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Hedlin, C. P.

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MOISTURE GAINS BY FOAM PLASTIC ROOF INSULATIONS UNDER CONTROLLED TEMPERATURE GRADIENTS

By C.P. Hedlin

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Moisture gains of three closed cell and one open cell foam plastic insulation were studied in the laboratory. The purpose of the study was to investigate the relationship between rates of moisture gain and temperature-moisture environment under laboratory conditions

L'augmentation de la teneur en humidite a l'interieur d'isolantes en mousse plastique dont trois a cellules fermees et un a cellules ouvertes a ete etudiee en laboratoire. L'etude avait pour objet la relation entre les taux d'augmentation d'humidite du materiau et les conditions de temperature-humidite du milieu, dans des conditions de laboratoire simulant celles existant sur une toiture a membrane d'etancheite protegee.

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ADDENDUM

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by C. P. Hedlin

The following information was omitted from the reprints of this paper issued by DBR as NRCC 16317

Hedlin – continued from p. 319

Report No. 202, Goteborg, August 1973.

7. J. Achtziger, "Measurement of the Thermal Conductivity of Plastic Foams with any Desired Moisture Content," *Kunststoffe im Bau*, Vol. 23, (1971). p. 3.
8. Ivar Paljak, "Condensation in Slabs of Cellular Plastics," *Materiaux et Constructions*, Vol. 6, No. 31, (1973), p. 53.

C. Hedlin

A native of Saskatchewan, Charles Hedlin obtained a B.Sc. degree from the University of Saskatchewan in 1950, an M.Sc. degree from the University of Minnesota in 1952 (both in Agricultural Engineering), and a Ph.D. degree from the University of Toronto in Mechanical Engineering in 1957. From 1952 to 1960, he taught engineering subjects and carried out research on the drying of agricultural products at the Ontario Agricultural College. In 1960 Dr. Hedlin joined the staff of the Division of Building Research, National Research Council of Canada at the Prairie Regional Station in Saskatoon, Saskatchewan, and has carried out research on humidity measurement, moisture absorption characteristics of some building materials, and on flat roofing. At present he is Officer-in-Charge of the Division's Prairie Regional Station.

Moisture Gains by Foam Plastic Roof Insulations Under Controlled Temperature Gradients

C. P. Hedlin

Prairie Regional Station
Division of Building Research
National Research Council of Canada
Saskatoon, Canada

Introduction

In protected membrane roofs thermal insulation is placed above the waterproof membrane. Thus it is exposed to moisture and the possibility that it may become wet must be considered. This is a relatively new building concept in which the effects of moisture on insulation have not been fully explored.

In protected membrane roofing, rainwater may flow between the roof insulation and the membrane if they are not bonded together. During much of the year, the temperature at this interface, θ_w, is higher than the temperature at the exterior surface of the insulation, θ_c. If moisture is present at the warm surface, the vapour gradient drives it into the insulation along the path of decreasing temperature. Some of the moisture entering the insulation (W_w) may pass through it (W_c) unless the upper surface is sealed (Figures 1a, b); some may condense in it (W_a). A similar situation may also occur at the top surface. If moisture is trapped between the insulation and a covering layer, such as a paving stone, solar heating will periodically raise the water vapor pressure and promote moisture entry into the insulation (Figure 1c).

Moisture reduces the thermal resistance of insulation and may contribute to its physical breakdown. The amount of moisture gained in service and the consequences vary with the nature of the insulation, the design of the system and the environmental conditions. The effects of moisture on thermal resistance and physical breakdown are important parts of the over-all insulation-moisture problem but are outside the scope of this study. It is part of an investigation of how to control moisture gain by insulation in protected membrane roofs which, in turn, will help to minimize its effects (1, 2).

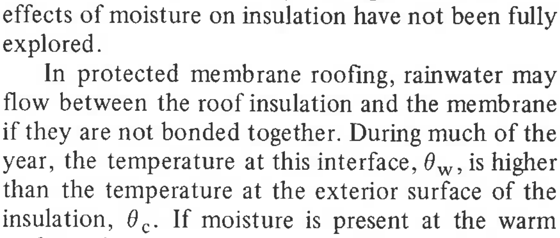

Figure 1. Moisture movement in insulations subjected to a combined temperature - moisture gradient on a protected membrane roof.

