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RÉSUMÉ

Des échantillons d'isolant en fibre de verre de 60 mm d'épaisseur dont la teneur en eau atteignait dans certains cas 15 % par volume ont été placés sur le toit du bâtiment pour essais à l'extérieur de l'Institut de recherche en construction (Conseil national de recherches du Canada), à Saskatoon, en Saskatchewan. On a enfermé les échantillons dans du polyéthylène pour empêcher l'eau de s'échapper.

Les températures ont été mesurées sur les faces supérieure et inférieure de chaque échantillon et aux points de quart à l'intérieur de certains d'eux. Les densités de flux de chaleur ont été mesurées à l'aide de thermofluxmètres étalonnés. Les mesures ont été enregistrées toutes les 20 minutes, toutes les saisons de l'année.

Les conductances thermiques ont été calculées à l'aide de fonctions de transfert. Les résultats ont montré un accroissement de la conductance thermique lorsque le temps était assez chaud pour produire des inversions quotidiennes du gradient de température de part et d'autre des éch[illegible]leur latente produit par l'évapora[illegible]té froid.

En hiver, l'[illegible]lant. À ce qu'il semble, elle [illegible] de se déposer en couche soli[illegible]ance thermique, indiquée pa[illegible]fondément dans l'isolant.

Seasonal Variations in the Modes of Heat Transfer in a Moist Porous Thermal Insulation in a Flat Roof

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ABSTRACT

Glass fiber insulation specimens 60 mm thick, with moisture contents ranging up to 15% by volume, were placed on the roof of the Outdoor Test Building of the Institute for Research in Construction, National Research Council of Canada in Saskatoon, Saskatchewan. The specimens were sealed in polyethylene to prevent the loss of moisture.

Temperatures were measured at the top and bottom surfaces of each specimen and at the quarter points inside some of them. Heat fluxes were measured with calibrated heat flux transducers. Measurements were recorded every 20 minutes at all seasons of the year.

Thermal conductances were calculated using transfer functions. The results showed an increase in thermal conductance when the weather was warm enough to produce daily reversals in temperature gradient across the wet specimens. This was attributed to latent heat transfer produced by evaporation of water at the warmer side of the insulation and its condensation at the cooler side.

In winter, the moisture was deposited in the upper, colder part of the insulation. It was apparently distributed through the upper part of the insulation and not deposited as a solid layer at the top surface, since its effect on thermal conductance, indicated by the interior temperature gradient, extended well down in the insulation.

KEY WORDS

Heat transfer, moist porous insulation, flat roof, heat flux transducers.

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THE THERMAL CONDUCTANCES of porous materials normally increase if they contain moisture. Calculations of heat transfer for design purposes assume that the thermal resistance obtained in practice is equal to that of dry material tested in the laboratory. This is of particular importance in thermal insulation. In order to achieve this, moisture must be prevented from entering the insulation. In practice, this is not always achieved. Moisture may enter as vapor and then condense, it may leak in or it may be built into the system if moist insulation is used. The matter is of appreciable importance for flat roof systems.

Diurnal and seasonal changes cause wide variations in the temperatures in flat roofs, producing freezing conditions in winter and high temperatures in summer. Observation of heat fluxes and temperatures throughout the seasons can provide information about the changes in moisture location, the form in which water is present and its influence on heat transfer. The behaviour of moisture in thermal insulation has been of interest to many investigators. Most have carried out their work in the laboratory or by theoretical analysis. These include studies in the migration of moisture under a thermal gradient [1], the importance of the vapor in the heat transfer process [2] and the overall effect of moisture on thermal resistance [3,4,5].

The purpose of this report is to present measurement information on aspects of heat flow in wet insulations under field-type conditions. Results are for all seasons of the year. These results demonstrate the variation in the effect of moisture with outdoor temperature conditions. They also demonstrate that in summer time the effect is significant even for low moisture contents. Further, it provides information about the distribution of moisture in the winter season when prevailing outdoor temperatures produce migration of moisture toward the cold upper surface of the insulation. The report does not analyse the heat transfer process in detail.

