The Effect of Moisture on the Thermal Conductance of Roofing Systems

by

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ABSTRACT

The results of laboratory tests are presented describing the effect of moisture content on the thermal conductance of roofing systems containing insulation. Roofing systems, consisting of five types of rigid-board roof insulations with attached four-ply bituminous built-up membrane, were tested. Moisture was induced into the roofing system specimens by maintaining a constant water vapor presure difference across them. Moisture gain in the insulation varied depending on the type and thickness of the insulation.

A procedure was developed, using a heat-flow meter apparatus (ASTM C 518 type), to carry out thermal conductance tests on roofing specimens containing moisture. More than 200 tests were performed over a wide range of moisture contents. The approximate moisture distribution in the insulation was determined from core samples.

Relationships between the thermal conductance and moisture content are presented. The relationships show that the presence of moisture in roofing systems can cause significant increases in thermal conductance, depending on the type and thickness of the insulation.

Key words: Built-up roofing, insulation, moisture, roofing, thermal conductance, thermal conductivity, thermal resistance

1. BACKGROUND

The roofing system is often a major component in the heat transmission through the envelope of a building. Most low-slope roofing in the United States consists of rigid board thermal insulation with an attached built-up bituminous membrane. The thermal resistance of this type of roofing depends on factors such as the type and thickness of insulation, the number and size of roof penetrations, the spacing of insulation joints, the number of metal fasteners penetrating through the insulation, and the amount and distribution of moisture in the roofing system. Small amounts of moisture in some insulations can significantly increase their thermal conductance.

A number of researchers have studied the effect of moisture content on the thermal conductivity of insulation. Dechow and Epstein[1*] reported the results for their own laboratory study, together with the results of five other empirical studies [2,3,4,5,6], all of which were performed to determine the effect of moisture on the thermal conductivity of various insulations. Dechow

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[*] Numbers refer to the references at the end of this report.

and Epstein also presented empirical relationships between thermal conductivity and the moisture content for polyurethane foam, polyisocyanurate, low and high density expanded polystyrene, extruded polystyrene, and glass fiber insulations. For these relationships, the thermal conductivity increased with increasing moisture content and the change in thermal conductivity per unit change in moisture (slope) was either constant or increased with respect to moisture content. The moisture content used in these relationships ranged from 0 to 30 percent by volume.

Cammerer [7], in a comprehensive review published in 1957, dealt at length with the effect of moisture distribution on the measurement of thermal conductivity and on the change in moisture distribution during the measurement period. He considered a number of building materials. In a more recent review, Tye [8] also considered the effect on thermal conductivity of moisture transmission in damp materials. Tye noted that the geometric arrangement of the moisture is a critical factor and that several processes of heat transfer need to be considered. Tye developed a number of models which may be useful in predicting the behavior of porous composite materials, such as roofing insulation.

Recently, Tobiasson and Ricard [9] presented laboratory results for moisture gain and its effect on the thermal resistance of some commonly used roof insulations. Powell and Robinson [10] investigated the effect of moisture on heat transfer through insulated concrete deck roof constructions with attached built-up bituminous membranes. No other studies to date, however, were available in the open literature on roofing systems containing insulation with a built-up roofing (BUR) membrane. Moreover, the effect of the amount and distribution of the moisture on the thermal conductance of roofing systems containing insulation has not been investigated.

This paper presents the test results of a laboratory program, sponsored by the Department of Energy (DOE), to determine the effect of the moisture content on the thermal conductance of roofing systems consisting of insulation and a BUR membrane. The study presented herein was performed in conjunction with another laboratory investigation, sponsored by the Department of the Air Force, to evaluate various techniques for nondestructively determining moisture content and its distribution in roofs.

2. SPECIMENS

Thermal conductance tests were performed on "room dry" roofing insulation boards, BUR membranes, and insulation boards with attached BUR membranes (BUR systems). The "room dry" roofing test specimens were stored at room conditions at approximately 70°F and 50% relative humidity (RH). The moisture contents of the insulation board and roofing felts were determined gravimetrically after oven drying. Thermal conductance tests ("wet") were also conducted on a set of BUR system specimens in which moisture was introduced into the specimens. All specimens were nominally 2 by 2 ft in area. Five types of rigid board roof insulations, in 1 and 2 in nominal thicknesses, were included in the study; they were glass fiber, perlite board, fiberboard, expanded polystyrene, and foamed polyurethane. The BUR system specimens were fabricated by a roofing contractor under the supervision of National Bureau of Standards' personnel. The BUR membranes consisted of four plies of type 15 asphalt saturated, organic felts (Type I - ASTM D 226-77 [11]). The felts were applied to the insulation boards in sandwich fashion by hot mopping with type III asphalt (ASTM D 312-77 [12]). Figure 1 shows a schematic of the composition of a BUR system specimen.

Table 1 gives the average measured properties for the insulation, felt, and asphalt used in the fabrication of the test specimens. The glass fiber board had an asphaltic facing sheet over which the BUR membrane was applied. In this study, the facing was considered as part of the membrane. The polyurethane board originally had asphaltic facing sheets on both sides. In order to increase the rate of moisture absorption, the asphaltic facing sheets were removed from both sides with a band saw to provide the required 1 and 2 in thicknesses. The thickness of the boards before cutting was 2.25 in for the 1 in specimens and 3.25 in for the 2 in specimens. The batch from which the 1 in thick specimens were cut was probably different from the batch from which the 2 in specimens were cut. This is supported by the difference in density (table 1) and visual difference; i.e. the 2 in thick boards appeared less uniform in texture than the 1 in thick boards.

Table 2 identifies the individual BUR system specimens for which "room dry" and subsequent "wet" thermal conductance tests were performed. The table gives average measured values for total specimen thickness, membrane thickness, and membrane weight per unit area in specimens which had been taken apart after completing the conductance tests. The insulation thickness was taken as the difference between the total specimen and the membrane thicknesses. In some cases, as noted in table 2, the thickness of the specimen could not be measured because the insulation had deformed. Therefore, the total specimen thickness had to be estimated using the measured membrane thickness and values of insulation thickness given in table 1. Some melting and consequent reduction in the thickness of the polystyrene insulation occurred during application of the hot asphalt and roofing felts.

The four membranes of the glass fiber BUR system specimens (nos. 3, 53, 7 and 57 in table 2) had an average thickness of 0.40 in and an average weight per unit area of 2.05 lb/ft^2. These four membranes were grouped separately since the facing sheet on the glass fiber insulation was considered as part of the membrane. The remaining 15 BUR system specimens in table 2 had an average membrane thickness of 0.35 in and an average weight per unit area of 1.76 lb/ft^2. The corresponding coefficients of variation (COV)* for the 15 measurements were 8.4 and 10.0 percent, respectively for the thickness and weight per unit area.

The values of individual membrane thicknesses in table 2 are the average of 6 to 9 measurements. The coefficients of variation for each membrane ranged from 4 to 14 percent, with the exception of specimen number 82, which was 22 per cent.

3. MOISTURE INTRODUCTION AND MEASUREMENT

Thermal conductance tests were performed on BUR system specimens containing a wide range of moisture contents. Moisture was induced in the 2 x 2 ft specimens by controlling temperature and relative humidity conditions on each side of the specimens. Specimens were placed on the top of insulated wooden chambers, as shown in figures 2 and 3. The inside of each of two large insulated chambers, 8 x 16 ft in area was maintained at 100°F (±7°F) and 100% RH by means of four pools (each about 25 ft^2) containing heated water. The two insulated chambers were in an environmental room which was maintained at 50°F (±4°F) and 25% (±5%) RH. Thus, the insulation (bottom) side of the specimens was subjected to 100°F and 100% RH while the membrane (top) side of the specimens was subjected to 50°F and 25% RH. The calculated vapor pressure difference was 1.84 in of Hg for the environmental conditions under which the specimens were exposed. The intent of using this relatively large vapor pressure difference was to induce moisture into the specimens at a rapid rate; usually, much lower vapor pressure differences exist under actual field environmental conditions.

