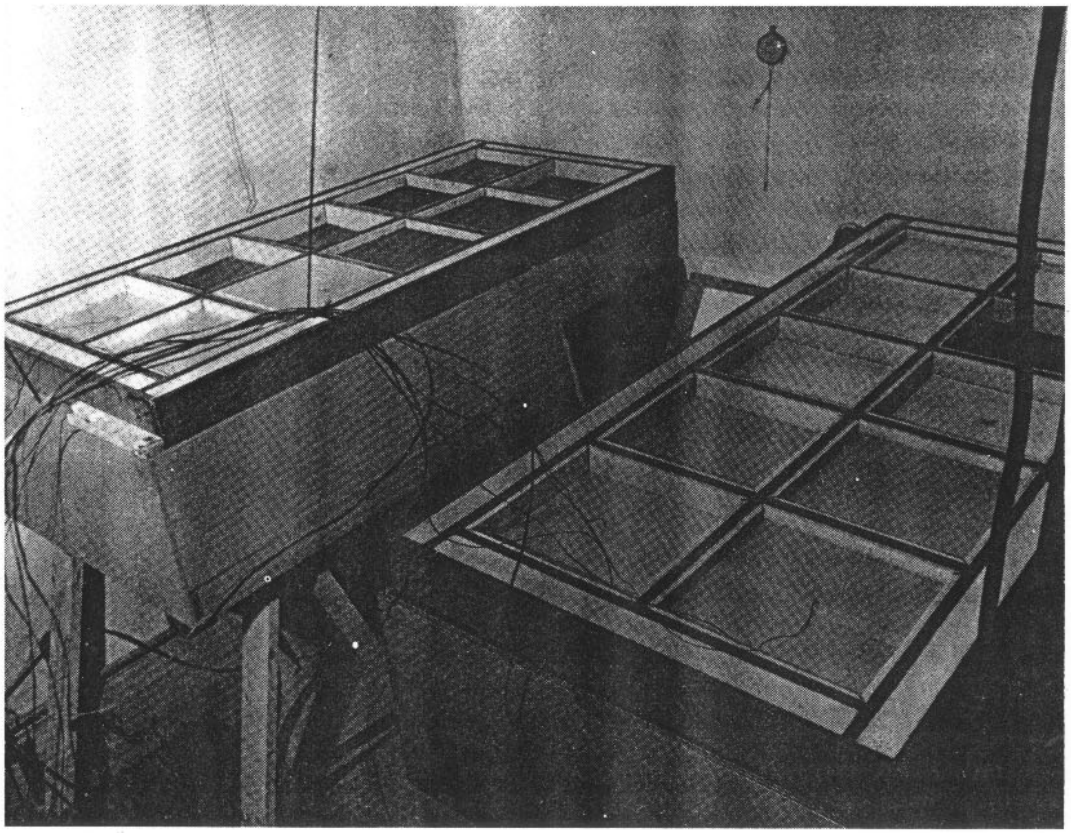

FIGURE 1 - SAMPLES IN THE PARTITIONED COVER OF THE WETTING BOXES.

FIGURE 2 - THE RAPID-K THERMAL CONDUCTIVITY INSTRUMENT.