The studies were carried out at the Outdoor Test Facility of the Prairie Regional Station, Institute for Research in Construction, National Research Council at Saskatoon. The continental climate produces outdoor air temperature extremes ranging from about +30°C to −40°C. Roof surface temperatures vary over a larger range; solar heating raised temperatures to 50°C on occasion. These conditions produce a wide range of moisture distribution and movement conditions.

A rigid mineral fiber insulation was used. Tests were made on specimens of these with moisture contents (mc) of about 0, 1, 3, 6, 9 and 15% by volume. There were two specimens with 9% and two with 15% and one specimen at each of the other moisture contents. The indoor temperature of the building was maintained at about 20°C but the upper surface of the roof was subject to the prevailing weather conditions. The experimental arrange-

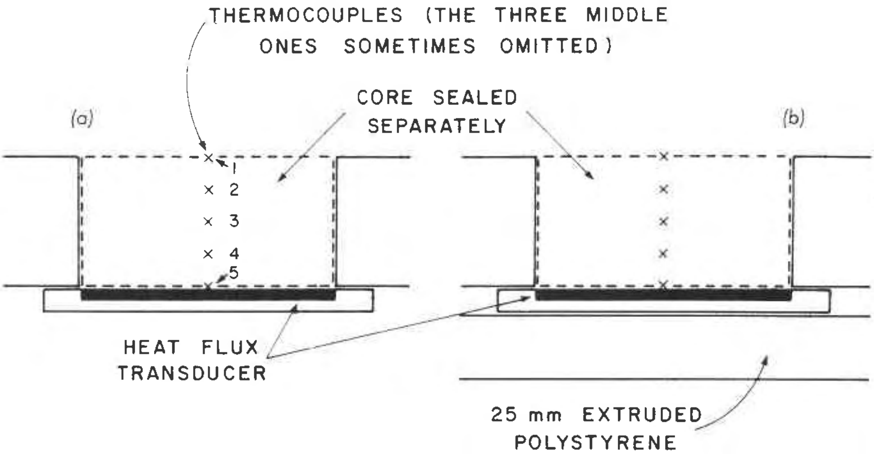

FIGURE 1. (a) Shows mounting of heat flux transducer, thermocouple locations and the core of the specimen. (b) Identical except for extruded polystyrene beneath the HFT.

ment is shown in Figure 1. Specimens, each 400 mm square, were sealed in polyethylene. The mineral fiber was 60 mm thick.

A core, 100 or 150 mm in diameter, was taken from the center of each specimen. The core was independently sealed in 0.15 mm thick polyethylene and replaced. The entire specimen was then sealed in polyethylene. Before sealing, thermocouples were placed at the top and bottom surface of the core and, in some cases, also at the quarter points.

Heat flux transducers (HFTs) of 50 and 105 mm diameter were used to measure the heat flow.* They were placed below the core specimens and secured to the deck by bakelite holders. For one of the two 9% specimens and one of the two 15% specimens, a piece of 25 mm thick extruded polystyrene was placed below the HFT. This was done to change the environment to which the insulation was subjected, in order to see if the different temperature conditions affected the heat flux results.

Heat flow and temperature data were recorded on magnetic tape at 20 minute intervals and processed by computer.

Most of the thermal conductance calculations were made using transfer functions. In this case the rate of heat flow (Q_0) can be expressed:

$$K_0Q_0 = I_0TT_0 + I_1TT_1 + \dots I_nTT_n + J_0TB_0 + J_1TB_1 + \dots + J_nTB_n + K_1Q_1 + \dots K_nQ_n \quad (1)$$

*The HFTs were calibrated in the facilities of the Institute for Research in Construction, Ottawa, Canada.

The subscripts 0, 1,---n, refer to values at the time 0 and values 1, 2,---n time steps earlier, e.g., 1 and 2 hours earlier [6,7,8].

Q, TT and TB represent heat flow rate (W/m^2) and top and bottom surface temperatures (°C) respectively.

The subscripted values of I, J and K are the transfer coefficients. K_0 is taken to be 1.