A wooden frame, approximately 2 x 2 ft, with a continuous wooden ledge at the bottom was used to support the individual specimens (figure 2). The ledge provided about a 1/2 in width of support at the bottom on all four specimen edges. When additional support was needed, aluminum angle, 1/2 in width, spanned the center of the wooden frame in both directions. The edges of the specimens for all insulations except the perlite boards were sealed with an impervious, vinyl, vapor-barrier paint in an effort to suppress the moisture migration at the edges. A wax was used to seal the edges of the perlite board specimens. Due to handling, some specimen edge seals cracked or fell off, thus leaving some of the edges unsealed. It is believed that this had little effect on the thermal conductance since the test area was approximately 7 to 12 inches from the edges. Figure 2 shows a schematic of the BUR system specimen, supporting frame, and the environmental conditions used to induce moisture in the specimens.

Before the specimens were placed into chambers, they were weighed and measured. When the specimens were removed from the chambers, the time was recorded and the specimens weighed; the difference in weight between the "room dry" and "wet" condition was taken as the moisture gain. The surface of the insulation was wiped with paper towels to remove any surface water prior to weighing. In most cases, the specimens containing free water, glass fiber insulation, were turned on edge for about 3 to 5 minutes to drain water prior to weighing. This procedure was followed to avoid water running out of the specimens during handling and testing. The rate of gain of moisture was determined from the exposure time in the chamber and the corresponding weight gain. When the specimen was returned to the chamber for additional exposure and moisture gain, the time and weight were again recorded. The exposure time ranged from about 10 to to 100 days, depending on the type of insulation. It is noted that there was interruption in the introduction of moisture in some specimens because the desired moisture contents had been reached and because of maintenance of the laboratory facilities. Some specimens were stored in plastic bags at room temperature up to about three weeks before testing.

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* The coefficient of variation is the standard deviation divided by the mean.

To estimate the vertical moisture distribution (from the cold to warm side of the specimen) of the water in the insulation, 0.91 in diameter cores were taken by hand using a cork-borer from several BUR system specimens containing perlite board and polystyrene. The cores were taken before and after the thermal conductance tests to determine if the distribution of water had changed during the test. Cores were generally not taken from the center 10 in square area, because this area was used as the heat flow monitoring section in the thermal conductance tests. The resulting holes were plugged with a core of polyurethane or polystyrene insulation. The cores were cut into four approximately equal length sections for the nominal 1 in insulations and into eight sections for the 2 in insulations. The core sections were immediately placed into preweighed glass flasks with tight sealing lids and weighed. After removing the lids and oven drying, the flasks were again weighed, to determine the moisture loss in each of the sections of insulation. These data provided an approximation of the moisture distribution. For higher moisture contents in the insulation and particularly for the polystyrene insulation, it was impossible to avoid some water loss during the coring and sectioning processes. None the less, some definite trends for water distribution in the insulations of the BUR system specimens were obtained.

4. THERMAL CONDUCTANCE TEST PROCEDURE, EQUIPMENT, AND MEASUREMENT

Measurements of thermal conductance of the "room dry" roofing insulation boards, BUR membranes, and the "room dry" and "wet" BUR system specimens were made using an ASTM C 518 [13] type heat-flow meter apparatus*.

The procedure used in this study differed from the ASTM C 518 procedure mainly because the moisture levels in the specimens tested are not considered in ASTM C 518 and the specimen surfaces (bituminous built-up membranes) were not always flat.

The apparatus* had a metering section consisting of a 10 in square, fully integrated, heat flow meter built into the lower (hot) plate. The hot and cold plate surface temperatures, the heat-flow meter output, and the specimen thickness were digitally displayed on a front panel meter (figure 4).

The following procedure was used to conduct the thermal conductance tests:

1. "Wet" specimens were removed from the chamber after exposure to moisture and wiped or drained to remove any free water. The time and specimen weight were recorded.

2. The specimen was then wrapped in 0.0005 in thick PVC sheet and placed in a 0.003 in thick polyethylene bag which was then stapled. This was done to prevent water leakage from the specimen and damage to the heat-flow meter apparatus. To be consistent, all specimens (including "room dry" specimens) were wrapped as described.

3. The wrapped 2 x 2 ft specimen was then inserted in the heat-flow meter apparatus (figure 4). The specimen was placed horizontally in the apparatus with the membrane side in contact with the upper (cold) plate, maintained at about 50°F and the insulation side in contact with the lower (hot) plate maintained at about 100°F. It is noted that in about 8 percent of the "wet" conductance tests performed on BUR specimens the lower plate temperature ranged from 86 to 90°F. The lower plate temperature was about 85°F during the 6 "room dry" roofing membrane tests. By means of a vacuum pump or by gradually and gently compressing the specimen with the hot and cold plates, most of the entrapped air was forced out of the bag. The plates were then brought in contact with the insulation or BUR system specimens by compressing them approximately 0.06 in after initial contact. It is noted that lack of flatness in bitumen surfaces makes it possible to trap air between the bitumen surface and the cold plate.

   The possibility of an air layer could affect the thermal conductance values. The temperatures of the plates in the heat-flow meter apparatus (adjacent to the membrane and insulation sides of the specimen) were about the same as the temperatures to which the specimens were exposed during introduction of moisture in the insulated chambers.

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* A Dynatech R-Matic heat-flow meter apparatus was used for these tests. This does not imply a recommendation or endorsement by the National Bureau of Standards.

This was done deliberately to maintain the same rate of moisture migration during testing and moisture introduction.

4. The above conditions were maintained until quasi-steady-state heat flow occurred. Then the following data were recorded: specimen thickness (distance between hot and cold plates), hot and cold plate surface temperature, and the heat flow. In this study, quasi-steady-state heat flow was defined to occur when three successive thermal conductance readings were taken 20 minutes apart and agreed to within 1 percent. This resulted in tests lasting from about 2 to 5 hours. It is noted that the ASTM C 518 method requires five successive readings with time intervals between readings of at least 5 minutes, depending on test specimen properties and test conditions; these readings are to agree within 1 percent.

   In 93 percent of the thermal conductance tests reported, the three succesive readings agreed to within 1 percent or less. In 6 percent of the tests reported, the three successive readings agreed to within 1 to 2 percent and for 1 percent of the tests, the readings agreed to within 2 to 4 percent. In most cases, the three successive readings were taken 20 minutes apart and, with the the exception of one test, all the readings were taken at least 17 minutes apart. The noted small deviations from the test procedure were believed to have an insignificant effect on the test results.

5. When the test was completed, the specimen was removed from the apparatus, unwrapped, weighed, and the time recorded before being returned to the chambers for further moisture gain.

   The mean temperature during the thermal conductance tests was about 75°F which was close to the temperature in the room in which the tests were conducted.

When steady-state heat flow is achieved, the thermal conductance of the specimen is determined from the one dimensional Fourier heat transfer equation:

$$q = C \cdot \Delta T. \tag{1}$$

Noting that

$$q = SQ$$

and solving for C gives:

$$C = \frac{SQ}{\Delta T} \tag{2}$$

where: C = thermal conductance in Btu/(h•ft^2•°F)

S = apparatus constant, having dimensions of Btu/(h•ft^2•mV); found [14] to be 4.05 for a specimen thickness of less than or equal to 2.25 in and 4.03 for a specimen thickness between 2.26 and 3.00 in. The apparatus constant was determined, with an uncertainty of about 2 percent, using a standard reference material. Calibration procedures are described in reference 14.