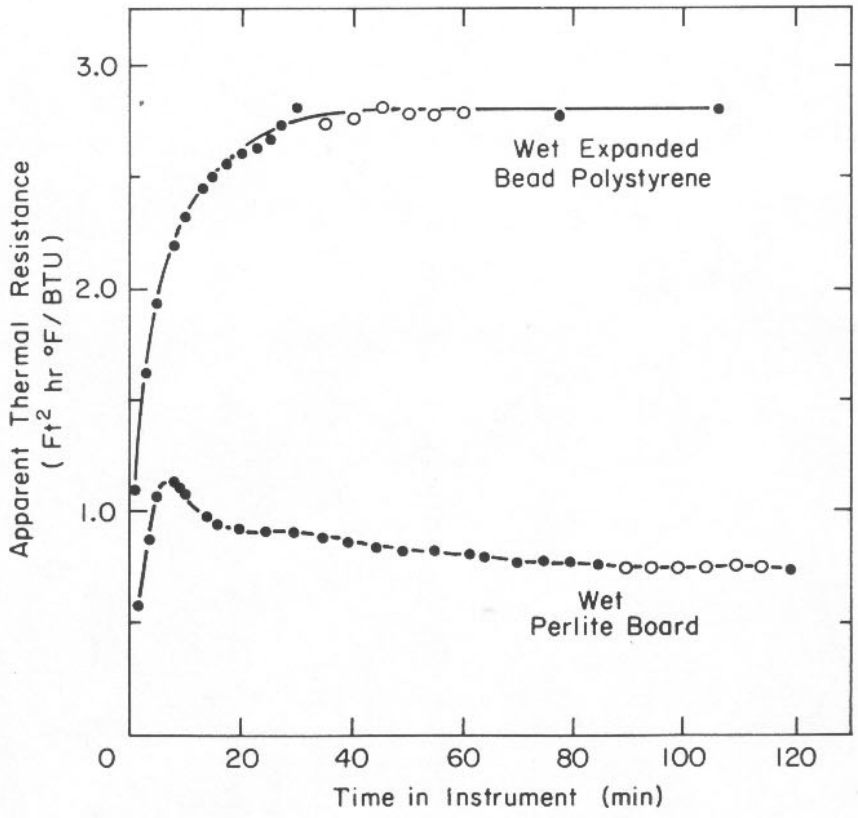

FIGURE 3 - TYPICAL THERMAL STABILIZATION CURVES. THE OPEN DOTS ARE THOSE AVERAGED TO DETERMINE THE APPARENT THERMAL RESISTANCE (R_a) OF EACH SAMPLE.

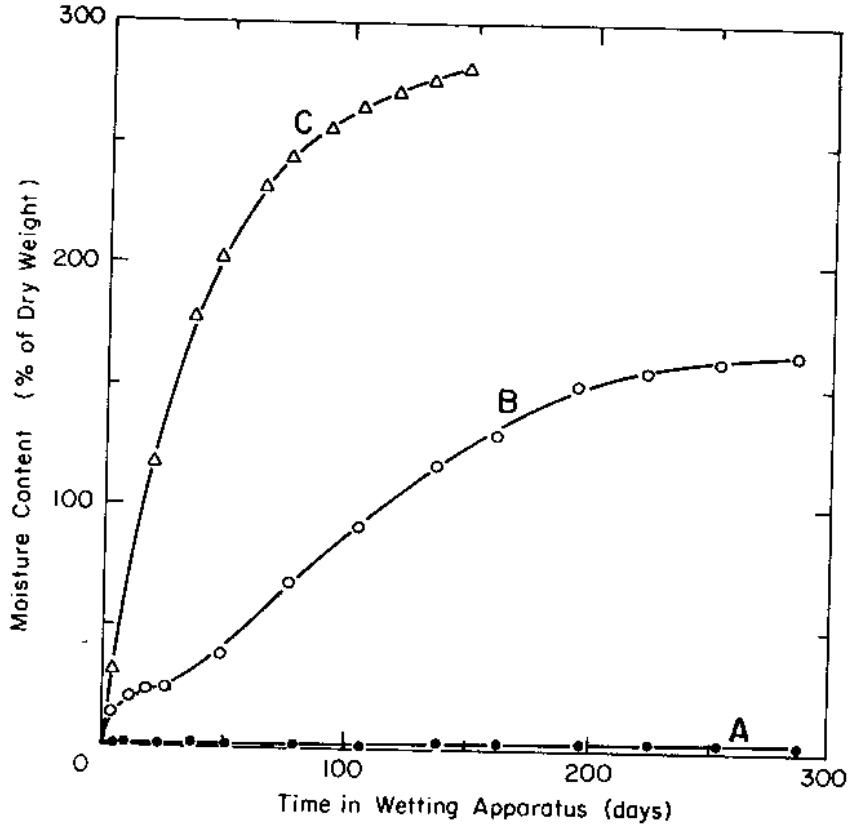

FIGURE 4 - MOISTURE GAIN VS TIME FOR 1-IN. THICK PERLITE BOARD INSULATION SAMPLES UNDER MOISTURE BOUNDARY CONDITIONS A, B AND C.