Transfer coefficients were used to estimate the thermal conductances [8].

$$C_{TF} = \frac{\sum_{i=0}^{n} I + \sum_{i=0}^{n} J}{2\left(1 - \sum_{i=1}^{n} K_i\right)} \tag{2}$$

RESULTS

Data for 100 days or more of observation, including all seasons of the year were used in the following analysis. Figures 2a, b, c and d show plots of daily average heat flux Q vs. the corresponding temperature difference (ΔT) for glass fiber containing 1, 6, 9 and 15% moisture by volume. The mean temperature is also given, the scale being based on the approximate relationship that it bears to ΔT.

Data were also available for dry specimens [8]. The relationship between heat flux, ΔT and T_m was found by a least squares analysis. There, the heat flux through a dry specimen of this insulation was represented as:

$$Q = 0.551\Delta T + .00175\ T_m \Delta T \qquad \text{W/m}^2{**} \tag{3}$$

or in terms of thermal conductance as:

$$C = 0.551 + .00175\ T_m \qquad \text{W/m}^2\text{K} \tag{4}$$

The data in Figure 2a to 2d demonstrate the Q-ΔT relationship. The dotted lines show the relationship for a dry specimen. The data are scattered and somewhat discontinuous. Part of this variation can be explained by seasonal differences in the heat transfer process. The results were divided in the following way to reflect this seasonal effect.

**The coefficient .00175 is not precise. It may vary by 30% or more for different sets of data.

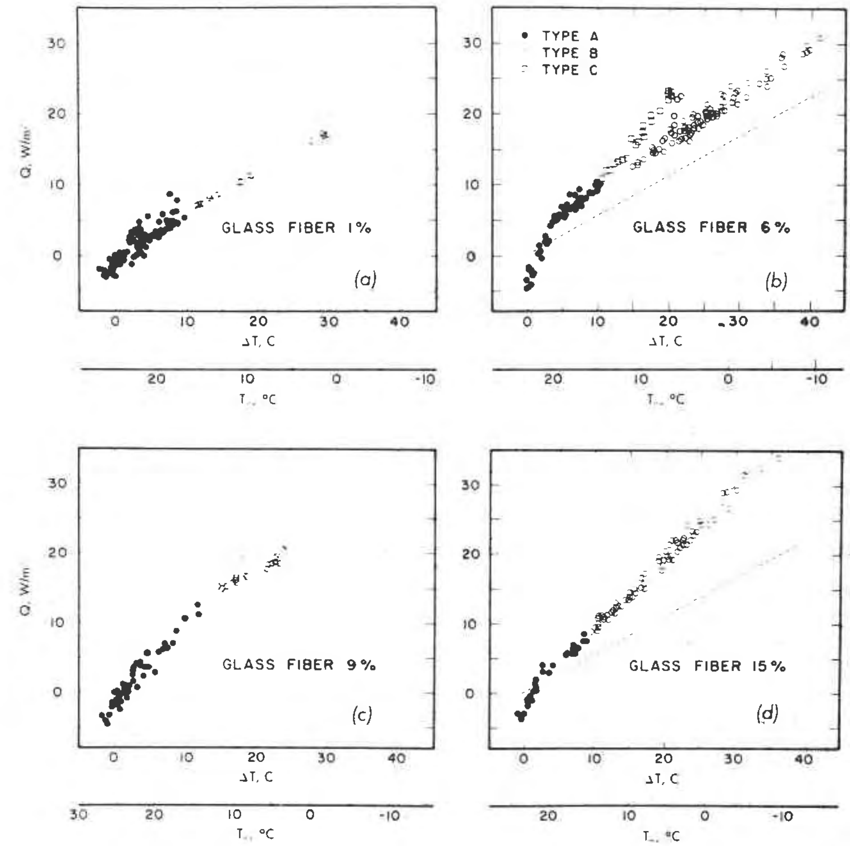

FIGURE 2. Heat flux versus temperature difference and mean insulation temperature for glass fiber with 1, 6, 9 and 15% mc (volume)—a, b, c, d, respectively. The same legend applies to all of the plots in Figure 2. The dotted lines show the Q vs. ΔT relationship for a dry insulation specimen.