The study was designed to gain information about the relationship between rates of moisture gain and temperature-moisture environment under laboratory conditions that simulated those on a protected membrane roof. The main emphasis was given to closed cell insulations, though one open cell material was included in some of the tests. Important differences existed between the field conditions and the laboratory model. In the laboratory, entry through only one side was considered, and that under steady state conditions. Freeze-thaw action which might damage cell walls and markedly modify the moisture uptake of some closed cell insulations was not included. Lastly, this study did not include the concept of moisture balance; in the field environment, the moisture that enters the insulation under moist conditions leaves when conditions favor drying.

The literature on moisture movement in materials is extensive but the major emphasis has been on capillary materials, with relatively little on closed cell materials. Studies involving moisture gain in closed cell materials under temperature gradients include studies of moisture gains by thermal insulations in protected membrane roofs (1, 2), an analysis of moisture movement in structural systems (3), the effect of freeze-thaw action (4), and studies by Levy (5), Thorsen (6), Achtizer (7) and Paljak (8) on the effect of moisture on heat transfer.

Moisture movement in materials may be ascribed generally to three agents: vapor pressure

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gradients, gravity forces and capillary forces. The first can be regarded as producing vapor flow and the other two liquid flow. Owing to the complex nature of the sorption process in hygroscopic materials and effect of water soluble components, the distinction between vapor and liquid movement may not always be clear. However, for the purpose of this study, this simple division is probably adequate.

The relative importance of each mode depends on the nature of the material; for example, in materials with large pores, percolation under gravity may be the principle mode of transfer; in some fibrous materials, capillary movement is the important factor. Neither of these forces is likely to be important in truly closed cell plastic materials, however, where vapor flow will probably dominate.

If it is assumed that moisture movement is due to a thermally induced vapor pressure gradient and that the material is wet on both surfaces, one can express the amount of moisture absorbed (W_a) as the difference between that entering at the warm surface (W_w) and that exiting at the cold surface (W_c):

$$W_a = W_w - W_c \qquad (1)$$

where

$$W_w = \mu_w A \left(\frac{dp}{d\theta}\frac{d\theta}{d\chi}\right)_w \tau \qquad (2)$$

$$W_c = \mu_c A \left(\frac{dp}{d\theta}\frac{d\theta}{d\chi}\right)_c \tau \qquad (3)$$

These units are defined as follows. SI units are given first, followed by English units in brackets:

μ_w, μ_c permeability of the materials at the warm and cold surfaces, respectively, kg/TPa·m·s* (perm-in.);

A surface area m^2 (ft^2);

$dp/d\theta$ slope of the water vapor saturation pressure curve Pa/K (in. Hg/°F);

$d\theta/d\chi$ temperature gradient K/m (°F/in.);

τ time elapsed, seconds s.

*kg/TPa·m·s simplifies to ps (T=tera=10^{12}, p=pico=10^{-12}); kg - kilogram; Pa - pascal; m - metre; K - degrees kelvin.

These equations represent boundary conditions only (warm and cold surfaces), and do not purport to represent the moisture movement within the insulation.

Experimental

Two apparatus were used to produce a temperature gradient across the specimens. One apparatus consisted of an aluminum plate, 6 mm thick, placed over the opening of a household freezer to provide the cold surface. The warm surface was controlled by a thermostatted, electrically heated plate (Figure 2a).

In the second apparatus, the temperatures of two plates were controlled by liquid pumped from thermostatted baths (Figure 2b). Temperatures were regulated by proportional controllers with sensors in the liquid supply lines. The lower plate was surrounded by a lip, 25 mm high secured and sealed to form a shallow water bath. Open cell urethane was placed in it and a water supply was arranged to maintain a level even with the top of the urethane. The insulation specimens rested on this surface.

Extruded polystyrene, bead polystyrene and urethane (all closed cell) and phenolic foam (open cell) were used. The specimens were cut from board stock and, except for a few tests, any skin or protective covering was removed to expose the foamed material. Three specimens of each insulation were used together for each measurement and the results were averaged.