ΔT = temperature difference between hot and cold plates in °F

q = heat flow rate per unit area, Btu/h•ft^2

Q = signal from heat-flow meter in millivolts (mV)

The thermal resistance or R-value is calculated from:

$$R = \frac{\Delta T}{SQ} \tag{3}$$

5. TEST RESULTS AND ANALYSIS

5.1 Thermal Conductance of "Room Dry" Specimens

Table 3 gives average values of "room dry" thermal conductance, C_D, and their corresponding coefficients of variation (COV) for insulation and BUR system specimens.

As shown in table 3, the COV values were relatively small, particularly since the COV values included both the within specimen and between specimen variability. For the two cases in table 3 where the COV values for C_D for the insulation specimens could be computed, the COV values for the BUR system specimens were higher than those for the corresponding insulation specimens. This was probably due to the variability of the membrane thickness (COV ranged from about 4 to 14 percent) which was present in the BUR system specimens but not in the insulation specimens. Table 2 shows the C_D values for individual BUR system specimens, many of which subsequently had moisture induced in them. The values from table 2 are the "room dry" reference values for the plots of thermal conductance vs moisture content presented later.

Preliminary tests on "room dry" insulation board with and without wrapping (0.0005 in PVC sheet and 0.003 in polyethylene bag) were conducted to determine the effect of the wrapping material. The procedure for the preliminary tests differed from the procedure given earlier in this report in that the time between readings was less. For the preliminary tests, the specimens were in the heat-flow meter apparatus for at least two hours, and two or three readings were taken at least 15 minutes apart. The results showed that for the insulation tested (glass fiber, 1 in; perlite board, 1 and 2 in; fiberboard, 1 and 2 in; polystyrene, 1 and 2 in; and polyurethane, 1 in) there was no appreciable difference in thermal conductance for specimens with and without wrapping. It was also shown by calculation that the effect of the wrapping material is not significant.

5.2. Moisture Gain and Distribution

Figure 5 shows the insulation moisture content, V_P, in terms of the elapsed time in the chambers for ten BUR system specimens, one for each of the five insulation types and two insulation thicknesses studied. The moisture content, V_P*, in the specimen insulation is expressed as the percent by volume of water in the insulation; V_P was based on the average moisture gain for the entire specimen. The volume of insulation was determined from the insulation thickness (table 2) and the overall specimen dimensions (about 2 x 2 ft). The volume of water was determined from the weight gain of the specimen (62.4 lb = 1 ft^3).

The lack of smoothness in the data plots in figure 5 for the glass fiber specimens is attributed in part to their being drained prior to being weighed. For equal exposure times (90 days), the 1 in polyurethane absorbed the largest amount of moisture (about 60%) while the 2 in polyurethane absorbed the smallest (about 5%). It is also noted that the rates of absorption of the 2 in polyurethane and 2 in polystyrene were lower than the other specimens. Both 1 in perlite board and 1 in fiberboard initially absorbed moisture very rapidly. The 2 in fiberboard specimen fell apart by delaminating, after absorbing about 18 percent moisture in a relatively short exposure period (17 days).

In general it can be seen from figure 5 that specimens with 1 in insulation absorbed moisture more rapidly and eventually absorbed more moisture per unit volume for a given exposure time than did their counterparts with 2 in insulation. Since the exposure conditions on the internal and external faces of the specimens were the same during forced introduction of moisture, the differences in the response of the 1 in and 2 in specimens may be due to the lesser permeance of thicker insulations or to the location of the plane of condensation. Other factors which may be significant are the physical state of the water introduced (vapor or liquid) and its distribution in the voids of the insulation.

The response of the generally considered closed cell materials included in this study suggests that some breakdown in cell structure occurred due to moisture, that the cells were not initially completely closed, or that continuous moisture paths developed around and through the cells. Large moisture gains in polyurethane foam and expanded polystyrene insulations have been reported by other investigations [1,9].

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* $V_P = \left(\frac{\text{Volume of moisture}}{\text{Volume of insulation}}\right) \times 100$

Cores were taken before and immediately after the thermal conductance tests to determine if the moisture distribution had changed. The moisture content of the cores and corresponding specimens is given in table 4 along with information regarding the sequence of coring relative to the thermal conductance tests. Figure 6 shows moisture distributions for three different moisture contents in 2 in polystyrene. The moisture distribution for each of these three moisture contents did not appear to be significantly different before and after testing. A similar trend is shown in figure 7 for 1 in perlite board (cores 4B and 4A). It is noted that core 2AA (2 in polystyrene), which was taken two hours after the thermal conductance test, had a moisture distribution similar to cores taken before and immediately after the test (cores 2B and 2A).

Some uncertainty in the reported moisture distributions may be attributed to the experimental technique of coring. The amount of water lost while coring can be estimated by comparing the average moisture content based on the core test with that based on the entire BUR system specimen weight. Table 4 shows these two average moisture content values. As can be seen, significant moisture was lost while coring the 2 in polystyrene, particularly at larger moisture contents.

Distinct areas of visible free water, particularly for higher moisture contents, were observed on the surface of the warm side of the glass fiber insulation. It appeared that the lateral distribution of moisture in these specimens varied considerably. As noted earlier, these specimens were drained prior to the thermal conductance tests; this also contributed to the variability in the lateral moisture distribution.

5.3 Thermal Conductance of "Wet" BUR System Specimens

Figures 8 to 12 show the thermal conductance, C_W, vs moisture content, V_P, relationships for the BUR system specimens. The curves plotted in figures 8 to 12 are either linear or quadratic best fit curves. These two polynomial forms were arbitrarily selected and quadratic curves were used when they exhibited a significant improvement in fit as compared to the linear curves. In each figure, the upper curve is for specimens containing 1 in insulation and the lower curve is for 2 in insulation. Table 5 presents linear or quadratic coefficients and the residual standard deviations for the best fit curves plotted in figures 8 to 12. It is noted that the C_W and V_P scales differ in these figures.

For specimens containing glass fiber insulation (figure 8) or 1 in polyurethane (figure 11) the C_W vs V_P curves are concave upward. Here the quadratic form provides a better fit. It is noted that the small moisture gain of the 2 in polyurethane insulation (figure 11) makes it difficult to comment on the C_W vs V_P trend for that configuration. In contrast, the C_W vs V_P curves for specimens containing the other insulations are nearly linear. Here the best fit curves are slightly concave downward (perlite - figure 9 or fiberboard - figure 10), slightly concave upward (2 in polystyrene - figure 12), or are linear (1 in polystyrene - figure 12).

To compare the thermal conductances of the BUR system specimens containing different types of insulations, the data and best fit curves (figures 8 to 12) are shown collectively for the specimens containing 1 in insulation in figure 13 and 2 in insulation in figure 14. As figures 13 and 14 indicate, C_W for all the BUR system specimens increased with an increase in V_P, except for the specimen containing 2 in fiberboard. The slopes of the curves in figure 13 were not appreciably different except for specimens containing glass fiber insulation. In general, all C_W vs V_P curves in figure 13 lie in a relatively narrow band bounded by the perlite and polyurethane insulations. In figure 14, the curves lie in an even narrower band than those in figure 13. Since the conductance of the BUR system specimens is dependent on thickness, it should be noted that the measured thicknesses of the nominal 1 and 2 in insulations differed from their nominal thickness (table 2).