- Type A heat flow occurs when $T_m > 15°C$.
- Type B includes the data for $T_m < 15°C$ on the lower limb (Figure 2b).
- Type C includes data for $T_m < 15°C$ on the upper limb (Figure 2b).

The difference between Types B and C is most clearly illustrated in Figure 2b. It should be emphasized that these divisions are based on interpretations of the heat flux-temperature data. No visual observations were available to confirm the deductions about moisture movement.

The reason for the division between Type A and the other types is illustrated in Figure 3. Thermal conductance C_{TF} was estimated using transfer functions and plotted against mean insulation temperature for the 6% mc

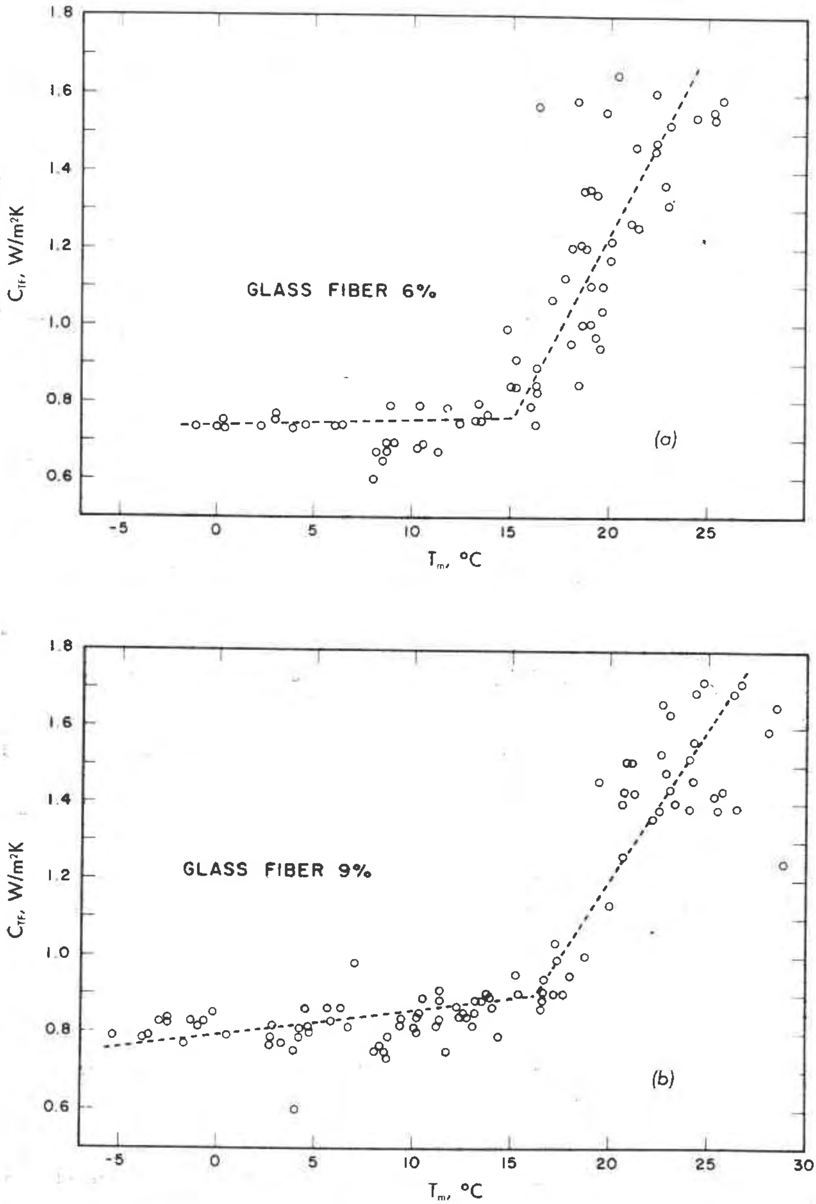

FIGURE 3. Thermal conductance versus mean insulation temperature: (a) glass fiber with 6% mc for a January to June period; (b) glass fiber with 9% moisture content. Roughly speaking, Type B heat flux occurs for T_m less than 15°C and Type A for T_m greater than 15°C.

