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EFFECT OF MOISTURE ON THERMAL RESISTANCE OF SOME INSULATIONS IN A FLAT ROOF UNDER FIELD–TYPE CONDITIONS

by C.P. Hedlin

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RÉSUMÉ

Pour cette étude, des échantillons d'isolant en fibres de verre, en mousse phénolique, et en polystyrène extrudé avec des pourcentages d'humidité atteignant 20 % en volume ont été mis en place dans le toit d'un bâtiment expérimental. Le bâtiment a été maintenu à 21°C à l'intérieur et à l'extérieur les conditions atmosphériques étaient normales.

On avait placé des thermocouples sur les surfaces supérieure et inférieure de tous les échantillons et dans certains cas, tous les quarts d'épaisseur. Un appareil de mesure de la transmission de chaleur étalonné a été mis en place sur chaque isolant pendant une période ininterrompue d'environ une année.

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C. P. Hedlin[1]

Effect of Moisture on Thermal Resistance of Some Insulations in a Flat Roof under Field-Type Conditions

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ABSTRACT: Specimens of glass fiber, phenolic foam, and extruded polystyrene foam insulation with moisture contents ranging up to about 25 percent by volume were mounted in the roof of an experimental building. The interior of the building was maintained at about 21°C and normal weather conditions prevailed outside.

Thermocouples were located at the upper and lower surface of each insulation specimen and at the quarter points of some specimens. A calibrated heat flow meter was used to measure heat flow through each specimen continuously for a period ranging from about 7½ to 18 months for wet specimens and somewhat less for some of the dry ones.

Heat flow rates were plotted against temperature difference using daily arithmetic averages in most cases; two-week averages were used in a few cases. For open-cell and fibrous insulations of 20 percent moisture content, heat flow rates exceeded rates for dry insulation by a factor of two or more. The data points were scattered. Inspection suggested that this was partly owing to moisture distribution, which affected the rate of heat flow at a given temperature difference.

Measurements at the quarter points provided information about temperature gradients along the path of heat flow, and hence about moisture distribution in the insulation. These results suggested that moisture migrated to the upper layers in the wintertime, leaving the lower layers nearly dry.

Ratios of heat flow in wet and dry specimens were in fairly good agreement with those obtained by other investigators.

KEY WORDS: moisture, moisture migration, thermal resistance, open-cell insulation, closed-cell insulation, wet insulation, heat flow, heat flow meters, roof insulation

Thermal insulation in flat roofs normally contains some moisture, both in the vapor form and in the adsorbed state. The effect of the moisture will vary

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with the amount of moisture and the physical properties of the insulation, and may be negligible. More important, and difficult to predict, is the effect of liquid moisture that may be built into the system (if wet material is used) or may result from vapor migration or water leakage into the completed system. This accumulation may occur because of inadequate protection methods or disruptive failure of components.

In spite of extensive efforts, methods for controlling such moisture and dealing rationally with its effects have not yet been perfected. Some moisture will always be present, even in the best systems. Further study of its effects, however, particularly in field environments, may lead to improved understanding of its behavior and to the development of more systematic methods of accommodating it. The problem is a complex one involving heat flow coupled with moisture migration. The thermal effect is only one factor; the degrading effects of moisture may also lead to physical failure of the roof system.

The present study was confined almost entirely to the effect of moisture on heat flow in three insulations; fragmentary results are given for a fourth one. Although some of the conclusions may be applicable to other configurations, most will be specific to the horizontal insulation arrangement used in these studies and to the vertical flow of heat, daily average flows being upward in cold weather and intermittently downward in warm weather. The study was done on the Canadian Prairies where the temperature ranges from about +35 to −40°C. Because of solar radiation and night-sky radiation, the upper surface of the insulation experiences even wider temperature swings. Prolonged cold weather in winter promotes one-directional migration of moisture and frost deposition at the upper surface of the insulation that would not occur in more moderate climates.

Test Method

Moisture moves about in insulation and consequently participates in the transport of heat; local concentrations of moisture change with time. Thus the relation between moisture content and heat flow is not fixed, and there may be a range of heat flow rates for a certain temperature difference at a given moisture content. One method of assessing this range of values is to subject moist specimens to conditions similar to those that occur in buildings and to measure periodically their heat flows and temperature differences over a period of time. Nominally a year would be required for a full cycle of effects to occur, and one might expect that data compiled over that period would give a complete picture of performance. The tests reported here indicate that that assumption is only partially correct, because more than one year may be required to produce every weather condition. There also may be long-term migration of moisture or degradation of the insulation owing to moisture that will not be evident in one year.

This report is based on measurements made at the Outdoor Test Facility of the

Division of Building Research, National Research Council of Canada, at Saskatoon [1,2].[2] The insulation specimens were located in experimental panels on the roof of the test building, and thus were exposed to conditions similar to those that prevail on the Prairies.

The interior temperature of the building was kept at about 21°C; thus, because the roof was exposed to outside conditions, the specimens were subjected to daily and annual temperature changes normal for the Prairie region. Mean insulation temperatures varied from about 25 to 0°C, and temperature differences across the insulation reached 40°C. Test periods ranged from about 7½ to 18 months.

Thermocouples were placed at the bottom and top surfaces of the insulation, located on the axis through the center of the heat flow meter (Fig. 1). In addition, three thermocouples were located in the insulation at the quarter points of some of the specimens in order to give intermediate temperatures. They were placed by carefully forming a hole normal to the direction of heat flow by using a sharpened welding rod rotated in a drill press. Heat flows were measured using meters calibrated at the Division of Building Research in Ottawa. The temperature and heat flow results were recorded using a digital data acquisition system and were processed by computer.

Extruded polystyrene foam, phenolic foam, and glass fiber specimens were used. A few results for urethane foam are also given. All are used in roofing and represent a wide range of permeability (a factor apt to affect the thermal behavior of wet material). A set comprising four or five specimens of each in-

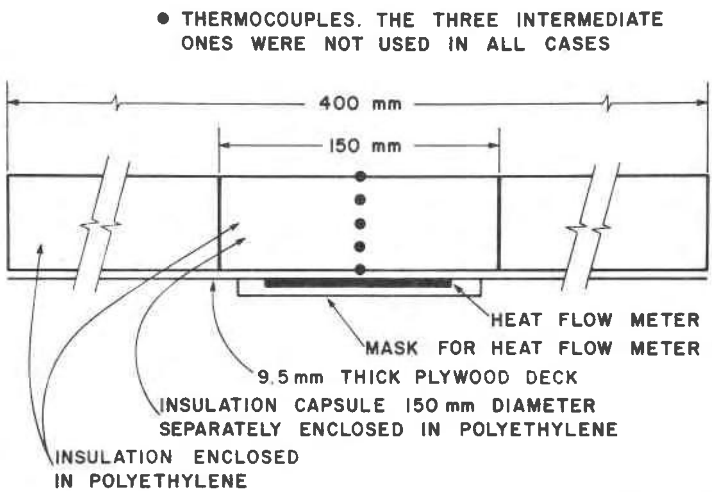

FIG. 1—*Arrangement for sealing and mounting specimens and for measuring heat flow rates and temperatures.*

[2]The italic numbers in brackets refer to the list of references appended to this paper.

sulation was prepared from the same lot of material. One specimen was kept dry and the others were wetted to predetermined levels. In this report all moisture contents (m.c.) are given as a percentage of specimen volume. Two sets of extruded polystyrene foam and one of each of the other materials were tested. A second set of glass fiber specimens was also prepared, with moisture contents of approximately 0, 1, 9, and 15 percent. They have not been subjected to long-term tests, but enough data were available from them to use them in a limited way in this report.