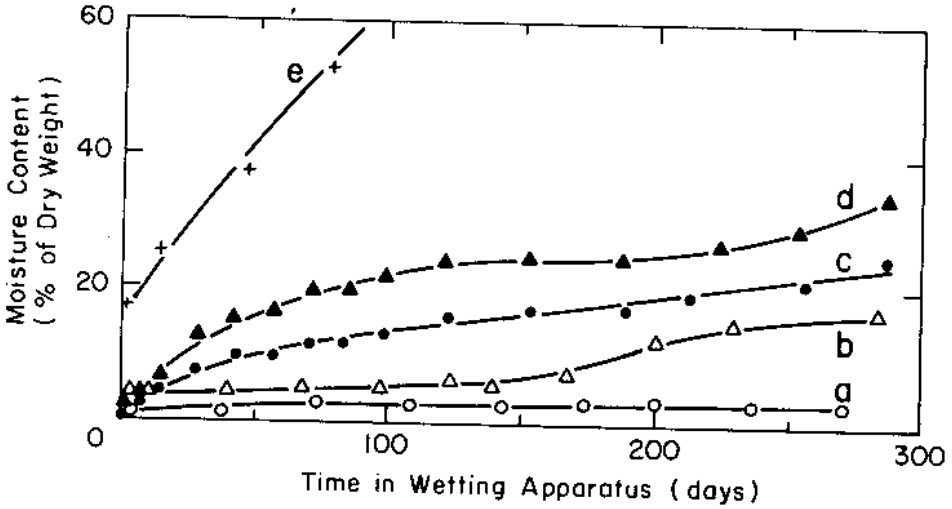

FIGURE 5 - MOISTURE GAIN VS TIME FOR THE FOLLOWING EXTRUDED POLYSTYRENE SAMPLES:

Curve	Moisture boundary condition	Edge sealed	Thickness (in.)	Remarks
a	A	Yes	1	with integral skins
b	B	Yes	1	" " "
c	B	No	2	" " "
d	B	No	1	" " "
e	B	Yes	1	integral skins cut away.