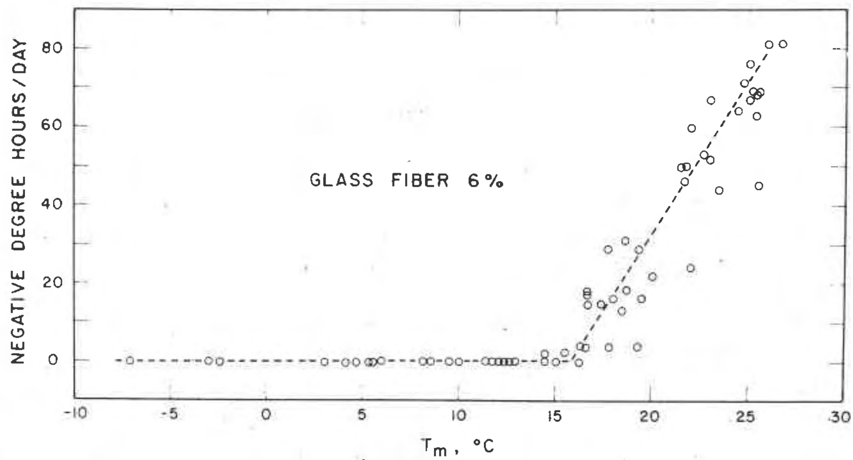

FIGURE 4. Negative degree hours/day versus mean insulation temperatures for glass fiber with 6% moisture content.

glass fiber, and 9% mc glass fiber, for a period running from January to the end of June. The conductances calculated in this way should not be regarded as rigorously accurate because of the complex nature of the heat transfer process when moisture is present. The method is used here as a device for detecting the transition from one heat transfer mode to another. In Figure 3a and b, C_{TF} rises slowly as the mean temperature increases from 0 to 15°C. Above 15°C it rises sharply from just under 0.8 W/m²K to over 1.5 W/m²K. Data at 1, 3 and 15% mc behaved similarly.

The discontinuity occurs at a mean temperature of about 15°C. It seems unlikely that T_m itself accounts for the change. A more likely cause is the onset of temperature gradient reversals (when *TT* exceeds *TB* for part of the day) and the consequent diurnal oscillations in moisture movement due to evaporation and condensation. Further evidence for this is given in Figure 4. Positive and negative temperature differences were summed separately to obtain positive and negative degree hours/day. During much of the year, there were no reversals of temperature gradient, i.e., *TT* never exceeded *TB*. However, in warm weather *TT* exceeded *TB* for a part of each day (though never for the entire 24 hour period) producing negative degree hours. Daily average negative degree hours are plotted against mean insulation temperature T_m for glass fiber having 6% mc. Up to about T_m = 15°C no negative degree hours occurred as illustrated in Figure 4. However, above that mean temperature negative degree hours with the attendant temperature gradient reversals occurred regularly. This correlation between increased thermal conductance and the onset of temperature reversals suggests that the two are related, as proposed above.

TYPE C HEAT FLOW

In Figure 5, C_{TF} is plotted against T_m from the beginning of September to the end of the year. This covers a period in which the outdoor conditions change from summer to winter. It shows a reduction in C_{TF} with reducing T_m, however, unlike the January-June period, a few high values of C_{TF} occur when T_m is well below 15°C.