The extruded polystyrene foam and phenolic foam specimens were approximately 50 mm thick. In the case of the phenolic foam, the 50 mm included corrugated paper on both surfaces. The depth of the corrugations was about 3 mm. The glass fiber specimens were 60 mm thick and did not have any surface covering. Average dry densities were approximately 31, 56, and 145 kg/m^3 for the polystyrene foam, phenolic foam, and glass fiber, respectively. Phenolic foam and polystyrene foam specimens were wetted by imposing a temperature-moisture gradient [*3*]. Glass fiber specimens were wetted by immersion or by applying water with a brush. Care was taken to keep the specimens horizontal to minimize lateral flow of water. In the majority of cases, sections 150 mm in diameter were cut out of the center of the conditioned pieces and weighed to determine their moisture contents. In the later set of tests on glass fiber, the sections were 106 mm in diameter. All sections were sealed in 0.050-mm-thick polyethylene and returned to their locations in the parent pieces. Each entire specimen was then sealed in polyethylene to inhibit moisture loss.

Data Analysis

Temperatures θ, °C, and heat flow rates Q, W/m^2, represent averages of 72 observations per day running from midnight to midnight. The parameter Q is the arithmetic average heat flow. Temperature difference $\Delta\theta$ is equal to $\theta_b - \theta_t$, where θ_b and θ_t are the average temperatures at the bottom and top surfaces of the insulation, respectively.

Periods of 24 h were used so that the conditions in the system would be approximately the same at the beginning and the end of the cycle. This, coupled with arithmetic averaging, was done to reduce the effect of thermal lag [*1,4*].

Daily averages of heat flow and temperature difference were used with two exceptions. Hourly averages were used to illustrate certain effects that occurred during the daily cycle. In some other cases, two-week averages were used since the longer averages reduced the scatter, which masked other effects. It should be noted that θ_b and θ_t differed from the air temperature inside (θ_i) and outside (θ_o) of the building because of the intervening panel components and air films (Fig. 1).

It is common practice to express the relation between Q and $\Delta\theta$ as a thermal conductance value

$$C = Q/\Delta\theta \tag{1}$$

or as a thermal resistance

$$R = \Delta\theta/Q \tag{2}$$

If moisture is present, its relatively high thermal conductivity and its migration change the heat flow mechanism, and this traditional approach may not be applicable.

In an earlier study [*1*], two approaches to calculating thermal conductance using *in situ* heat flow and temperature difference data were discussed. One involved the ratio expressed in Eq 1; the other used the slope of the Q versus $\Delta\theta$ relation as given by $\delta Q/\delta\Delta\theta$.

Plots of Q versus $\Delta\theta$ indicated that the best-fit curve did not necessarily pass through the origin of the plot; that is, there might be an ordinate intercept, usually negative, when $\Delta\theta = 0$. If this occurred, the error in the conductance as expressed by Eq 1 became increasingly large as $\Delta\theta$ decreased and became meaningless; that is, went to infinity or became negative near the origin. (The same effect applied to resistance given by Eq 2.) This error decreased as $\Delta\theta$ increased or reached larger negative values. If the finite ordinate intercept is assumed to be caused by measurement error, its effect can be avoided simply by subtracting the intercept value from each heat flow value.

In the second approach, slope $\delta Q/\delta\Delta\theta$ can be found for a straight line representing two or more points, or for a continuous second-order curve determined by least-squares analysis of a set of data covering a broad range of $\Delta\theta$, for example, at least 25°C. Then

$$Q = a + b\Delta\theta + c\Delta\theta^2 \tag{3}$$

$$\delta Q/\delta\Delta\theta = b + 2c\Delta\theta \tag{4}$$

If $a = 0$ then, based on Eqs 1 and 3,

$$C = b + c\Delta\theta \tag{5}$$

and, from Eq 4,

$$C = \delta Q/\delta\Delta\theta - c\Delta\theta \tag{6}$$

In the present case, involving moist insulation, the heat transfer process is more complex than it is for dry insulation. Some of the effects, such as large ordinate intercepts and apparent differences in the heat transfer mechanism observed for open-cell insulations, are described later.

In the present case, Q versus $\Delta\theta$ plots and equations are used to illustrate the relation between heat flow and temperature difference. Because of the complexity of the relationship and uncertainties about the phenomena, conductances were used only sparingly in this study. Instead, the ratio of heat flow in wet insulation to that in dry insulation was usually employed to quantify the moisture effect.

Results and Discussion

In these tests the interior temperature of the building remained fairly constant, but the temperatures in the roof system rose and fell with changing outdoor temperature. The temperature at the top surface of the insulation (θ_t) would be expected to play an important role in the migration of moisture and its deposition in the upper part of the insulation in winter. Therefore scales for θ_t were shown on some of the graphs. Inspection indicated that the relation between θ_t and $\Delta\theta$ was approximately linear. These θ_t-values were provided for information only and should not be considered as equivalent to the corresponding $\Delta\theta$-scale.

The moisture contents given in Table 1 are approximate; some moisture will be lost or gained through the polyethylene covering during the test period. The two quoted values were those measured at the beginning and end of the test, respectively. Approximate values are quoted in the text. Also, although efforts were made to produce uniform lateral moisture content at the outset, that condition was difficult to achieve. Lateral nonuniformity at the beginning of the test, coupled with subsequent movement of the moisture, means that lateral differences no doubt existed and may have varied during the tests. The stated moisture contents given were average values for the entire capsule. Vertical distribution will vary. Uniform moisture distribution from top to bottom is an idealized condition that is unlikely ever to occur in the field, and then only as a transient condition.

The size of the capsule, 150 mm in diameter or 106 mm in a few cases, was greater than that of the heat flow meters, which were 100 mm or 50 mm in diameter. The capsule size was made larger than the meters to reduce the effect on measured heat flow of the junction of the insulation capsule and the surrounding insulation (Fig. 1). However, no such effect was detected even when 106-mm specimens were used with 100-mm heat flow meters.

The effect of moisture on the heat flow results varied considerably between different types of insulation. Major differences existed between open- and closed-cell insulations; therefore they are discussed separately.

Open-Cell and Fibrous Insulations

One open-cell and one fibrous insulation were used in the tests. Plots of Q versus $\Delta\theta$ for glass fiber at 6 and 20 percent moisture content are given in Fig. 2, and for phenolic foam at 10 and 20 percent in Fig. 3. In each case the dry insulation was also tested in the roof and that curve is shown as a dotted line.

TABLE 1—*Moisture contents, constants for the equation* $Q = a + b\Delta\theta + c\Delta\theta^2$, *and stantdard errors of estimate* SE_Q *(W/m²) for glass fiber and phenolic foam specimens.*

m.c., % volume	A-Segment				B-Segment				Test Period
	a	*b*	10^3c	SE_Q	*a*	*b*	10^3c	SE_Q	
GLASS FIBER									
dry	−0.02	0.59	−1.46	...	...	...	...	...	10/79 to 180/79
3.1 to 3.5	−1.46	1.11	−15.07	1.09	−0.14	0.67	−2.30	0.30	206/79 to 351/80
6.1 to 6.6	−2.22	1.46	−17.5	1.38	−1.09	0.92	−3.68	0.76	206/79 to 351/80
12.0[a]	−4.33	3.00	−114	1.23	...	...	...	...	206/79 to 165/81
20.5 to 20.2	−0.52	1.77	35	3.09	...	...	...	...	10/79 to 352/80
PHENOLIC FOAM									
dry	−0.03	0.731	−1.15	...	...	...	...	...	280/78 to 212/79
5.8 to 5.5	−3.00	1.67	−30.6	0.88	−1.00	0.91	−3.2	0.43	280/78 to 180/79
9.7 to 10.5	−2.15	1.99	−38.9	1.06	−0.52	1.10	−5.5	1.26	280/78 to 35/80
12.4 to 12.9	−2.35	2.18	−38.6	1.30	...	...	...	...	347/79 to 165/81
21.1 to 20.2	−2.28	2.91	−55.6	1.11	...	...	...	...	206/79 to 352/80
...	−1.90	2.43	−36.4	...	...	...	...	...	...
EXTRUDED POLYSTYRENE FOAM									
(I)									
dry	−0.15	0.641	−1.18	...	...	...	...	...	24/79 to 180/79
3.7 to 4.2	+0.02	0.636	+1.29	...	...	...	...	...	280/78 to 180/79
8.0 to 8.4	−0.04	0.652	+1.36	...	...	...	...	...	280/78 to 180/79
15.1 to 16.1	−0.29	1.018	+0.54	...	...	...	...	...	280/78 to 180/79
19.3 to 19.6	+0.07	0.943	+2.08	...	...	...	...	...	280/78 to 180/79
(II)									
dry	0.0	0.575	−1.00	...	...	...	...	...	347/79 to 207/80
4.8 to 5.4	0.2	0.60	0.0	...	...	...	...	...	296/79 to 207/80
7.7 to 8.3	0.0	0.65	+0.5	...	...	...	...	...	296/79 to 207/80
24.7 to 25.3	...	...	...	...	...	...	...	...	296/79 to 207/80

[a] Seal failed before the final weighing was done.