Figures 15 and 16 are similar to Figures 13 and 14 and show the ratios of the "wet" to "room dry" thermal conductance (C_W/C_D). The C_W/C_D ratio gives the relative change in the thermal conductance by removing the magnitude of the "room dry" thermal conductance from consideration. The C_D values for the individual BUR system specimens (table 2) were used when computing the C_W/C_D ratio. Table 5 shows the coefficients for the best fit linear or quadratic curves for C_W/C_D vs V_P.

The curves for C_W/C_D vs V_P were close to each other over the entire range of V_P for the BUR system specimens, except curves for specimens containing 1 and 2 in glass fiber and 1 in polyurethane insulations (figures 15 and 16). For example, at 20 percent moisture content, specimens containing 1 and 2 in glass fiber insulation had values of C_W/C_D of about 3 whereas C_W/C_D for the other specimens (figures 15 and 16) ranged from about 1.5 to 2.4. Similarly at 40 percent moisture content the specimen containing 1 in polyurethane had a C_W/C_D value of about 4.5 compared to about 2.2 to 2.9 for the other specimens (figure 15).

6. SUMMARY AND CONCLUSIONS

Laboratory thermal conductance vs moisture content relationships are presented for roofing system specimens containing moisture. The specimens consisted of built-up bituminous membranes applied to rigid board insulation. The following five types of insulations in 1 and 2 in thicknesses were included in the study: glass fiber, perlite board, fiberboard, polyurethane and expanded polystyrene.

The thermal conductance was measured on roofing specimens containing a wide range of moisture contents in the insulations. Moisture was introduced by imposing temperature and vapor pressure gradients across the specimen thickness using large insulated chambers in an environmentally controlled laboratory. The moisture content and approximate distribution were determined from specimen weight gain and coring data. Thermal conductance tests were conducted over relatively short time periods, about 2 to 5 hours, using an ASTM C 518 type heat-flow meter apparatus. A procedure was developed to test "wet" specimens and interpret the results for heterogenous roofing systems.

Linear and quadratic best fit curves are presented for thermal conductance vs moisture content (percent by volume of insulation) of roofing specimens containing different insulations. The thermal conductance of the roofing specimens in general increased with an increase in moisture content for all insulations. The best fit curves for thermal conductance vs moisture content lie in relatively narrow bands for specimens containing the 1 and 2 in insulations (figures 13 and 14).

For comparison, the thermal conductance data for individual specimens were normalized by dividing by the "room dry" thermal conductance value. The normalized curves were relatively close to each other throughout the entire moisture content range, with the exception of specimens containing glass fiber and 1 in polyurethane insulations (figures 15 and 16).

The amount and rate of gain of moisture varied considerably depending on the insulation type and thickness. The moisture gain in about 100 days or less of exposure ranged from about 20 to 60 percent moisture content by volume of insulation, for all specimens, including those containing nominally closed cell insulations. A notable exception was the specimen containing 2 in polyurethane which gained only about 5 percent moisture in 90 days of exposure.

The vertical moisture distribution in specimens containing 1 in perlite and 2 in polystyrene insulations did not appear to change appreciably during the thermal conductance tests (figures 6 and 7). Lateral movement of free water in glass fiber insulations precluded the determination of representative vertical moisture distributions.

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METRIC CONVERSION

Since the roofing industry generally uses conventional U.S. units, the following table is provided for converting to metric units.

CONVERSION FACTORS TO METRIC (SI) UNITS

Physical Quantity	To Convert From	To	Multiply By
Length	ft	m	3.05×10^{-1}
Area	ft^2	m^2	9.29×10^{-2}
Volume	ft^3	m^3	2.83×10^{-2}
Temperature	Fahrenheit	Celsius	$T_C = (T_F - 32)/1.8$
Temp. Diff.	Fahrenheit	Kelvin	$K = (\Delta T_F)/1.8$
Density	lbm/ft^3	kg/m^3	$1.602 \times 10^{+1}$
Thermal Transmittance (or Conductance)	$Btu/h \cdot ft^2 \cdot {}^\circ F$	$W/m^2 \cdot K$	5.68
Thermal Resistance	$h \cdot ft^2 \cdot F/Btu$	$m^2 \cdot K/W$	0.176
Heat Flow	Btu/h	W	2.93×10^{-1}
Mass per Unit Area	lbm/ft^2	kg/m^2	4.88

Table 1. Properties of Roofing System Components

Material	Thickness (in)			Density (lb/ft^3)			Moisture Content "room dry"[c] Percent by Volume			$(W_p/V_p)^d$
	Average	COV[a] (%)	N[b]	Average (oven dry)	COV (%)	N	Average	COV (%)	N	
Glass fiber 1 in[e]	0.75	4.72	7	9.56	11.9	7	0.0733	60.7	7	6.53
Glass fiber 2 in[e]	2.07	1.94	7	8.17	4.78	7	0.0348	48.0	7	7.64
Perlite board 1 in	1.02	2.18	6	10.4	3.15	6	0.222	18.5	9	5.99
Perlite board 2 in	2.06	1.59	6	9.47	3.70	6	0.295	17.6	9	6.59
Fiberboard 1 in	1.00	--	3	16.4	--	3	1.32	2.96	6	3.80
Fiberboard 2 in	2.00	--	3	15.2	--	3	1.41	2.10	6	4.12
Polystyrene 1 in	0.99	1.53	6	1.30	9.71	6	0.00245	160.	9	48.1
Polystyrene 2 in	1.99	0.643	6	1.13	9.05	6	0.00128	154.	9	55.6
Polyurethene 1 in	0.97	4.56	9	1.59	4.93	9	0.101	20.8	12	39.2
Polyurethene 2 in	2.16	8.90	9	1.86	9.37	9	0.0357	38.1	12	33.5
Roofing Felt, ASTM Type 15	0.035	--	2	.122[f] lb/ft^2	9.1	4	2.0[g]	--	2	--
Asphalt[h] ASTM Type III	--	--	--	about 62.4	--	--	--	--	--	--

[a] Coefficient of variation in percent, defined as the standard deviation divided by the mean.

[b] Number of specimens.

[c] Refers to storage at room conditions at approximately 70°F and 50% relative humidity.

[d] Ratio of moisture content expressed as percent by dry weight of insulation to moisture content expressed as percent by volume of insulation.

[e] Excludes asphalt facing sheet. Facing was treated as part of the membrane - see table 2.

[f] Weight per unit area.

[g] Moisture content - percent by dry weight of felt.

[h] Average softening point of 187°F based on 16 measurements (COV=1.7%).