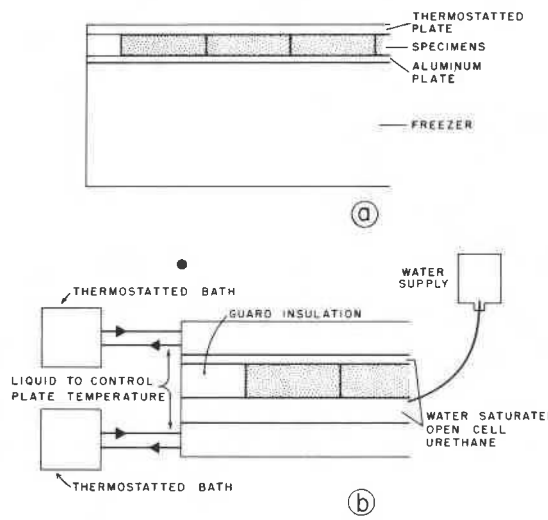

Figure 2. Two types of apparatus for maintaining temperature and moisture gradients across the insulation specimens.

Results and Discussion

I (a). In the first set of experiments, extruded polystyrene with a density of 32 kg/m^3, a bead polystyrene (16 kg/m^3) and phenolic foam (52 kg/m^3) were cut into pieces 100 mm square and 25.5 mm thick. (Specimen thicknesses varied by about ±0.5 mm). Specimens of a urethane (29 kg/m^3), 95 mm in diameter and 25.5 mm thick, were fitted into acrylic plastic collars to prevent them from deforming when they gained moisture. The edges and one surface of all specimens were wax sealed. Trios of specimens of each insulation were prepared.

Specimens were placed open-face down on a wet surface. The waxed surface was kept at the same temperature as the unwaxed one[1] or was cooled to approximately 2.8, 11 or 22°C below that of the open surface by using the apparatus shown in Figure 2b. These differentials deviated somewhat and calculations are based on temperatures measured with a thermocouple in the middle of each main surface. The warm surface was kept at 27±1°C except for some measurements at the largest temperature differential when, toward the end of tests, the high moisture content caused it to fall as low as 24.5°C for the closed cell plastics, and to 21°C for the open cell plastic.

Each test lasted from 4 to 9 weeks. At intervals ranging from 3 days to a week, the specimens were taken out of the test apparatus, surface dried with tissue paper, weighed and immediately returned to the apparatus. At the end of a test, they were dried at room conditions and reused.

Moisture contents are given in terms of the gross volume of dry material.[2] This provides a basis for comparing total amounts of moisture in different materials which is independent of their densities. To a first approximation, some effects, such as loss of thermal resistance, are likely to vary in proportion to the total moisture content of the insulation. Changes in volume due to moisture absorption introduce a corresponding error, however.

The results are plotted in three different ways:

1. moisture content vs time in Figures 3 (closed cell) and 4 (open cell insulation);
2. average rate of gain, $W/A\tau$ vs $dp/d\theta\ \Delta\theta/\Delta\chi$ in

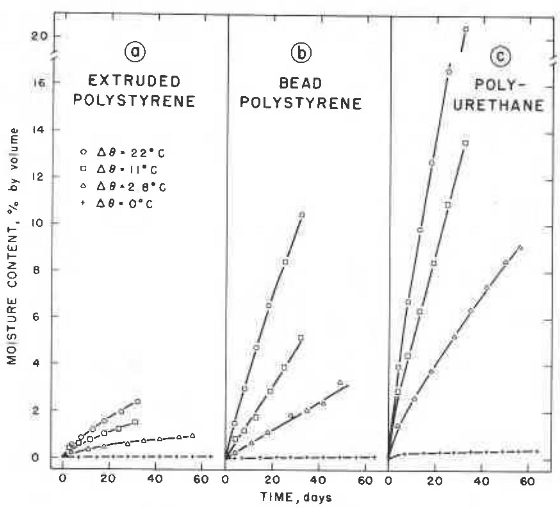

Figure 3. Moisture gain in three foam plastic insulations, % of gross volume vs time elapsed in days, for 0, 2.8, 11, and 22°C temperature differentials. Specimen thickness 25.5± 0.5 mm thick. Cold surfaces wax sealed.