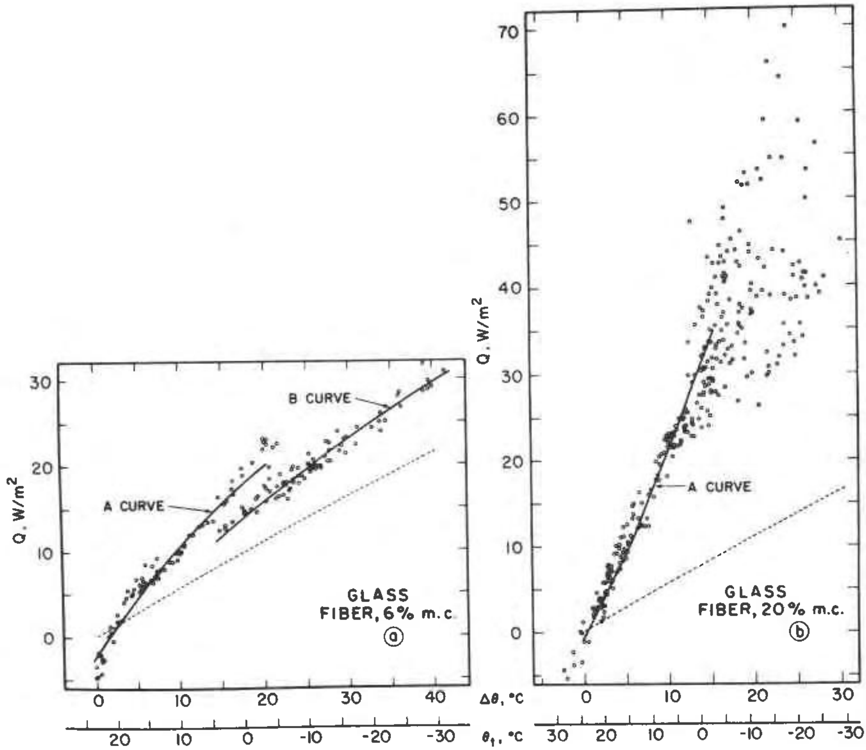

FIG. 2—*Heat flow rates versus temperature difference for glass fiber at* (a) *6 and* (b) *20 percent moisture content by volume. The dotted lines are for dry insulation.* θ_t *is the approximate temperature at the top surface of the insulation. (The apparent filling of some circles is caused by overlap, not because they are different from the open circles.)*

Analysis of the results suggested that there is a difference in the character of the heat flow mechanism at low and high values of $\Delta\theta$. Therefore in this report the data are divided into two parts; they are referred to as the *A* (smaller $\Delta\theta$) and *B* (larger $\Delta\theta$) segments.

The proposition that the *Q* versus $\Delta\theta$ plots may sometimes be divided into two sections rested on two observations. Firstly, in many of the plots there was some evidence of discontinuity in the data. Secondly, sudden seasonal changes in heat flow rate, at approximately constant $\Delta\theta$, occurred in a number of cases. This effect is discussed in more detail later.

Second-order curves of best fit were found using Eq 3 with one-day averages of *Q* and $\Delta\theta$. Sometimes it was uncertain whether given points belonged to the *A* or *B* segment. Some of them fell in the transition region. Arbitrary decisions were made; in a few cases points were excluded. Coefficients and standard errors of estimate of heat flow for the open-cell and fibrous insulations are given in Table 1. The standard error of estimate is not a valid mea-

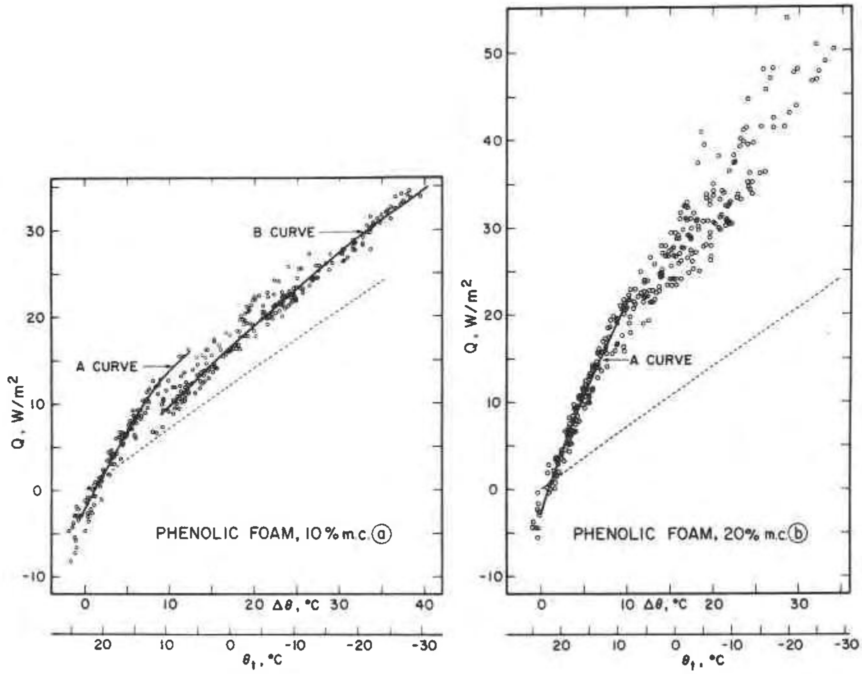

FIG. 3—*Heat flow rates versus temperature difference for phenolic foam at* (a) *10 and* (b) *20 percent moisture content.*

sure of the scatter since the distribution is not really random; systematic seasonal effects account for some of the variation. Nevertheless, it does provide a measure of the deviation of the points from the curve of best fit.

Usually the *A*-curves were concave downward and had negative ordinate intercepts. The coefficient *c*, in the best fit relationships, reached −0.017 $W/(m^2 \cdot °C^2)$ for the glass fiber and was greater for the phenolic foam. Ordinate intercepts reached −4 W/m^2. The *B*-segments showed less curvature than the *A*-segments. The coefficient *c* ranged from −0.0023 to −0.0055 $W/(m^2 \cdot °C^2)$. Ordinate intercepts, found by extrapolation, were closer to zero heat flow than for the *A*-curves.

Hourly plots of Q versus $\Delta\theta$ suggested that the negative intercept was caused by accelerated heat flow downward during that part of the day when $\theta_t > \theta_b$. This nonisotropic effect is illustrated in Fig. 4 for the 3 percent moisture content glass fiber for a 24-h period in July (day 207, 1979). The positive and negative values of temperature difference nearly balanced for the day; that is, the arithmetic average was −0.1°C. However, the relatively rapid influx of heat when the temperature gradient was inward produced an average in-flow rate of 3.8 W/m^2 for the day.