Type A heat flow continues through warm weather, but, as the weather becomes cooler temperature reversals cease, i.e., the maximum temperature at the upper surface of the insulation never exceeds that at the lower surface. Under these conditions the thermal effect can only drive moisture upward toward the cold upper surface of the insulation. In Figure 2b, Type C data

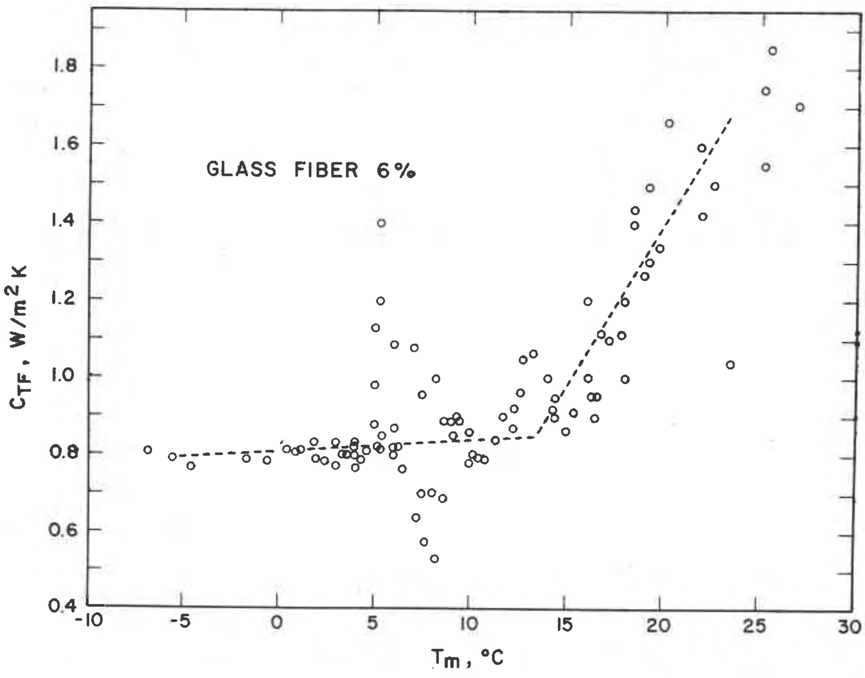

FIGURE 5. Thermal conductance versus mean insulation temperature for glass fiber with 6% moisture content for the period from September to the end of December. Approximately Type A heat flux occurs for T_m greater than 15°C. Type B and Type C (shown by high values of C_{TF}) occur when T_m is less than 15°C.

represent the time interval from about October 1 to November 5. During this five week period, as the winter became gradually colder, a large outward flow of heat continued to occur. If the movement of moisture occurred only in one direction the supply should have been exhausted early in the period. It would appear either that there is a special moisture distribution producing large heat fluxes or that moisture was continuously returned, perhaps by liquid flow under the force of gravity, to be re-evaporated. The same pattern exists for 3% (not shown) and it is barely evident for the 9% mc insulation but not evident for the 1 and 15% mc specimens. The reason for its absence in the 1% mc specimens is not clear. Perhaps the reservoir of moisture is too small to sustain Type C heat flow at the lower temperatures.

The conductance of the specimens, under Type B conditions, increased with moisture content. If Type C conductance does not increase in a similar manner, the two sets (Types B and C) would tend to merge and be indistinguishable from one another at the higher moisture contents.

TYPE B HEAT FLOW

As weather conditions became cooler, the heat flux changed from Type C to Type B (at about day 315). This is shown in Figure 2b. The latter values decreased with time, corresponding to a reduced heat flux. Inspection of data shows that the onset of Type B heat flow coincides approximately with continuous sub-freezing temperatures at the upper surface of the insulation. It appears that the moisture then accumulates in a frozen form. As the source of moisture in the warm region dried up, heat flow would decrease [3].

During subsequent warm periods, the top maximum surface temperatures briefly reached roughly 10°C but this excursion to higher temperatures did not, apparently, trigger a return to Type C conditions.

The bulk of the Type B heat flow data is represented by the line of points below Type C points in Figure 2b. The thermal conductance C is

$$C = Q/\Delta T \tag{5}$$

Similarly, the thermal resistance R is

$$R = \Delta T/Q \tag{6}$$

Inspection of Figure 2b shows that the thermal resistance for Type C heat flux is less than it is for Type B flux at the same ΔT, i.e., that the thermal resistance increased as it changed from Type C to Type B heat flux.