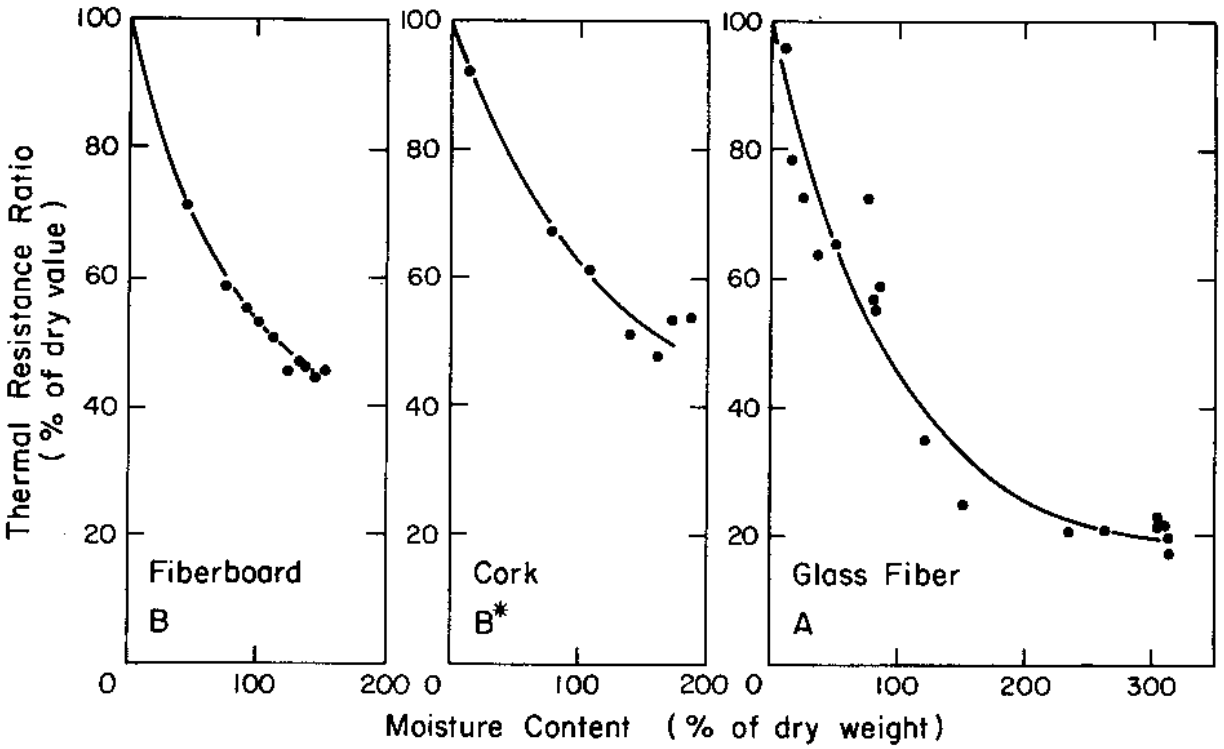

FIGURE 6 – THERMAL RESISTANCE VS MOISTURE CONTENT CURVES FOR FIBERBOARD, CORK, AND GLASS FIBER SAMPLES FOR MOISTURE BOUNDARY CONDITIONS A AND B.

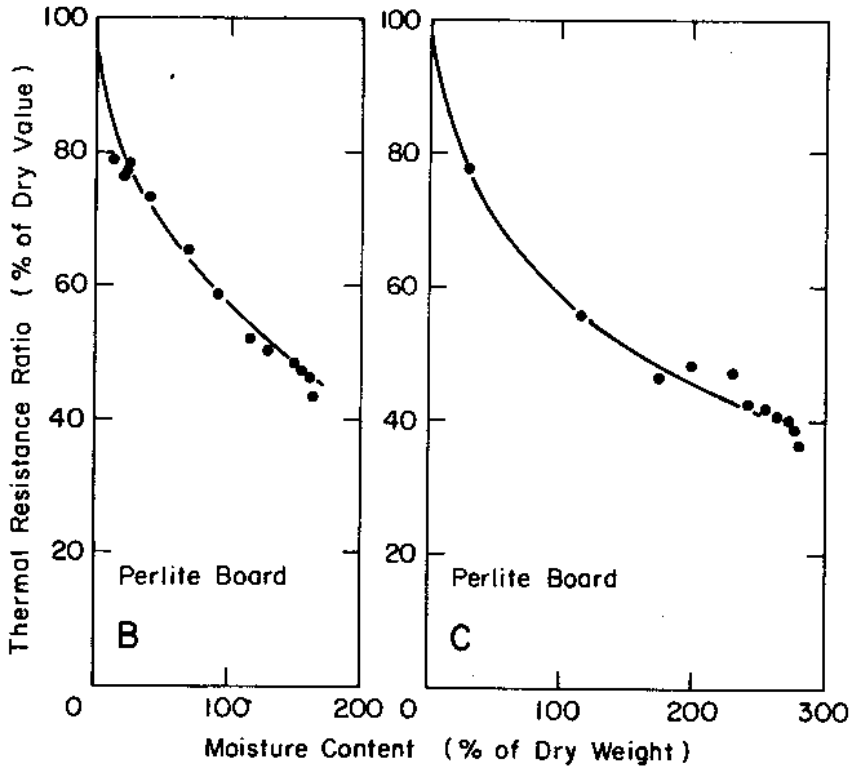

FIGURE 7 – THERMAL RESISTANCE VS MOISTURE CONTENT CURVES FOR PERLITE BOARD INSULATION SAMPLES FOR MOISTURE BOUNDARY CONDITIONS B AND C.