Figure 5 shows the transition from the *A* to *B* segments for glass fiber spec-

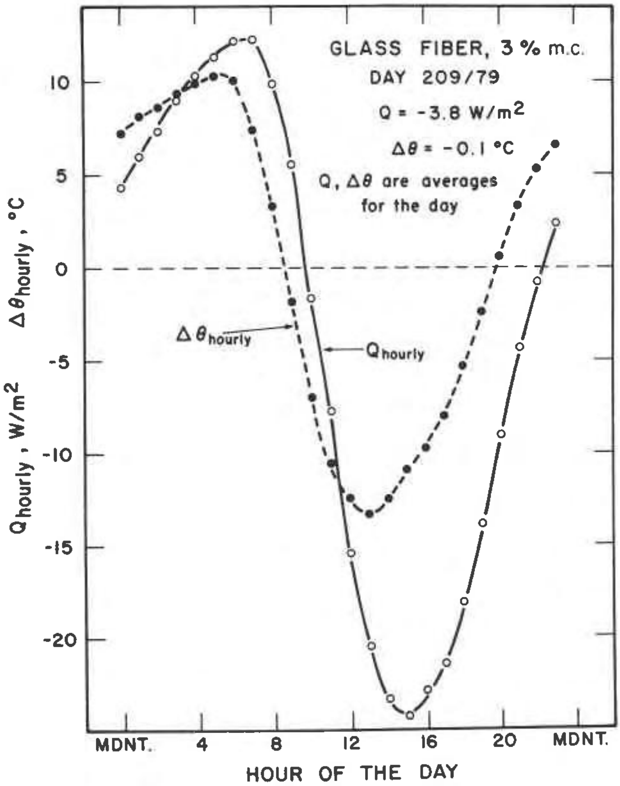

FIG. 4—*Hourly plots of heat flow and temperature difference for a summer day for glass fiber at 3 percent moisture content.*

imens at 3 and 6 percent moisture contents. Starting on day 309 (5 November) the rate of heat flow for the 3 percent specimen decreased, and by day 314 had reached the lower level where it remained. For the 6 percent glass fiber specimen, the transition occurred in a five-day period from days 312 to 316 in 1979 (Fig. 5*b*). A similar transition recurred in the 3 percent specimen a year later, but was not evident in the 6 percent specimen.

Similarly, for the 12 percent glass fiber specimen rapid changes occurred in the fall and spring. The time scale is not fine enough to show it, but these changes took place more rapidly than for the 3 and 6 percent materials. For example, the changes occurred in the 24-h period between day 75 and 76 in 1979. In that case the thermal resistance of the bottom slice, which would have been affected by a sudden downward migration of moisture, remained nearly fixed for three more days, that is, until day 79 before starting to rise. The 20 percent specimen (not shown) behaved somewhat similarly.

Relatively long-term variations in thermal resistance of the slices occurred

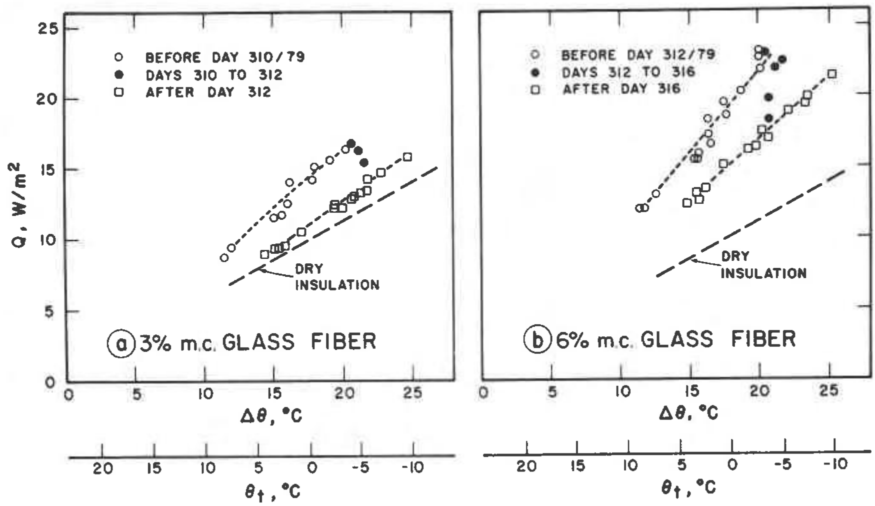

FIG. 5—*Heat flow rates during the transition from* A *to* B *curves for glass fiber with* (a) *3 and* (b) *6 percent moisture content.*

owing to relocation of moisture; for example, upward migration in the fall and winter deposits moisture in the upper regions. However, the sudden changes described did not appear to be explained by that effect. They may be caused by reduction or cessation of another heat flow mechanism, such as moisture migration that followed a daily cycle in the *A*-regions [5].

The nature of the Q versus $\Delta\theta$ relationship varies with moisture content. Glass fiber at 3 and 6 percent and phenolic foam at 5, 10, and 12.5 percent moisture contents all followed a similar pattern (Figs. 2*a* and 3*a*).

For the 20 percent glass fiber (Fig. 2*b*) and the 20 percent phenolic foam (Fig. 3*b*), the scatter was relatively small for $\Delta\theta$ up to about 12°C. Above that, the points were widely scattered and superficial inspection did not reveal a consistent behavior pattern. However, when two-week averages of data for the 20 percent glass fiber were plotted, a more systematic pattern was obtained. Based on trends in the day-long averages, similar to those shown in Fig. 5, the scattered points could be divided into an *A*-group and into a second group that included *B*-type and transition-type points (Fig. 6). The *B* or transition points were few in number and *B*-type conditions were never firmly established. The *A*-type conditions prevailed through most of the year. The *A*-type data can be represented by the equation

$$Q = -0.5 + 1.77\Delta\theta + 0.035\Delta\theta^2 \quad (7)$$

Thermocouples located at the quarter points in some of the specimens provided information about the effect of seasonal moisture movement on ther-

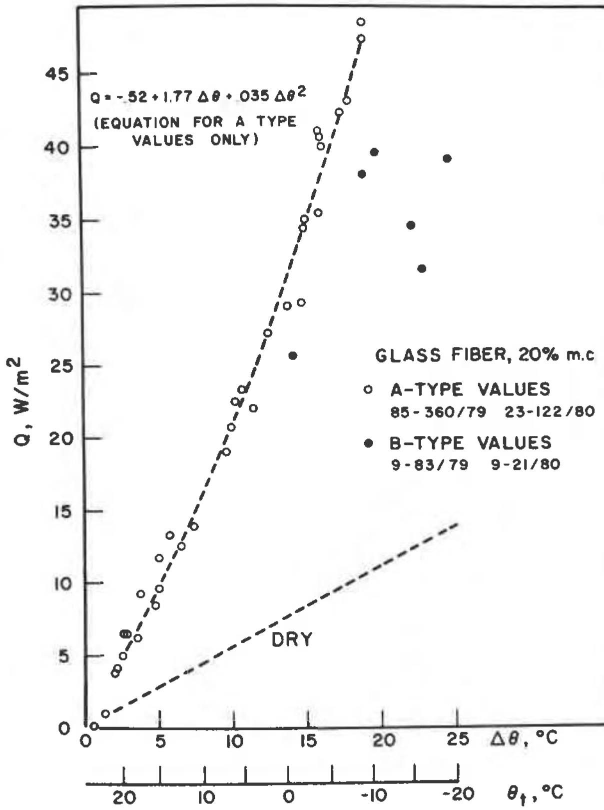

FIG. 6—*Heat flow rates versus temperature difference for glass fiber with 20 percent moisture content using data points representing two-week averages.*

mal resistance. The fraction of temperature change occurring in each quarter is shown in the middle section of Fig. 7. Values in the summer period were somewhat unreliable since temperature differences were very small. The parameter $\Delta\theta$ is also shown and θ_t is given in the top section of the figure.