Table 2. Thickness, Density and "Room Dry" Thermal Conductance Results[a] for Individual BUR System Specimens

Spec No.	Insulation Type and Nominal Thickness	(in)	Total Specimen Thickness (in)	Insulation Thickness (in)	Membrane Thickness (in)	Membrane Weight Per Unit Area (lb/ft^2)	Thermal Conductance C_D No. of Tests	Thermal Conductance C_D Average C_D ($Btu/h \cdot ft^2 \cdot °F$)
3	Glass fiber	1	1.15[c]	0.75[d]	0.40[e]	2.05[e]	2	0.266
53	Glass fiber	1	1.25	0.87	0.38[e]	1.94[e]	1	0.250
7	Glass fiber	2	2.59	2.17	0.42[e]	2.17[e]	2	0.110
57[b]	Glass fiber	2	2.60	2.20	0.40[e]	2.05[e]	2	0.110
13	Perlite board	1	1.37[c]	1.02[d]	0.35	1.90	--	0.341[f]
63	Perlite board	1	1.43	1.08	0.35	1.75	2	0.335
17	Perlite board	2	2.39[c]	2.06[d]	0.33	1.63	1	0.177
67	Perlite board	2	2.35[c]	2.06[d]	0.29	1.41	2	0.181
22	Fiberboard	1	1.32[c]	1.00[d]	0.32	1.57	2	0.340
28	Fiberboard	2	2.38[c]	2.00[d]	0.38	1.98	2	0.176
33	Polystyrene	1	1.12	0.78	0.34	1.76	1	0.273
751[b]	Polystyrene	1	1.16	0.78	0.38	1.76	1	0.276
82[b]	Polystyrene	1	1.24	0.88	0.36	1.75	4	0.250
37	Polystyrene	2	2.38	2.02	0.36	1.83	-	0.131[f]
155[b]	Polystyrene	2	2.29	1.89	0.40	2.06	1	0.132
87[b]	Polystyrene	2	2.30	1.95	0.35	1.84	2	0.130
42	Polyurethane	1	1.41	1.09	0.32	1.65	2	0.157
48	Polyurethane	2	2.31	2.00	0.31	1.55	-	0.0795[f]
98[b]	Polyurethane	2	2.25	1.89	0.36	1.94	1	0.0726
M_1[h]	Membrane	-	--	--	0.35	1.78	4	1.24[g]
M_2[h]	Membrane	-	--	--	0.40	2.15	2	1.40

[a] Unless noted otherwise, specimens were used for "room dry" and subsequent "wet" thermal conductance tests.

[b] Thermal conductance tests performed for "room dry" conditions only; note that for specimen no. 82, no moisture was induced; specimen no. 98 was soaked in water for 5 months rather than exposed to water vapor prior to thickness measurements.

[c] Based on sum of insulation thickness (estimated from table 1) and the membrane thickness.

[d] Based on table 1.

[e] Includes an asphaltic facing sheet. Estimates of the average density ($\bar{d}$), thickness ($\bar{t}$), and coefficients of variation (shown in parentheses) for 7 facing specimens are:

Asphaltic facing on 1 inch glass fiber insulation: $\bar{d}$ =43 lb/ft^3 (11%); $\bar{t}$ = 0.14 inch (9.9%)

Asphaltic facing on 2 inch glass fiber insulation: $\bar{d}$ = 40 lb/ft^3 (3.1%); $\bar{t}$ = 0.13 inch (9.7%)

[f] Value based on table 3; "room dry" thermal conductance test not performed on this specimen.

[g] Coefficient of variation was 1.7%.

[h] Membrane only, tested at "room dry" conditions.

Table 3. Summary of Thermal Conductance Results for "Room Dry" Conditions

System	Insulation Type and Nominal Thickness	(in)	No. of Specimens	Total No. of C_D Tests	Average Thermal Conductance C_D ($Btu/h \cdot ft^2 \cdot °F$)	COV[a](%)
Insulation[b]	Glass fiber[d]	1	2	4	0.266	0.673
BUR[c]	Glass fiber[d]	1	3	5	0.256	3.39
Insulation	Glass fiber	2	1	2	0.115	--
BUR	Glass fiber	2	3	6	0.111	1.17
Insulation	Perlite board	1	2	3	0.375	--
BUR	Perlite board	1	3	8	0.341	1.64
Insulation	Perlite board	2	1	2	0.184	--
BUR	Perlite board	2	4	8	0.176	1.52
Insulation	Fiberboard	1	1	2	0.364	--
BUR	Fiberboard	1	3	7	0.330	3.94
Insulation	Fiberboard	2	1	2	0.199	--
BUR	Fiberboard	2	3	5	0.173	1.30
Insulation	Polystyrene	1	1	2	0.266	--
BUR	Polystyrene	1	3	6	0.258	4.96
Insulation	Polystyrene	2	1	2	0.137	--
BUR	Polystyrene	2	2	3	0.131	--
Insulation	Polyurethane	1	1	2	0.166	--
BUR	Polyurethane	1	2	7	0.168	4.41
Insulation	Polyurethane	2	2	4	0.0741	7.72
BUR	Polyurethane	2	2	5	0.0795	5.37

[a] Coefficient of Variation.

[b] Insulation (without built-up roofing membrane).

[c] BUR system specimen (insulation with built-up roofing membrane).

[d] Facing on glass fiber insulation in contact with cold plate of heat-flow meter apparatus.

Table 4. Insulation Moisture Content for Cores and BUR System Specimens and Conditions of Specimens Before Coring

Specimen No.	Core No.	Average Moisture Content[a]		History of Specimen Before Coring
		Core[b]	BUR System Specimen	
37 - 2" Polystyrene	1B	3.51	4.49	Before test. Specimen cored 15-30 minutes after removal from chamber.[c]
	1A	2.82	4.49	After test. Specimen was in apparatus[d] for 3-1/2 hours and then cored 5-15 minutes after removal from apparatus.
	2B	10.4	18.0	Before test. Specimen cored 5-15 minutes after removal from chamber.
	2A	13.3	18.0	After test. Specimen was in apparatus for 4-1/2 hours and then cored 5-15 minutes after removal from apparatus.
	2AA	13.8	18.0	After test. Specimen cored 2 hours after removal from apparatus.
	3B	21.3	29.7	Before test. Specimen wrapped in plastic bag and had been at room temperature for 194 hours before being cored.
	3A	14.4	29.7	After test. Specimen was in apparatus for 6-1/2 hours and then cored 2 minutes after removal from apparatus.
63 - 1" Perlite	4B	5.27	4.95	Before test. Specimen wrapped in plastic bag and had been at room temperature for 23-1/2 hours before being cored.
	4A	4.50	4.87	After test. Specimen was in apparatus for 12-2/3[e] hours and then cored 15-30 minutes after removal from apparatus.
13 - 1" Perlite	5A	69.0	57.3	After test. Specimen wrapped in plastic bag and had been at room temperature for 399-3/4 hours before being put in apparatus. Specimen in apparatus for 6 hours and then cored 15 minutes after removal from apparatus.
	5AA	59.2	57.3	After test. Specimen cored 2-1/2 hours after removal from apparatus.

[a] Percent by volume.

[b] Based on core data.

[c] Insulated chamber used to induce moisture.

[d] Heat-flow meter apparatus.

[e] Specimen stayed in apparatus overnight.

Table 5. Curve Fit Coefficients for C_W and C_W/C_D

Type Insulation in BUR System Specimen	Number of Tests	$C^*_W = a_0 + a_1 V^{**}_P + a_2 V^2_P$ (Figures 8-12)				$C^*_W/C_D = b_0 + b_1 V_P + b_2 V^2_P$ (Figures 15 and 16)			
		C_W Curve Coefficients			Residual Standard Deviation	C_W/C_D Curve Coefficients			Residual Standard Deviation
		a_0	a_1	a_2		b_0	b_1	b_2	
Glass fiber 1 in	24	.258571	-.000957572	.00139389	.0378	.994558	-.00463115	.00565024	.169
Glass fiber 2 in	19	.118008	-.000277890	.000610987	.0580	1.06973	-.00251317	.00553837	.526
Perlite 1 in	23	.372569	.0189125	-.0000871547	.0285	1.10677	.0554255	-.000258881	.0802
Perlite 2 in	15	.212833	.0119370	-.0000508645	.0243	1.18729	.0700821	-.000371967	.141
Fiberboard 1 in	14	.373006	.0122040	-.0000617180	.0192	1.09595	.0358573	-.000181341	.0564
Fiberboard 2 in	13	.195819	.0100616	-.000330270	.0142	1.11148	.0571105	-.00187464	.0804
Polystyrene 1 in	20	.288351	.0119111	--	.0341	1.05596	.0436193	--	.125
Polystyrene 2 in	20	.129210	.00245697	.0000609823	.00269	.986572	.0187599	.000465623	.0206
Polyurethane 1 in	21	.160161	.00719091	.000163073	.0368	1.01765	.0456906	.00103615	.234
Polyurethane 2 in	15	.0730231	-.000481150	.000501665	.00232	.918235	-.00605768	.00630970	.0292

* C_W, C_D = "wet" and "dry" thermal conductance in Btu/h·ft^2·°F.