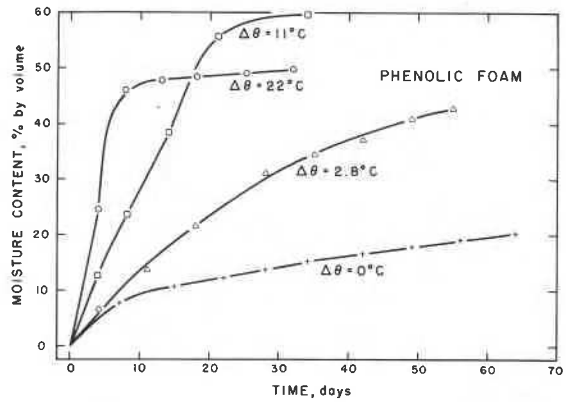

Figure 4. Moisture gain in phenolic foam, % of gross volume vs time elapsed in days, for 0, 2.8, 11, and 22° C temperature differentials. Specimen thickness 25.5 ± 0.5 mm thick. Cold surfaces wax sealed.

Figure 5 (closed cell insulation); and

3. accumulated gain, W/A, or moisture content vs $dp/d\theta\ \Delta\theta/\Delta\chi\ \tau$ in Figure 6.

In the isothermal tests, the polystyrenes gained about 0.1% by volume, the urethane 0.4%, and the phenolic foam over 20% in the 64-day period. The rates of gain were highest at the outset and declined with time. In the non-isothermal measurements the initial gains were usually relatively high and were followed by a nearly constant gain rate or one that continued to decline (Figures 3 and 4).

In order to include the vapor pressure in the calculations, rates of gain ($W/\tau A$) and vapor pressure gradient ($dp/d\theta\ \Delta\theta/\Delta\chi$) were computed, the latter using measured surface temperatures. ($W/\tau A$ and $dp/d\theta$ have been defined; $\Delta\theta/\Delta\chi$ is the temperature difference across the specimen divided by its thickness). The first reading, taken 3 or 4 days after the beginning of the test, was arbitrarily neglected to avoid "starting" effects. The data following it, for which the moisture content-time plot was linear, or nearly so, were used to estimate the average values of the above parameters. These results are plotted in Figure 5, and first order equations were fitted to the data by least squares analysis.

As shown in Figures 3, 4 and 5, temperature induced vapor pressure gradients have a large effect on the rate of transmission of moisture into the insulations, e.g., average rates of gain with an 11°C differential ranged from 10 times the isothermal rates for the open cell plastic to over 100 times for the bead polystyrene.

The slopes of the plots in Figure 5 have the dimensions of permeability, μ. These μ values were 1.16 (0.80), 6.8 (4.7) and 11.6 (8.0) ps (perm.-in.) for the extruded polystyrene, bead polystyrene and urethane, respectively. For the phenolic foam the value was 118 (81.1) ps (perm-in.). These were apparent rather than real values (hence are designated μ_a) because the temperature gradient used to

[1] The measurements were made in a constant temperature air bath (±0.5°C). The specimens were surrounded by insulation to minimize the effect of temperature fluctuations.

[2] To convert moisture contents in % of gross volume to % weight, multiply by 997 ÷ insulation density kg/m³ or by 62.3 ÷ insulation density lb/ft³.

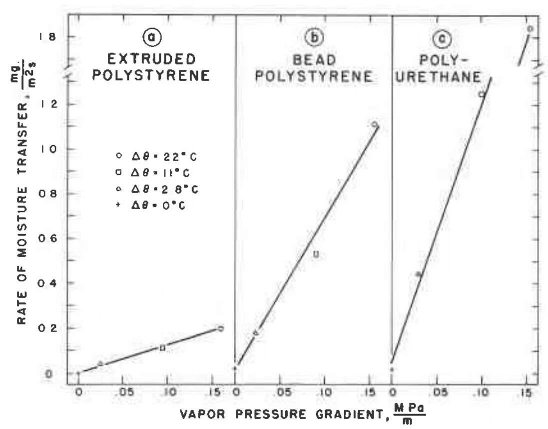

Figure 5. Rate of moisture gain by closed cell insulations vs vapor pressure gradient. Individual values are averages of the tests at 0, 2.8, 11, and 22°C differentials using the data shown in Figure 3.

calculate them was the average through the specimens. This assumed linearity of the temperature gradient. In fact, it may have been nearly linear at the outset, but would probably become non-linear because of non-uniform deposition of moisture in the insulation which affects the local thermal conductivity, hence the temperature gradient.