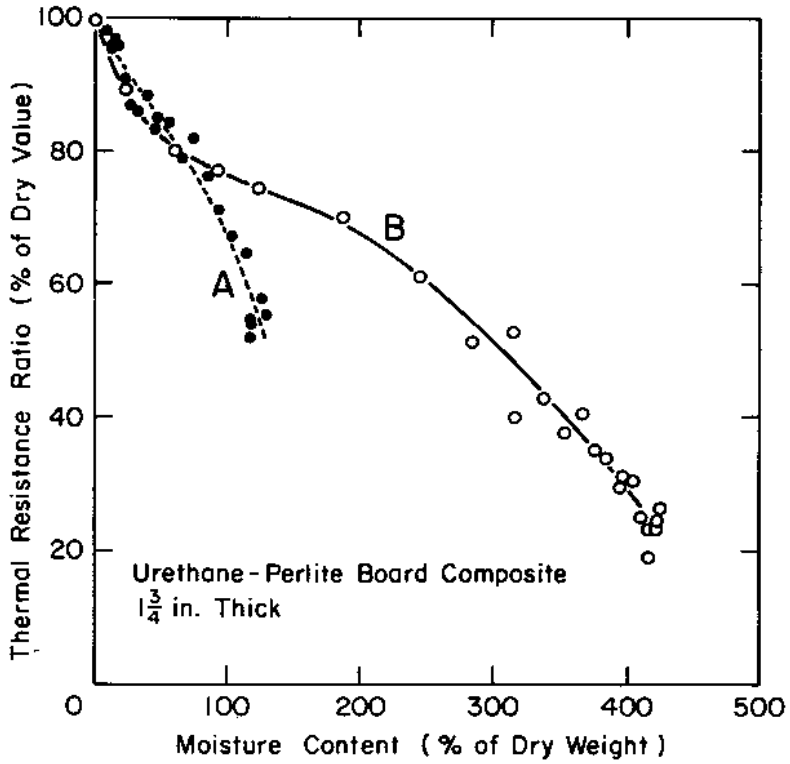

FIGURE 8 – THERMAL RESISTANCE VS MOISTURE CONTENT CURVES FOR URETHANE-PERLITE BOARD COMPOSITE INSULATION SAMPLES UNDER MOISTURE BOUNDARY CONDITIONS A AND B.

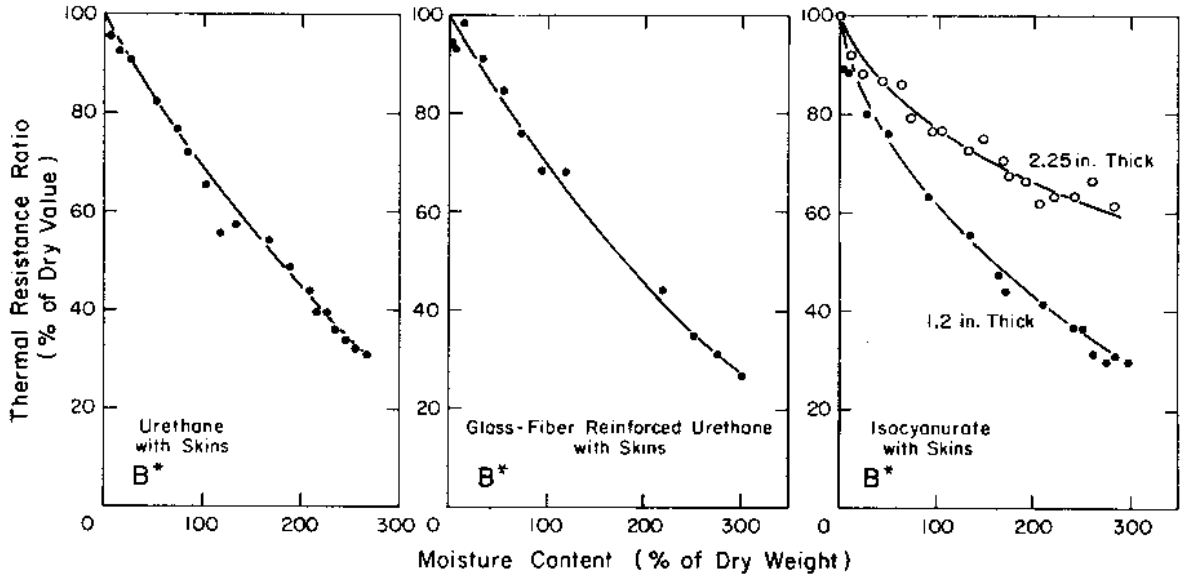

FIGURE 9 – THERMAL RESISTANCE VS MOISTURE CONTENT CURVES FOR URETHANE AND ISOCYANURATE SAMPLES.