** V_P = moisture content, percent by volume of insulation ($V_P = \frac{\text{volume of water}}{\text{volume of insulation}} \times 100$)

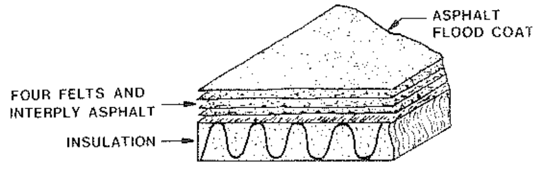

Fig. 1 BUR system specimen composition

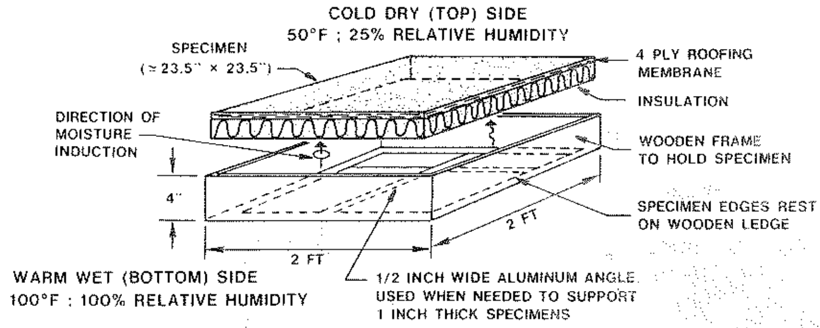

Fig. 2 BUR system specimen, wooden supporting frame and the environmental conditions used to induce moisture

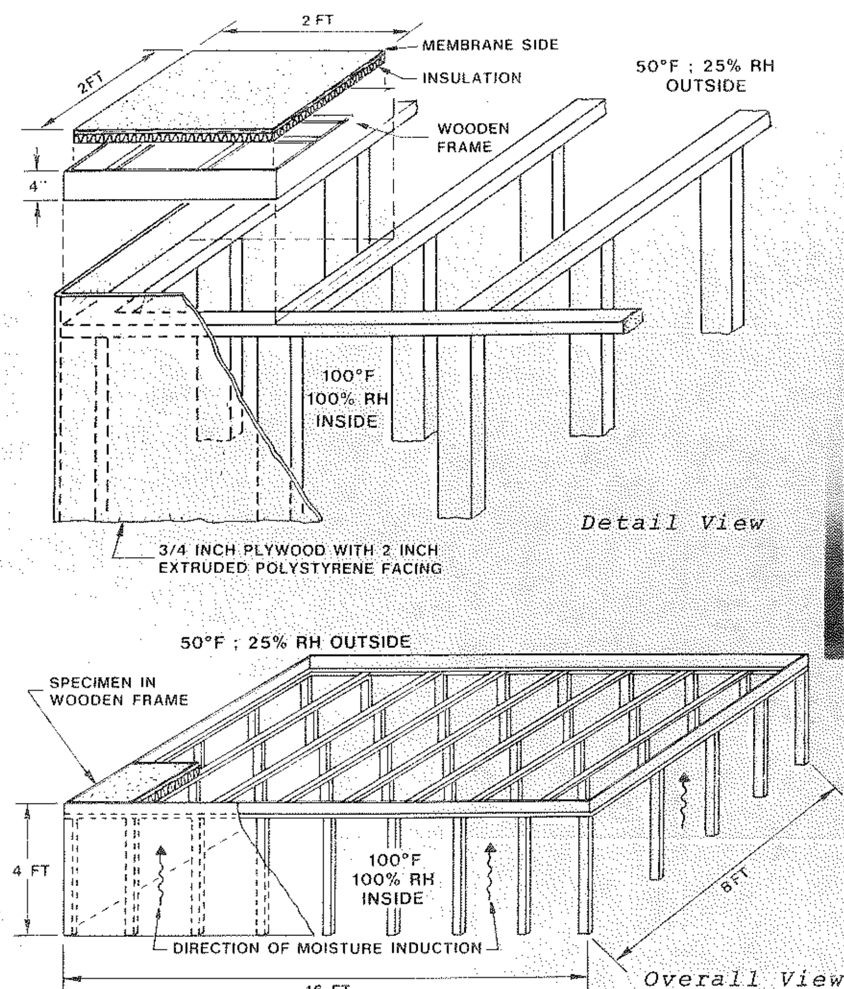

Fig. 4 Heat-flow-meter apparatus used to conduct thermal conductance tests

Fig. 3 Insulated wooden chambers used to induce moisture in the BUR system specimens

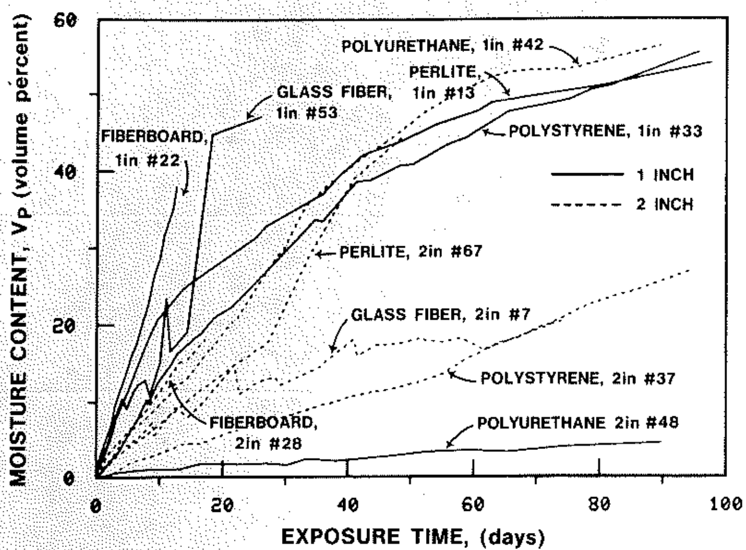

Fig. 5 Moi re gain in BUR system spe ns

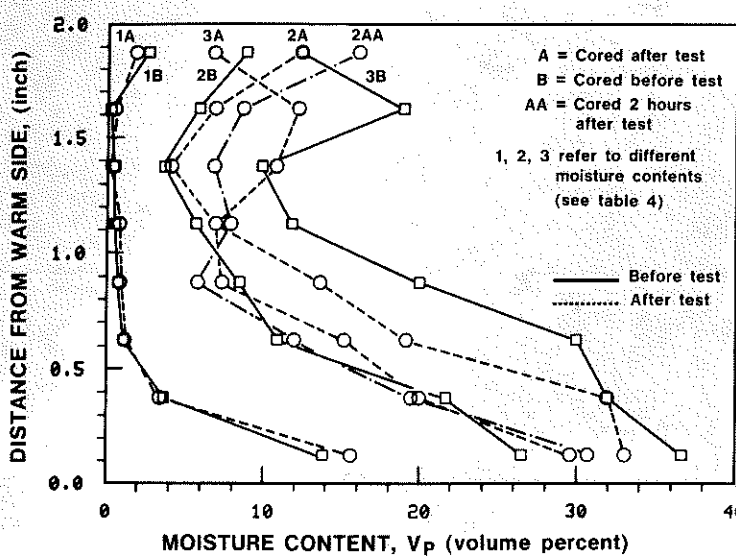

Fig. 6 Moisture distributions by coring for 2 in polystyrene, BUR System Specimen No. 37