The bottom section of Fig. 7 shows the thermal resistances for each quarter and for the full thickness of the specimens. These were based on Eq 2. As discussed earlier, the validity of Eq 2 for use with these data is uncertain at low values of $\Delta\theta$. However, by using only values for which $\Delta\theta > 10°C$, results can be found which, although approximate, are useful in showing seasonal variations in resistance. Thermal resistances for the full thickness of the wet and dry specimens are given by lines 5 and 6. They are referred to the left-hand ordinate scale. The quarters are numbered from one to four starting at the top and are referred to the right-hand scale. For reasons indicated previously, the thermal resistance curves are given only for the colder part of

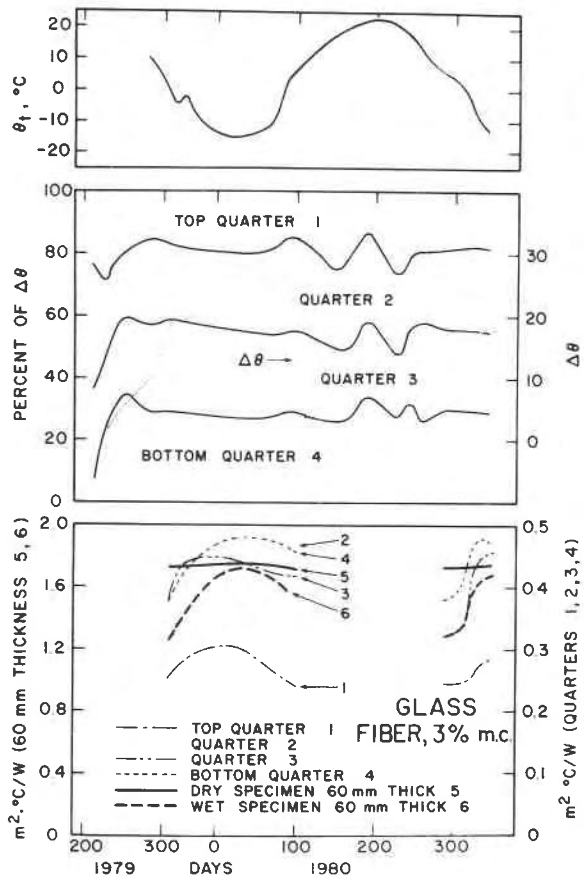

FIG. 7a—*Glass fiber with 3 percent moisture content. Temperature at the top surface of the insulation* (θ_t) (top), *fractional temperature drops in each quarter of the insulation (percentage of* $\Delta\theta$*) and temperature difference* $\Delta\theta$ (middle), *and thermal resistances for the full specimen (dry and wet) and for each quarter* (bottom).

the year. The left- and right-hand scales are in a four-to-one ratio; thus the resistances of the slices as a fraction of their dry resistances can be found approximately by comparison with the dry specimen curve.

The seasonal changes shown in Fig. 7 varied with insulation type and moisture content. All gave evidence of moisture migration and changes in thermal resistance at different levels in the insulations. Changes in the glass fiber were more abrupt than they were in the phenolic foam.

From inspection of the thermal resistance curves it appeared that lower slices might approach dryness, since their resistances (when multiplied by four) were approximately equal to those of the dry specimen. For example, the bottom three slices of the 3 percent moisture glass fiber each reached a

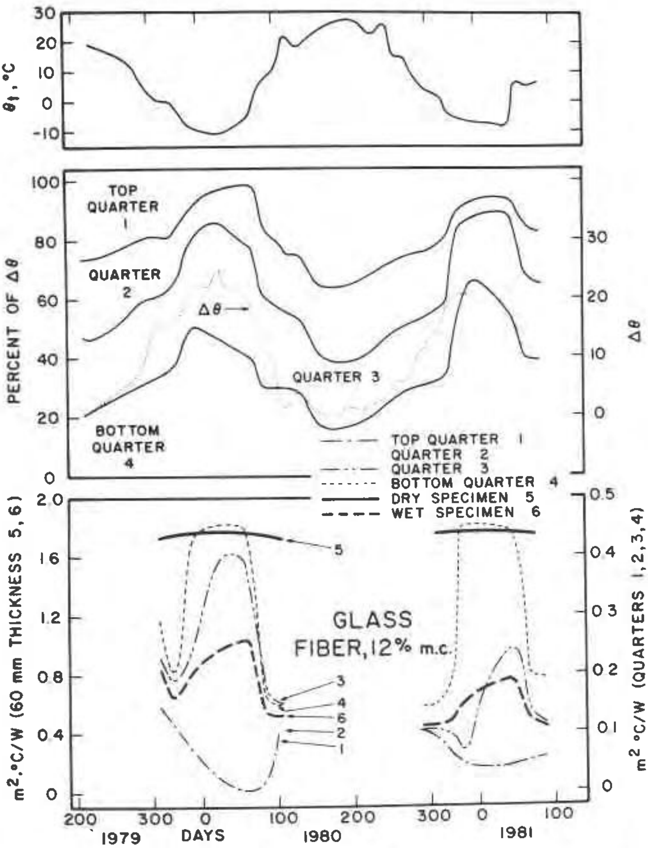

FIG. 7*b*—*Glass fiber with an initial moisture content of 12 percent. Moisture content increased due to failure of the seal around the capsule. This caused a reduction in thermal resistance in the 1980-81 period. Temperature at the top surface of the insulation* (θ_t) (top), *fractional temperature drops in each quarter of the insulation (percentage of* Δθ) *and temperature difference* Δθ (middle), *and thermal resistances for the full specimen (dry and wet) and for each quarter* (bottom).

thermal resistance of about 0.45 (m²·°C)/W. Based on a thickness equal to that of the full specimen, this would be 1.80 (m²·°C)/W, which is similar to the dry specimen value of 1.75 (m²·°C)/W.

Closed-Cell Insulation

Two batches of extruded polystyrene foam, comprising seven specimens, ranged from 4 to 25 percent moisture content. In each case a dry specimen (as-received, not dried in the laboratory) from the same batch of insulation was included in the tests.

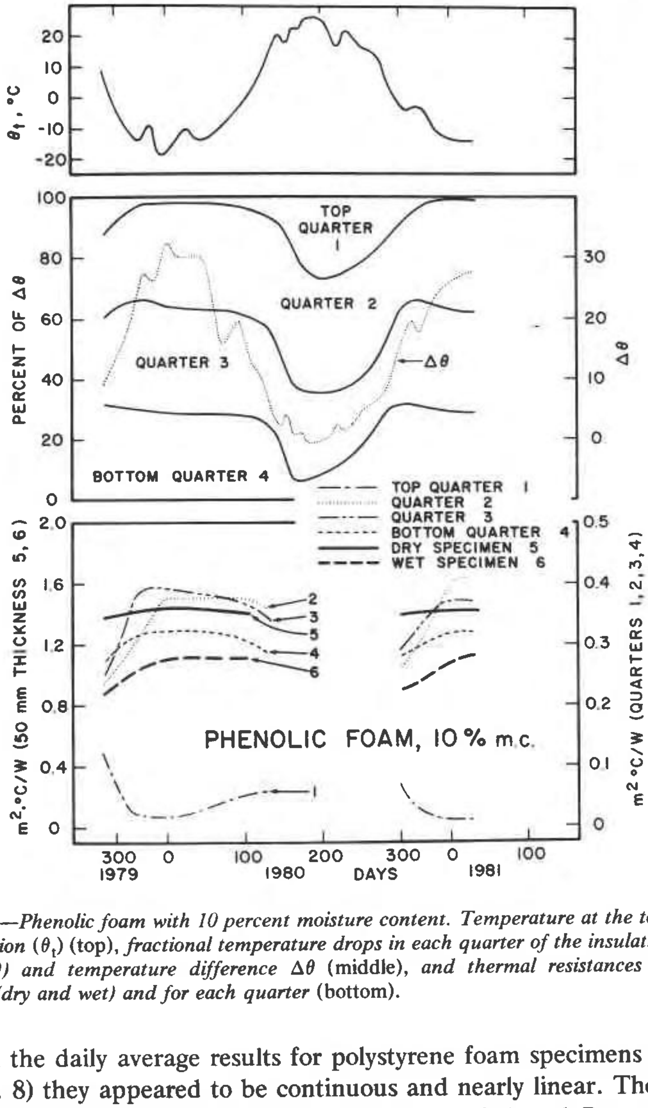

FIG. 7c—*Phenolic foam with 10 percent moisture content. Temperature at the top surface of the insulation* (θ_t) (top), *fractional temperature drops in each quarter of the insulation (percentage of* $\Delta\theta$*) and temperature difference* $\Delta\theta$ (middle), *and thermal resistances for the full specimen (dry and wet) and for each quarter* (bottom).