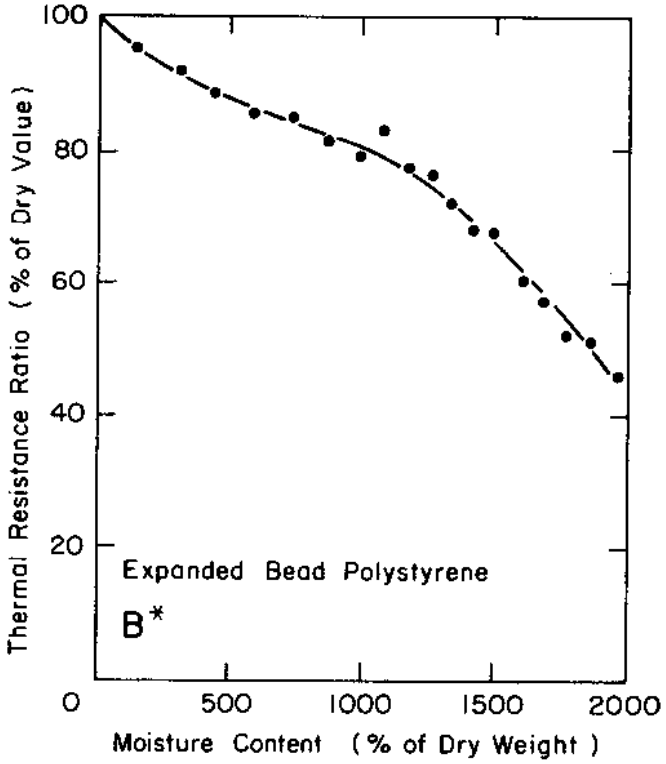

FIGURE 10 - THERMAL RESISTANCE VS MOISTURE CONTENT CURVE FOR AN EXPANDED BEAD POLYSTYRENE SAMPLE. NOTE THE CHANGE IN SCALE FOR MOISTURE CONTENT.

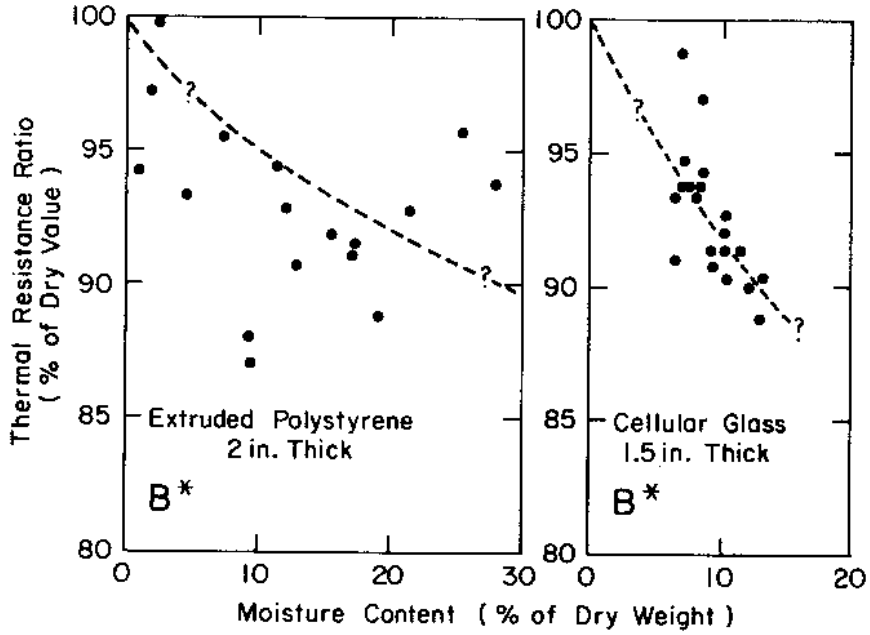

FIGURE 11 - THERMAL RESISTANCE VS MOISTURE CONTENT CURVES FOR EXTRUDED POLYSTYRENE AND CELLULAR GLASS SAMPLES.