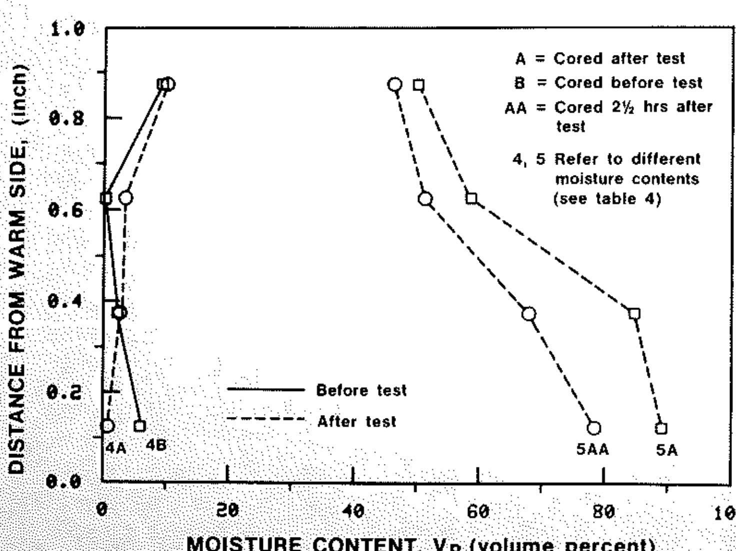

Fig. 7 Moisture distributions by coring for 1 in perlite board BUR System Specimen No. 13

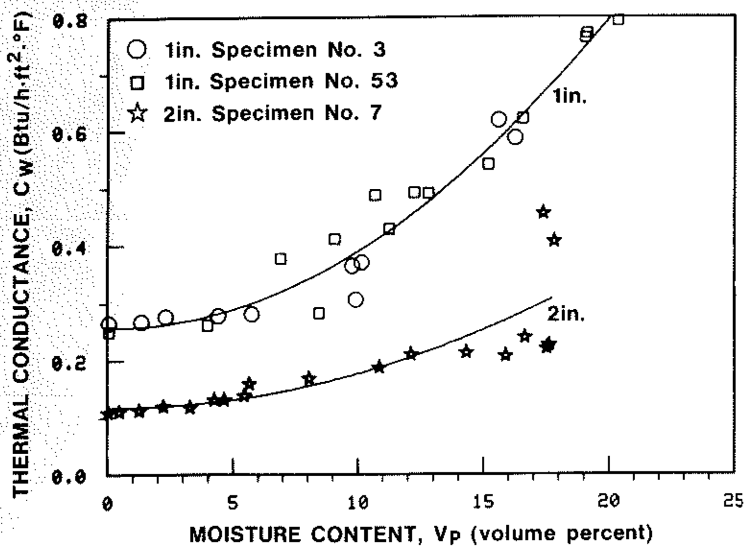

Fig. 8 Thermal conductance vs moisture content for glass fiber BUR System Specimen No. 13

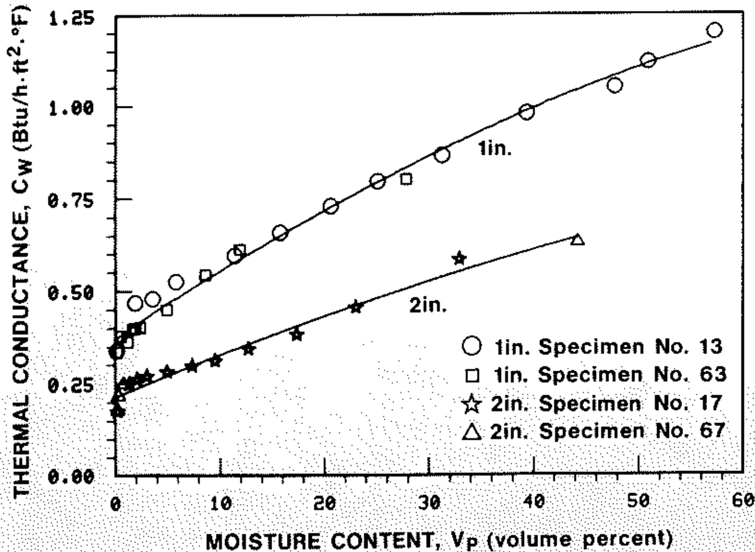

Fig. 9 Thermal conductance vs moisture content for perlite board BUR system specimens

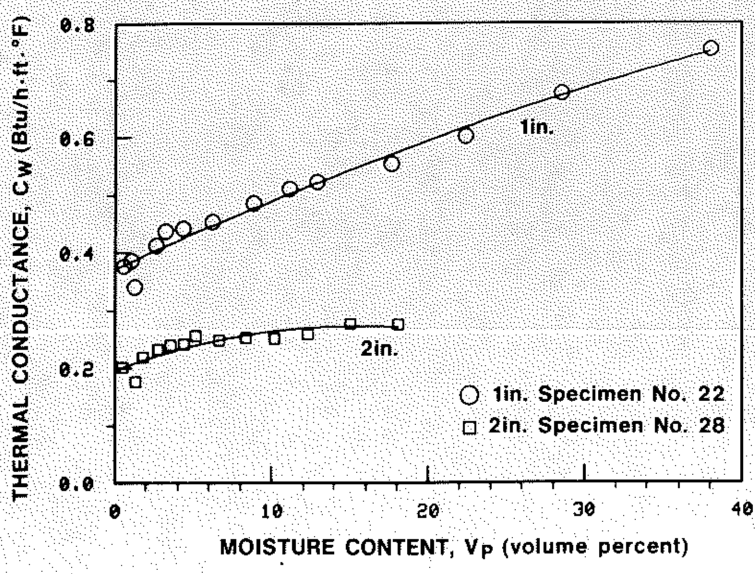

Fig. 10 Thermal conductance vs moisture content for fiberboard BUR system specimens

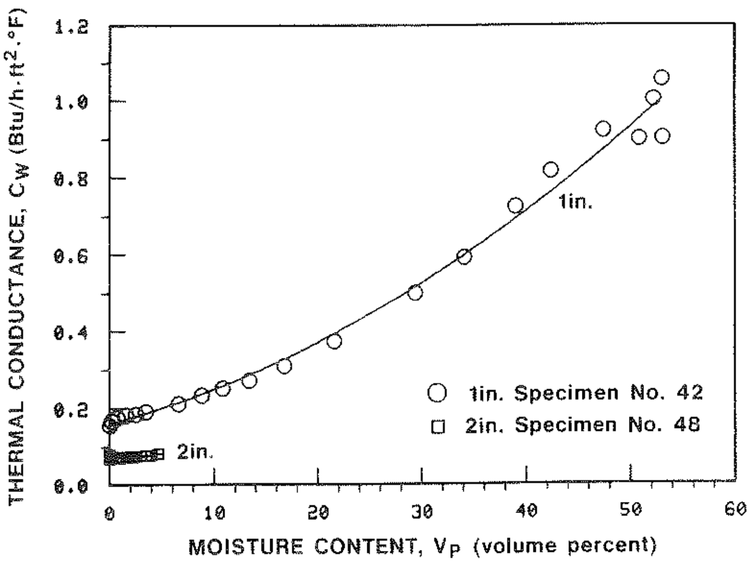

Fig. 11 Thermal conductance vs moisture content for polyurethane BUR system specimens