When the daily average results for polystyrene foam specimens were plotted (Fig. 8) they appeared to be continuous and nearly linear. There was no evidence of the discontinuity that led to the use of *A* and *B* curves for the open-cell and fibrous insulations. However, there was evidence of increasing scatter with increasing moisture content. When the results were plotted as two-week averages (thus reducing the masking effect of data point scattering), there appeared to be a hysteresis effect; the heat flow was larger on the returning leg (decreasing $\Delta\theta$) (Fig. 9). This might be caused by redistribution of moisture or freeze-thaw damage [*6*].

Interior temperatures were measured in some of the polystyrene foam specimens. Plots of percentage temperature drop and thermal resistances for

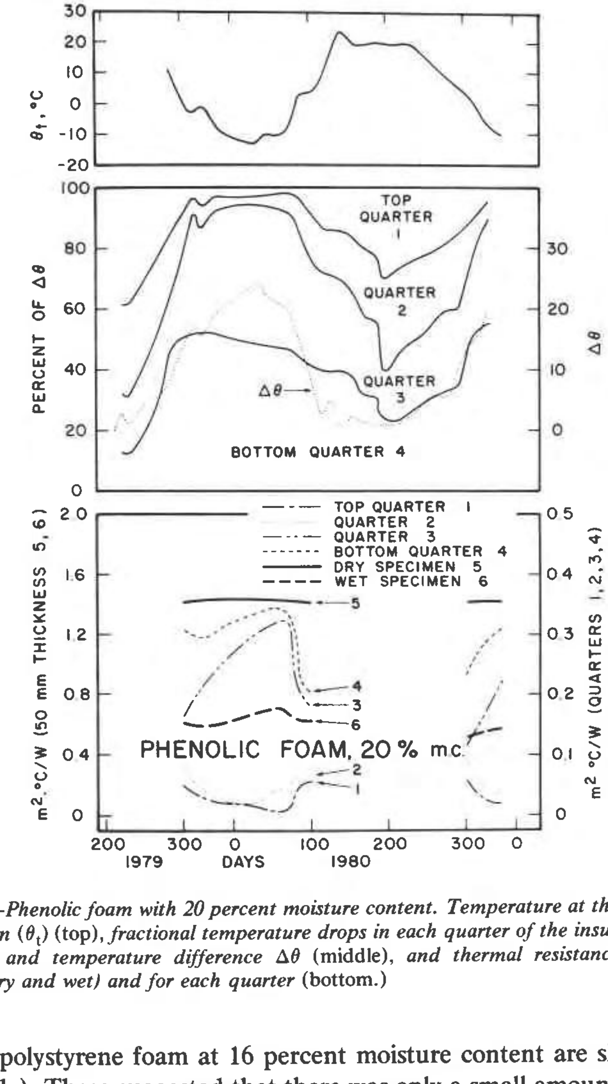

FIG. 7*d*—*Phenolic foam with 20 percent moisture content. Temperature at the top surface of the insulation* (θ_t) (top), *fractional temperature drops in each quarter of the insulation (percentage of* $\Delta\theta$*) and temperature difference* $\Delta\theta$ (middle), *and thermal resistances for the full specimen (dry and wet) and for each quarter* (bottom.)

extruded polystyrene foam at 16 percent moisture content are shown in Fig. 10 (left side). These suggested that there was only a small amount of moisture migration. A similar plot is shown for a urethane foam sample. In that case the moisture content increased from 8.9 to 11.7 percent.

Comparison with Results of Other Investigators

A number of studies have been done to assess the effect of moisture on the thermal resistance of insulation [*5-19*]. Table 2 contains a summary of some of the published data for laboratory measurements. The accuracy of the values in Table 2 is influenced by interpretations that were made in prepar-

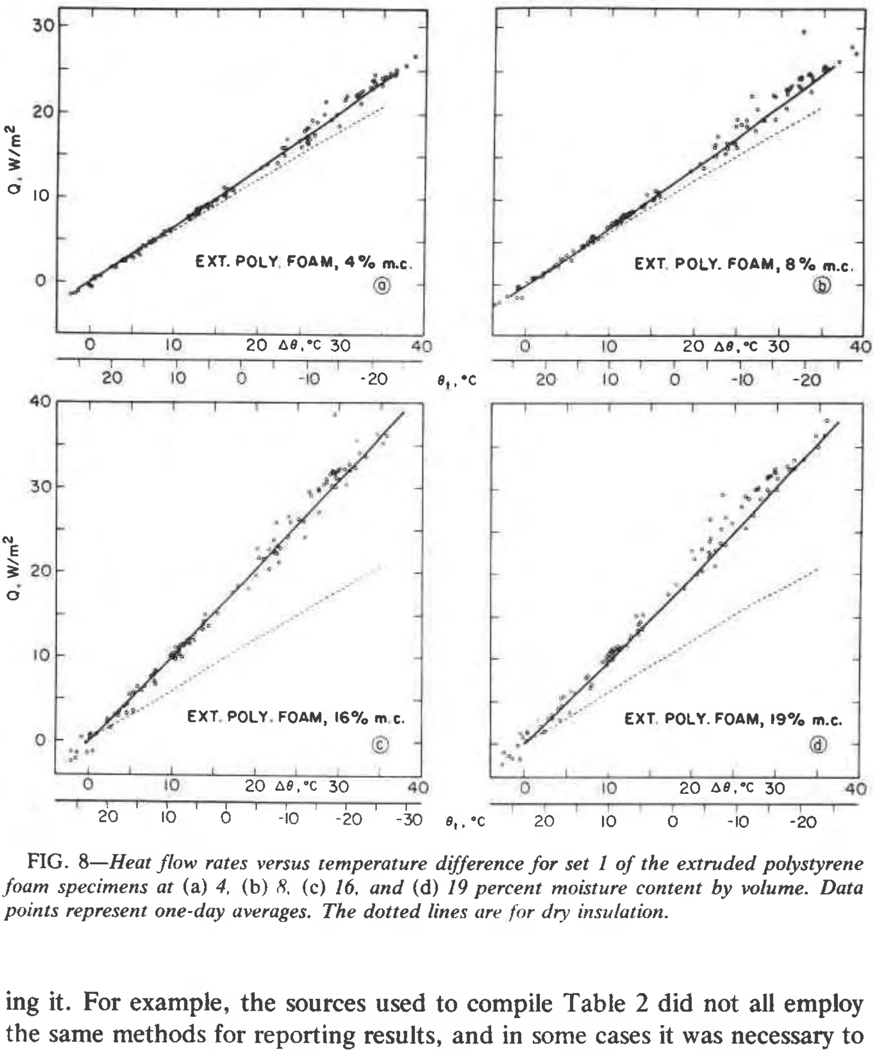

FIG. 8—*Heat flow rates versus temperature difference for set 1 of the extruded polystyrene foam specimens at* (a) *4,* (b) *8,* (c) *16, and* (d) *19 percent moisture content by volume. Data points represent one-day averages. The dotted lines are for dry insulation.*

ing it. For example, the sources used to compile Table 2 did not all employ the same methods for reporting results, and in some cases it was necessary to estimate values from graphs. Further, classification is by generic type only; the density of the insulations and the conditions of tests varied from one investigator to another.