Two things occurred in the change from Type C to Type B heat flux. First, as mentioned above, the evaporation-condensation process ceases. Second, the moisture accumulates in the upper regions of the insulation. Presumably it could be deposited there in a diffuse manner, as frost (or, perhaps, dendritic ice), distributed throughout a portion of the insulation or as a solid layer of ice. The evidence suggests that diffuse deposition (shown qualitatively in Figure 6) occurs.

If it was a layer of ice, the thermal resistance would be reduced approximately by the volume which the ice would occupy, i.e., the thermal conductivity of the ice is so much greater than that of dry insulation that its presence would practically nullify the effect of the insulation where it was present. The reduction in thermal resistance would be about 1.1% for 1% mc specimen, 6.6% for the 6% moisture content specimens, etc.

In fact, if one calculates the thermal resistances using Equation (6) along with data for the dashed line and compares it to resistance at the same ΔT for the plotted data, it is apparent that the loss in resistance is considerably greater than that, e.g., about 25% for the 6% specimen (Figure 2b). This can be explained if one assumes that frost or ice crystals are dispersed through the upper potion of the insulation in such a way as to act as conductive fins which impair the effectiveness of perhaps the upper ¼ or ½ of the insulation.

The changes in thermal resistances that accompany the relocation of moisture are shown in Figure 7. Results for four specimens of insulation are given. Two of the specimens contained 9% moisture by volume and two contained 15% by volume. For one of the 9% and one of the 15% specimens

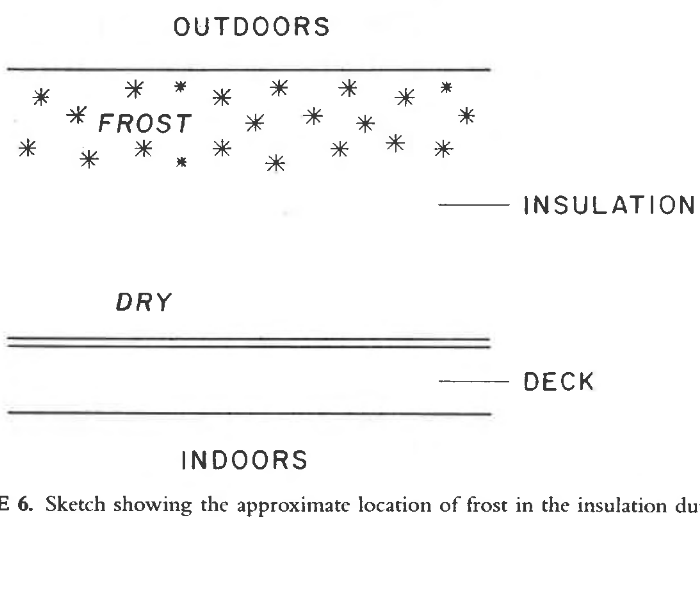

FIGURE 6. Sketch showing the approximate location of frost in the insulation during cold weather.