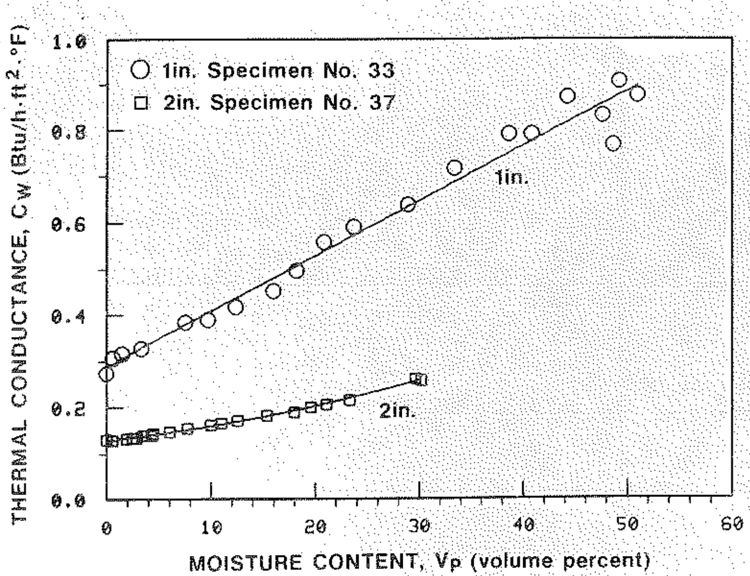

Fig. 12 Thermal conductance vs moisture content for polystyrene BUR systems specimens

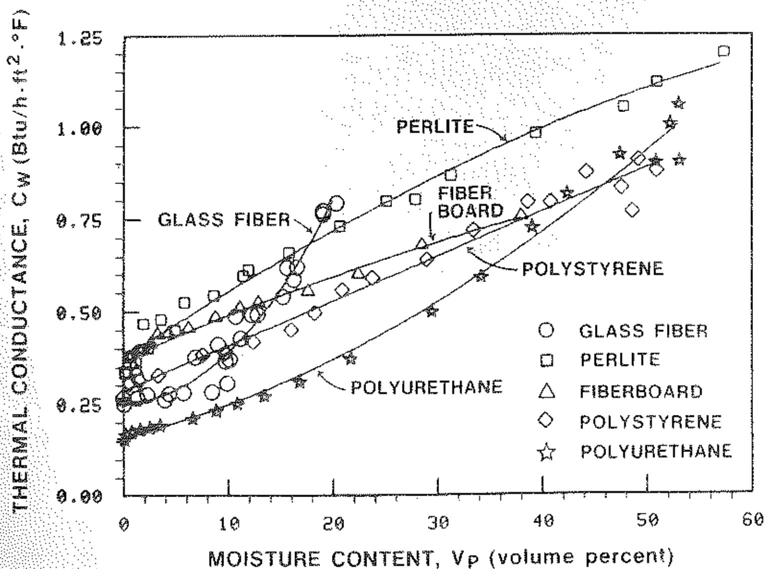

Fig. 13 Thermal conductance vs moisture content for all BUR system specimens containing 1 in insulation (Fig. 8 to 12)

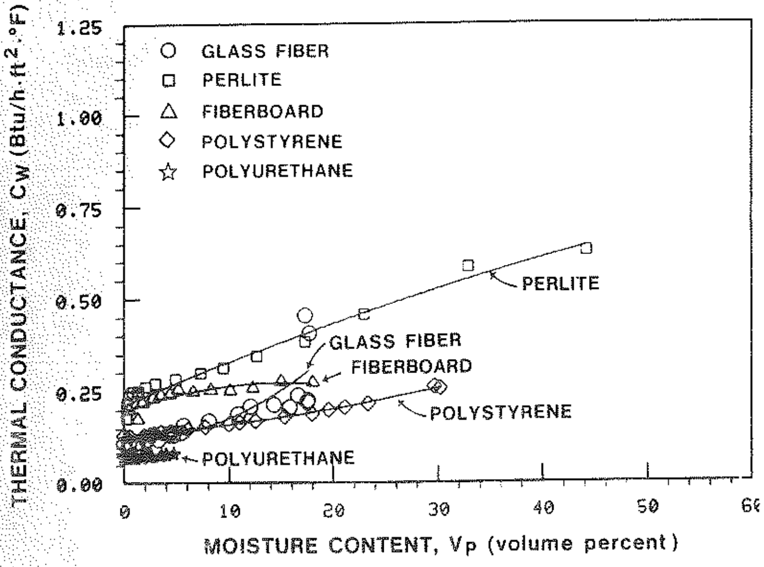

Fig. 14 Thermal conductance vs moisture content for all BUR system specimens containing 2 in insulation (Fig. 8 to 12)

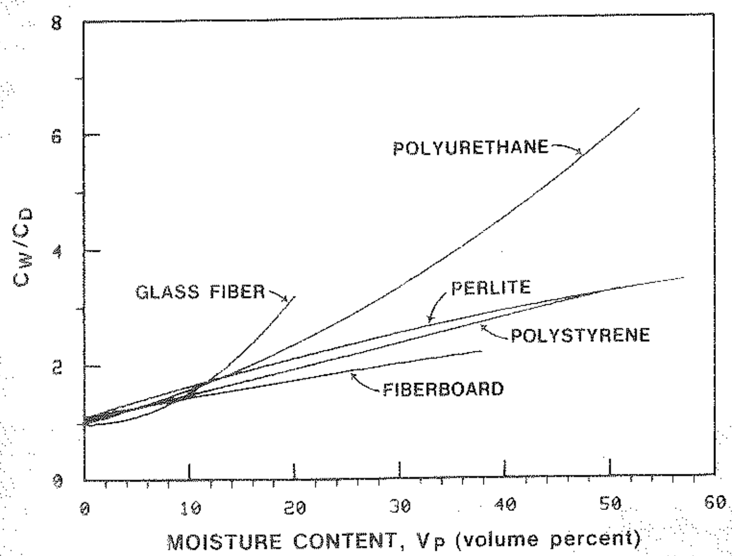

Fig. 15 Ratio of "wet" to "room dry" thermal conductance vs moisture content for all BUR system specimens containing 1 in insulation

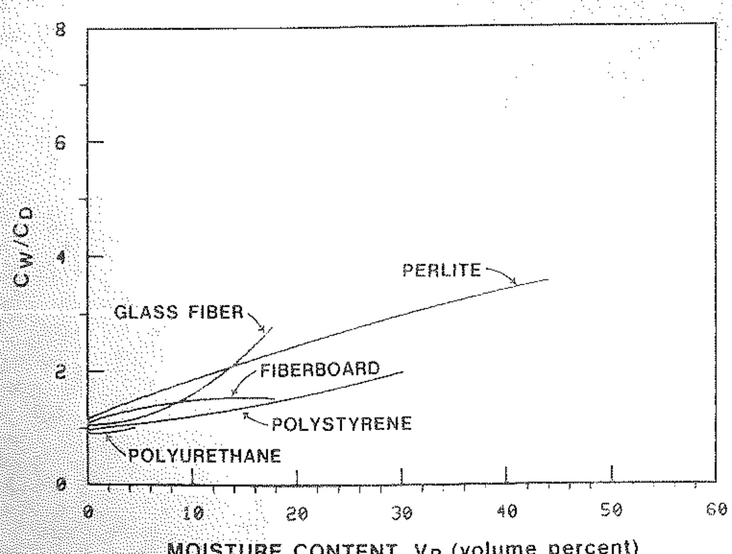

Fig. 16 Ratio of "wet" to "room dry" thermal conductance vs moisture content for all BUR system specimens containing 2 in insulation