The values in Table 2 are ratios K_w/K_d where K_w (wet insulation) and K_d (dry insulation) are the values reported as thermal conductivities for the stated moisture content.

Tables of thermal resistance for insulations are normally based on measurements on dry material. Since the mechanism of heat flow in wet materials is different, comparison of wet and dry materials requires careful consideration.

Figure 11 describes the effect of moisture on the heat flow rate by finding

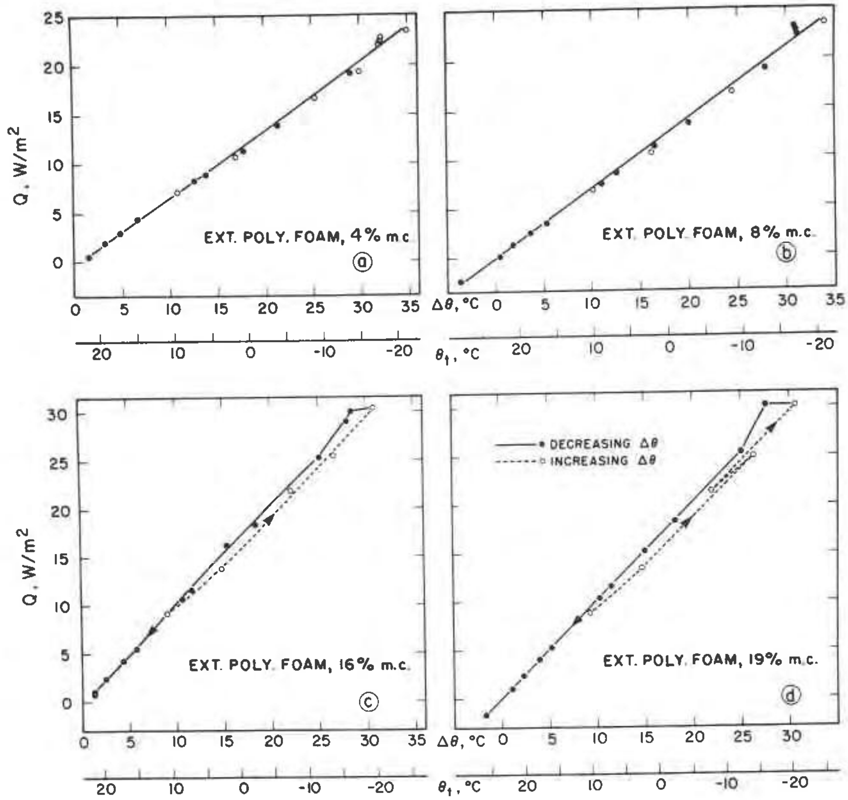

FIG. 9—*Heat flow rates versus temperature difference for set 1 of the extruded polystyrene foam specimens at* (a) *4,* (b) *8,* (c) *16, and* (d) *19 percent moisture content by volume. Data points represent two-week averages. The dotted lines are for dry insulation.*

an average heat flow rate in wet insulation (Q_{w_a}) and comparing it with an average heat flow rate for dry insulation (Q_{d_a}). In the A-region, Q_w usually becomes negative at some positive value of $\Delta\theta$; therefore Q_{wa} was found by using absolute values of Q_w.

$$Q_{w_a} = (|Q_{w_1}| + |Q_{w_2}| + \cdots + |Q_{w_n}|)/n \tag{8}$$

where the subscripts 1, 2, and n correspond to a series of values of $\Delta\theta$; for example, 0, 5, 10, and 15°C. A corresponding average value of heat flow in dry insulation was found by using the same values of $\Delta\theta$. In this way the ratio Q_{w_a}/Q_{wd} is obtained. Because of the scatter in the data, a maximum and minimum value of Q_{w_a} occurred for each value of $\Delta\theta$. This results in the envelopes shown in Fig. 11. It should be noted that this contrivance—the

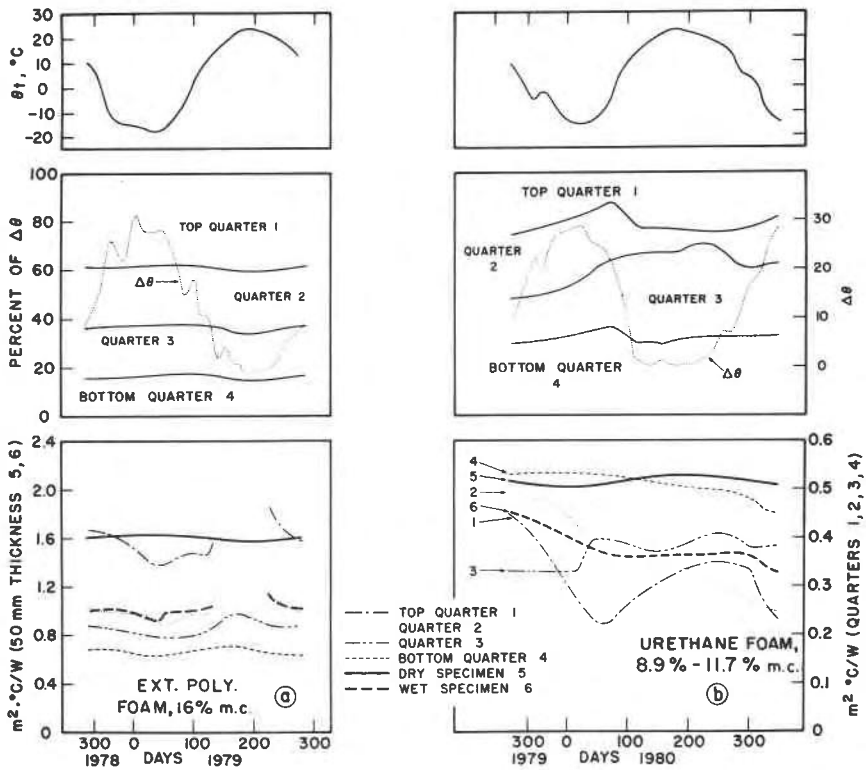

FIG. 10—*Temperature of the top surface of the insulation* (θ_t) (top), *fractional temperature difference in each quarter and temperature difference* (middle), *and thermal resistances for the full specimen (wet and dry) for each quarter (wet specimen)* (bottom) *for extruded polystyrene foam at 16 percent moisture content* (left) *and urethane foam* (right). *The urethane specimen moisture content* (b) *rose from 8.9 to 11.7 percent during the test, producing a decrease in its thermal resistance.*

averaging of absolute values of Q_w—is of limited practical significance, but it does represent one basis for comparing heat flows in wet and dry insulations.

The shaded areas in Fig. 11 represent the envelopes encompassing data points of other investigators.

Figure 12 gives Q_{w_a}/Q_{w_d} based on mean rather than extreme values of $\Delta\theta$ by using the relation

$$Q_{w_a}/Q_{d_a} = 1 + S\,(\text{m.c.}) \qquad (9)$$

where S is the fractional change in Q_{w_a}/Q_{d_a} for each 1 percent change in moisture content (m.c.). The value of S varies with the type of insulation and whether A- or B-type data are involved. For A and B data, S was respectively 0.12 and 0.05 $(\text{m.c.})^{-1}$ for glass fiber, and 0.08 and 0.03 $(\text{m.c.})^{-1}$ for the

TABLE 2—*Ranges of K_w/K_d for several insulations based on data published by several investigators.*[a]

Moisture Content, % volume	Glass Fiber [*7, 8, 15, 16*]	Phenolic Foam [*9, 10, 14*]	Extruded Polystyrene Foam [*7, 11–14*]	Urethane Foam [*7, 9, 11–14, 16*]	Bead Polystyrene Foam[b] [*7–9, 11–14, 16*]
5	1.2 to 1.7	1.35 to 1.9	1.06 to 1.2	1.15 to 1.5	1.1 to 1.4
10	1.5 to 1.85	1.5 to 2.8	1.25 to 1.4	1.4 to 2.1	1.2 to 1.6
20	2.0 to 2.7	2.5	1.8	2.0 to 2.7	1.6 to 2.4
30	2.7 to 3.6	. . .	. . .	3.0 to 4.1	2.2 to 3.0

[a]The italic numbers in brackets refer to the list of references appended to this paper.
[b]Studies on this material not included in the present work.