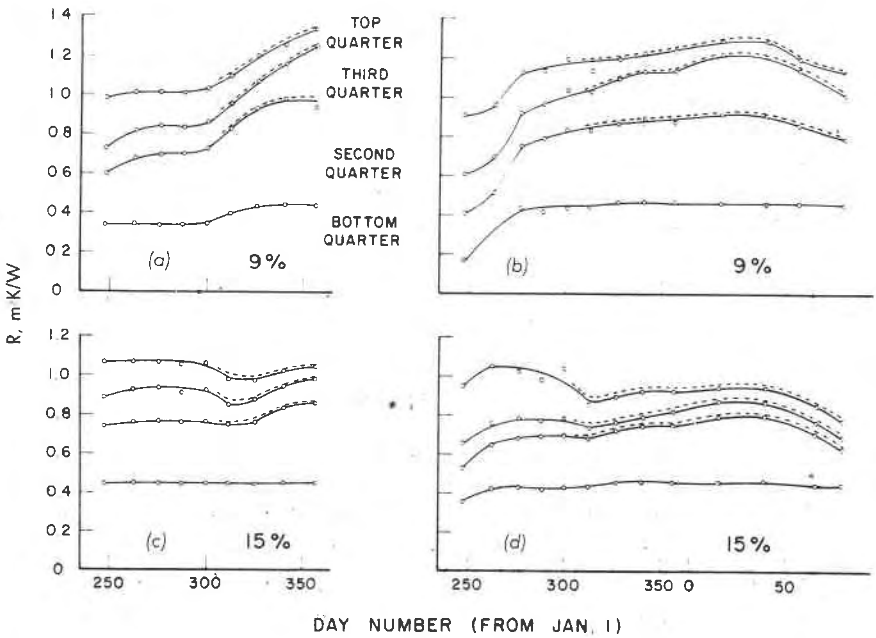

FIGURE 7. Thermal resistances for each quarter of four glass fiber insulation specimens. For the 9 and 15% moisture content specimens on the right of the Figure (b,d) 25 mm of extruded polystyrene was placed beneath the heat flux transducer. The results in (a) and (c) run from September to December, those on the right from September to late March. The dashed lines indicate sub-freezing temperatures.

25 mm thick extruded polystyrene was placed beneath the HFT (Figure 1b), thus increasing the isolation of the specimens from the moderating influence of the indoor temperature.

Thermocouples were placed at the top and bottom surfaces of each specimen and also at the quarter points. From these temperatures information can be deduced about the thermal resistances of slices of the insulation demarcated by these three interior thermocouples. During the winter season some of the temperatures were continuously below freezing (Figure 7).

The thermal resistances were calculated using Equation (3) for each quarter of the specimen for the period day 250 to 365 and are plotted additively, one on top of the other. As moisture accumulated in the upper part of the insulation, with the onset of cold weather, the lower part of the insulation specimens became dry as evidenced by their thermal resistances. From Equation (7) the thermal resistance of the dry specimen is approximately $1/0.551 = 1.81$ m^2K/W. The resistance for ¼ of it should therefore be about 0.45 m^2K/W.

The changes in thermal resistance are gradual. In the test period, thermal resistances for the 9% specimens rose from about 1.0 to 1.3 m^2K/W (day 315 to 350, Figure 7a) corresponding to the transition from Type C to Type B conditions. They remained at the higher level until the next spring when they gradually fell to about 0.9 m^2K/W.

The overall thermal resistances of the 15% specimens did not rise, in fact, the one over extruded polystyrene fell slightly. In the latter case, the mean temperature of about ¾ of the insulation was below freezing, toward the end of the test period. Hence, the decrease in thermal resistance would appear to be due to the fact that ice (frost) has a thermal conductivity approximately three times as great as that of water.

SUMMARY

1. The presence of moisture affects the transfer of heat in porous insulations. Its effect is two-fold. It increases sensible heat transfer by thermal conductance and produces latent heat flow when moisture is evaporated at the warm surface and condensed in a cooler region.
2. In cold weather the moisture was deposited as frost but not as a layer of ice. The transfer of heat with frost present was substantially greater than it would have been if an ice layer had formed.
3. The heat transfer mechanism is different in warm weather from what it is in cold seasons. Under test conditions with these temperature extremes varying from about +35 to −40°C, three heat transfer modes appeared to occur. One type prevailed in warm weather when reversals of temperature gradient occurred regularly—usually daily (Type A). A second type occurred in cold weather when moisture was deposited as frost in the colder part of the insulation (Type B). A third type occurred during the transition from the first to the second type of heat flow (Type C).
4. The work was done in a flat roof so that heat and moisture transfer takes place in a vertical direction. The mechanism may be relevant to heat-moisture movement in a wall, but it is important to recognize that the gravity effect would then be normal to the main flow of heat and moisture, causing moisture to flow to the bottom of the insulation. This would strongly affect location of moisture accumulation, e.g., as frost in winter.

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BIOGRAPHY

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He has carried out a variety of types of research related to humidity and moisture in materials. In recent years much of the latter activity has been related to field-type measurements at the Outdoor Test Facility in Saskatoon.

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