In Figure 6, W/A is plotted against $dp/d\theta\ \Delta\theta/\Delta\chi\,\tau$. The moisture content is given on the right hand side of the plots. The isothermal gain was ignored, thus introducing an error. The correct plot should be $W/A - W/A_{isoth}$ vs $dp/d\theta\ \Delta\theta/\Delta\chi\,\tau$. The error was calculated using the results in Figure

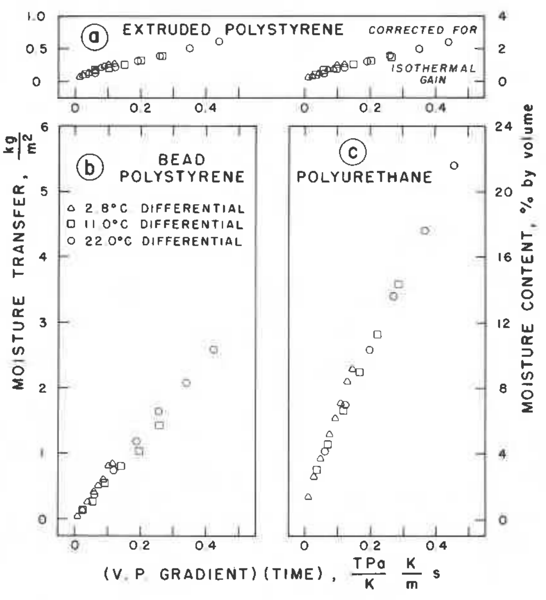

Figure 6. Moisture gain kg/m² and % of gross volume vs (vapor pressure gradient) (time elapsed) for the closed cell insulations. The results for extruded polystyrene are given without and with correction for isothermal gain.

4 and assuming that the factor producing a gain under isothermal conditions continued to contribute at the same rate under non-isothermal conditions (see Table 1). The error decreased as the temperature differential increased and was highest for the open cell phenolic foam, followed by extruded polystyrene, the urethane and the bead polystyrene.

Table 1. Calculated Percentage Errors in W/A Due to Isothermal Moisture Gain Based on Data in Figure 4.

	Temperature Differential—°C 2.8	11	22
Extruded Polystyrene	10.0	3.7	2.1
Bead Polystyrene	3.1	1.0	0.5
Urethane	4.1	1.6	1.1
Phenolic Foam	32.1	11.2	6.2

If the data were well correlated by this method of plotting, the curves for each material would be superimposed on one another. Failure to do so arises from three main causes: error in measurement, difference between groups of specimens and inadequacy of the method of plotting. The last includes the errors involved arising from neglect of the isothermal gain and the approximation inherent in the assumption of a linear temperature gradient.

The effectiveness of the method of correlating the data to accommodate the effects of temperature differential and isothermal gain can be estimated by statistical treatment. The data used were taken from the sections of the curves that overlapped. These sections were short and covered only the lower moisture content regions, e.g., to about 1% for extruded polystyrene and 4% for bead polystyrene. The first three points for each of the 22°C differentials were used (two for the phenolic foam) along with three points each for the 2.8 and 11°C differentials that fall within the same range of abscissa values. They were then grouped for each insulation, and a linear least squares fit was found. The coefficients of variation and correlation coefficients (in brackets) were 6.5 (.975), 7.5 (.973), 12.2 (.968) and 19.4% (.952) for extruded polystyrene, urethane, bead polystyrene and phenolic foam, respectively. When corrections for isothermal gains were applied to the extruded polystyrene and phenolic foam, using figures from Table 1, the coefficients of variation and correlation coefficients were 3.5 (.994) and 4.9% (.992), respectively.

The slopes of these curves also have the units of permeability. From the above analysis, they were 1.27 (0.89), 11.4 (7.8), 5.6 (3.9) and 107 (74) ps (perm-in.) for the extruded polystyrene, urethane, bead polystyrene and phenolic foam, respectively. When the corrections for isothermal gain were applied, the slope of the extruded polystyrene did not change but that of the phenolic foam increased to 109 (75) ps (perm-in.).

I (b). The extruded polystyrenes used in these experiments came with a thin skin on the surface, produced in the manufacturing process. Normally this would have been removed, but was left in place for a test with specimens 13.6, 25.2 and 48.7 mm thick. The other surfaces were wax sealed. The unsealed surfaces (with skin) were kept at about 28.5°C and the opposite ones at about 10°C. In each case, the measured average temperature was used in the calculations. The slopes were 0.50 (0.34), 0.60 (0.41) and 0.68 (0.47) ps (perm-in.) for 13.6, 25.2 and 48.7 mm specimens, respectively[3] (Figure 7). This illustrates that surface skin reduces moisture uptake and its effect decreases when specimen thickness, hence total resistance, increases.