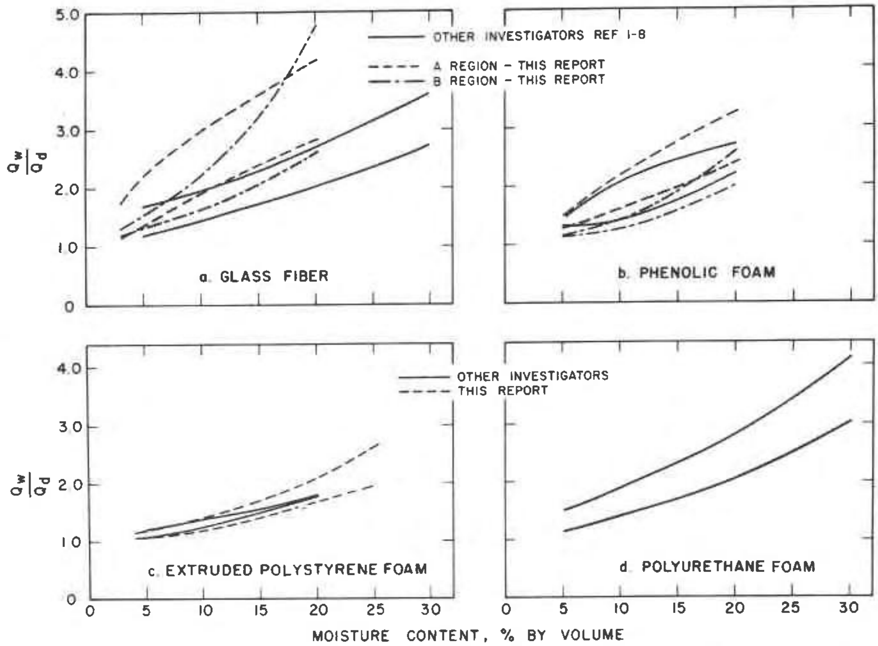

FIG. 11—*Plots of* Q_w/Q_d *for glass fiber, phenolic foam, and extruded polystyrene foam from the present investigation, and for these three insulations and urethane foam based on the data of others.*

phenolic foam. For the extruded polystyrene foam there was some evidence of curvilinearity; the slope appeared to be 0.04 $(\text{m.c.})^{-1}$ or less.

Summary and Conclusions

1. Heat flow measurements were made on three different types of insulation having moisture contents ranging up to about 25 percent by volume. Glass fiber, phenolic foam, and extruded polystyrene foam were selected since they are used on flat roofs and because they differ widely in character. Moisture would be expected to move most readily in the glass fiber, but only at a slow rate in the closed-cell insulation. This behavior should be reflected in the heat transfer rates.

2. Test periods for wet specimens ranged from about 7½ to 18 months. During this interval some changes of moisture content occurred. Typically these ranged from 0.3 to 1 percent by volume. Also, there was probably some variation in moisture content within the test specimens.

3. Daily arithmetic average heat flow rates (Q) were plotted against daily average temperature differences ($\Delta\theta$). There was very little scatter of the points for dry materials. For moist materials the scatter varied with insulation type, moisture content, and temperature difference. Generally the scat-

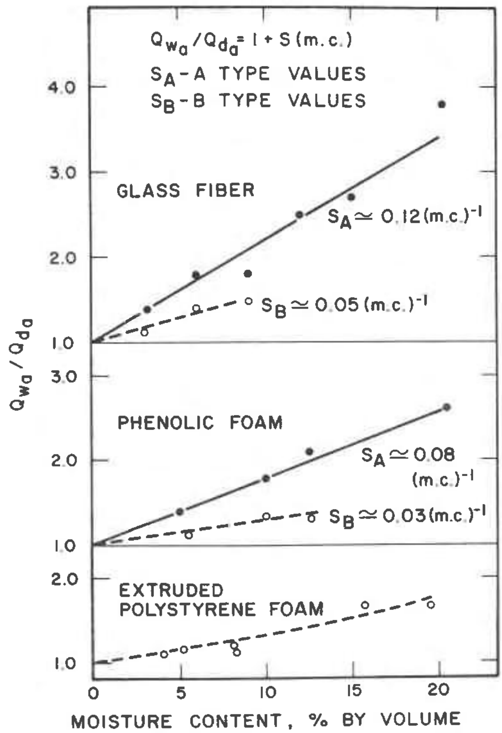

FIG. 12—*Values of* Q_{w_a}/Q_{d_a} *plotted against moisture content for glass fiber, phenolic foam, and extruded polystyrene foam (present investigation).*

ter was not strictly random in nature, but was partly owing to moisture distribution and its movement, which varied with the time of year. The Q versus $\Delta\theta$ plots for closed-cell insulation were continuous and nearly linear and intersected the ordinate near the origin. For the open-cell and fibrous insulations, abscissa intercepts occurred at up to $+2°C$ and ordinate intercepts were as low as -4 W/m^2. Thus over a narrow range of $\Delta\theta$ near the origin there may be a net average daily heat flow counter to the average daily temperature difference. This may be explained by nonisotropic heat flow. The effect is evident in hourly plots of Q versus $\Delta\theta$; the inward (downward) rate of heat flow exceeds the outward (upward) heat flow for the same temperature difference.

4. For the open-cell and fibrous insulations, the character of the heat flow appeared to change significantly at temperature differences of about 8 to 10°C (top surface temperatures of roughly 0°C). Observations above and below this transition were treated separately. The *A*-section (smaller $\Delta\theta$) had a larger slope than the *B*-section (larger $\Delta\theta$) and usually had a negative ordinate intercept. For the 3 and 6 percent glass fiber, transition from the *A* to

the *B* mode sometimes occurred over a period of three to four days and was evidenced by a marked reduction in heat flow. For the 12 percent glass fiber the transition in both directions between the *A* and *B* modes occurred in about one day and was accompanied by a twofold change in heat flow rate. The rapidity of these changes suggests that a sudden change in the manner of heat transmission occurred. The lower moisture content insulations remained in the *B*-mode for three or four months in the winter. For the 20 percent glass fiber specimen, operation in the *B*-mode was transitory. In warmer climates the fraction of time in the *B*-mode would be reduced or might not occur at all, depending on the insulation moisture content.

5. Thermocouples placed at the quarter points of the insulation along the path of heat flow provided information about relative temperature drops at different levels in the insulation and about the location of moisture and its movement. The temperature profiles were almost fixed for the extruded polystyrene foam for periods of up to one year, which suggests that very little transfer of moisture occurred. In most of the open-cell and fibrous specimens the temperature profiles underwent seasonal changes, indicating deposition of moisture in the top layers of insulation in the winter. Estimates of thermal resistance based on heat flow rates and measured temperature differences showed regular patterns of change in the thermal resistance of the specimens. These plots suggested that the lower parts of some of the open-cell and fibrous insulations reached near-dryness in the winter season.

6. Results of these tests were compared with those of other investigators. The present data for glass fiber were somewhat higher, particularly in the high moisture ranges. Those for extruded polystyrene foam and phenolic foam were in closer agreement.

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