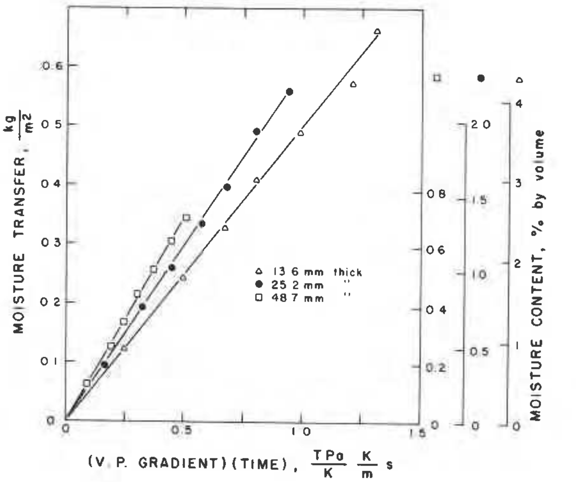

Figure 7. Moisture gains by specimens of extruded polystyrene of three different thicknesses. Skin produced in the extrusion process was left on the warm side of all specimens.

II. A second set of measurements was carried out to determine the rate of moisture transmission through the insulation. The first temperature control apparatus described previously was used. The apparatus was devised so that the moisture passing through the cold surface could be measured. For each insulation, a trio of specimens, 95 mm in diameter and 25.5 ±0.5 mm thick, were prepared and wax sealed in acrylic plastic collars. Plastic cups of the same diameter were filled with water saturated filter paper. They were sealed to the collars using stopcock grease. A thermocouple was placed at each of the warm and cold surfaces of the specimens (Figure 8).

Moisture gain of the warm surface, W_w, was found by weighing the entire assembly at the beginning and end of an observation period. The cup was then removed and the specimen weight determined, thus obtaining W_a. The difference between these was assumed to be the moisture transmitted from the cold surface, W_c.

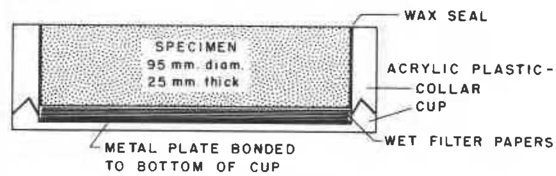

Figure 8. Apparatus used to measure moisture transmission into the warm surface, out through the cold surface and absorbed by the specimen.

II (a). One test was carried out with three extruded polystyrene specimens, a bead polystyrene (26 kg/m³) and a urethane specimen, with the warm surfaces uppermost. The warm and cold side temperatures were 40 and 29°C, respectively. The moisture transmitted to the warm surface $(W/A)_w$ and from the cold surface $(W/A)_c$ for the extruded polystyrene, the bead polystyrene and urethane is plotted (neglecting isothermal gain) in Figures 9a, b and c, respectively, against the corresponding values of $dp/d\theta\ \Delta\theta/\Delta\chi\ \tau$. Moisture content is also given. It was obtained by taking the difference in the total moisture that had entered and left the specimen, i.e., $(W/A)_w - (W/A)_c$ at the time of each observation. The abscissa in this case is the difference between the corresponding values of the (average vapour pressure gradient) × time for the cold and warm surfaces. The slopes of the curves representing moisture content have the units of permeability though this does not have any easily recognizable

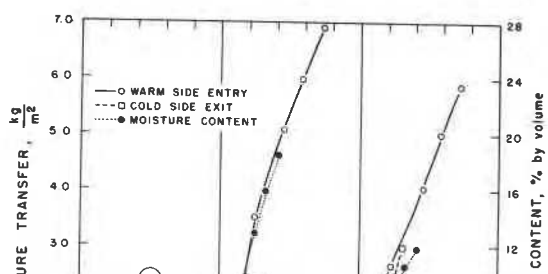

Figure 9. Moisture entering the warm surface, exiting from the cold surface and remaining in the specimen vs (vapor pressure gradient) (time elapsed). Warm surface uppermost. Specimen thickness 25.5 ± 0.5 mm. The abscissa for the moisture content is

$$\left[\left(\frac{\Delta p}{\Delta x}\right)_w - \left(\frac{\Delta p}{\Delta x}\right)_c\right] \text{time}$$

[3]These are pseudo permeabilities because the specimens are not homogeneous with a surface coating.

physical meaning. However, the slopes give a measure of the tendency of the insulations to retain moisture under these conditions.

A slope was calculated for each set of points in Figures 9 and 10. These are approximate values since the plots are more or less curved. These values have not been placed on the graphs but are given below. From Figure 9, for the extruded polystyrene, the slope of the curve representing the warm surface, μ_{aw} = 0.93 ps (0.64 perm-in.); μ_{ac} (the moisture leaving the cold surface), however, was 1.9 ps (1.3 perm-in.). The high value for μ_{ac} might be accounted for if there had been an air gap between the specimen and the wet filter paper; the humidity at the surface would then have been below 100% which would have increased the vapor outflow. It was not apparent that this had occurred however.

II (b). The procedure was repeated but the assemblies were inverted so that the warm surface was downward. Warm and cold surface temperatures were 42 and 25°C, respectively (Figure 10).

For extruded polystyrene (Figure 10a), the initial moisture transfer rate was relatively high at both the warm and cold surfaces, but decreased thereafter. The value for μ_{aw}, calculated from the data in the upper part of the curve, was 1.3 ps (0.89 perm-in.).

For Figure 10b, μ_{aw} varied from an initial value of about 8.0 ps (5.5 perm-in.) to 4.0 ps (2.8 perm-in.); μ_{ac} varied widely. In the period during which the moisture content rose to nearly 20%, it averaged about 3.0 ps (2.0 perm-in.).

For Figure 10c, μ_{aw} varied from roughly 15 ps (10 perm-in.) initially to 2.2 ps (1.5 perm-in.) at the upper part of the plot. The value for μ_{ac} averaged about 4.0 ps (2.8 perm-in.).

The results in Figures 9 and 10 differ somewhat. It appears that egress of the moisture in an upward direction was lower than when the movement was downward. This may have been the effect of gravity or of moisture conditions at the cold surface.

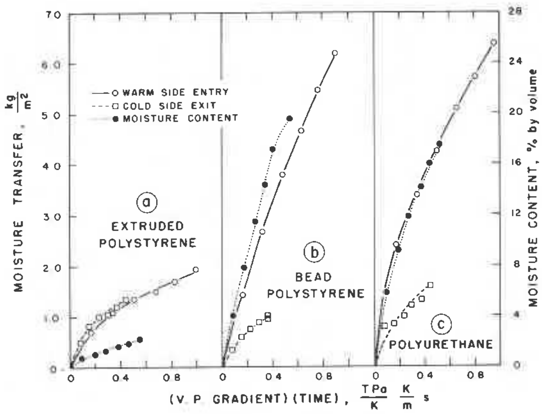

Figure 10. Moisture entering the warm surface, exiting from the cold surface, and remaining in the specimen vs (vapor pressure gradient) (time elapsed). Warm surface on the bottom. Specimen thickness 25.5 ± 0.5 mm. The abscissa for the moisture content is

$$\left[\left(\frac{\Delta p}{\Delta x}\right)_w - \left(\frac{\Delta p}{\Delta x}\right)_c\right] \text{time}$$

Moisture permeability of these materials was found using the procedure outlined in ASTM C355. The values in Table 2 were averages of 3 to 6 specimens of each material.

Summary

Laboratory experiments were carried out to assess the moisture absorption and transmission properties of several foam plastic insulations when subjected to combined thermal-moisture gradients. Extruded polystyrene, two bead polystyrenes, a

Table 2. Wet Cup Permeabilities (ASTM E355) and Apparent Permeabilities Estimated from the Temperature-Moisture Tests ps (perm-in.).

	Wet cup permeabilities		Temperature-moisture gradient results		Figure No.
	Vapor	Liquid ps (perm-in.)	u aw ps (perm-in.)	u ac ps (perm-in.)	
Extruded polystyrene (32 kg/m³)	1.1 (.76)	1.1 (.76)	1.1 (.80)		5
			1.0-1.7 (.69-1.2)	1.9 (1.3)	9
			1.3-1.4 (.89-.95)	1.7-4.5 (1.2-3.1)	10
Bead Polystyrene (16 kg/m³)	3.0 (2.0)	—*	6.8 (4.7		5
Bead polystyrene (26 kg/m³)	2.2 (1.5)	—*	10-14 (6.9-9.5)	8.0 (5.5)	9
			5.5-9 (3.8-6.2)	2.8 (1.9)	10
Polyurethane (29 kg/m³)	7.1 (4.9)	7.1 (4.9)	11.6 (8.0)	10 (6.9)	5
			10-12 (6.9-8.3)	2.5 (1.7)	9
			4.5-14 (3.1-9.6)		
Phenolic foam (52 kg/m³)	38 (26)		118 (81)		Calculated from data in Figure 4

*Test not applicable — liquid flow through fissures.

urethane and a phenolic foam were placed under temperature differences ranging from 0 to 22°C in the presence of free water.

The study was part of a research program on protected membrane roofing where insulations are exposed to combined temperature-moisture gradients; the experimental arrangements were modeled after that system. Important differences existed between the field and laboratory environments; the former involving idealized conditions, e.g., steady state conditions and saturated conditions at the insulation surfaces.

In most of the laboratory measurements, surface skins were removed to expose the base material, thus voiding any protection provided by the manufacturer which would have reduced moisture gains.

The laboratory results indicate:

1. The rate of moisture entry into the insulation increased with the applied vapor pressure gradient. In the early stages when moisture content was not too high, e.g., 20% by volume or less, the proportion was approximately linear, or gradually declining. The rate of gain decreased as the moisture content increased. In the open cell plastic, it nearly ceased when the moisture content reached 50 to 60%.

2. Rates of gain under zero temperature gradient were measured. These were small compared to those produced when a temperature gradient was applied, i.e., using these results, average rates of gain under isothermal conditions, over a test period of 64 days, were estimated to be equivalent to those produced by the application of a temperature gradient of about 1.2°C for the open cell plastic, 0.4°C for the extruded polystyrene, and 0.1°C for the bead polystyrene and urethane.

3. Data for moisture transmission for 25.5 mm thick specimens of extruded and bead polystyrene, a urethane, and a phenolic foam were correlated using an equation based on Fick's Law. Temperature differences across the specimens were 2.8, 11 and 22°C. Calculations were based on conditions at the warm surface and no attempt was made specifically to include the effects of internal transport and deposition. The correlation coefficient for short, over-lapping sections of the curves ranged from 0.97 to 0.99 for the four materials.

4. Apparent permeability values corresponding to the imposed surface conditions were estimated from measured rates of moisture movement and the vapor pressure gradient based on an assumed linear temperature gradient. The values were higher than wet cup permeability values (ASTM C355) in nearly all cases – about 50% higher for extruded polystyrene and urethane, and 150 to 500% higher for bead polystyrene and phenolic foam.

5. When the cold surfaces of the polystyrenes and urethane were left open and kept wet, they exuded significant amounts of moisture.

6. In most of these tests, any protective surface coating was removed. In one test, where the natural skin was left on extruded polystyrene, the rate of moisture gain was reduced, as expected. In outdoor tests (1, 2), specimens were surface-sealed with coated base sheet. The tests showed that under practical conditions surface-sealing could dramatically reduce the moisture gains. In practice this kind of protection could be achieved by applying a protective membrane and would also be obtained if the insulation were fully bonded to the membrane, e.g., in a bitumen pour coat.

7. In this study, attention has been given primarily to the rate of moisture gain under a temperature-moisture gradient. Moisture will also escape from insulations if the proper conditions exist. Thus a model based on the concept of moisture balance, in which both gain and loss play a part, may more nearly approximate the practical situation.

8. The procedure used in this work simulates the conditions on protected membrane roofs in that thermal-moisture gradients exist in both cases. Field conditions are different because temperature will fluctuate, moisture conditions will not always be saturated and freeze-thaw cycles may occur. Nevertheless, a test based on the use of a thermal-moisture gradient may provide useful, though not complete, information about field performance of insulations in which the vapor mode of transport predominates.

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C. Hedlin

A native of Saskatchewan, Charles Hedlin obtained a B.Sc. degree from the University of Saskatchewan in 1950, an M.Sc. degree from the University of Minnesota in 1952 (both in Agricultural Engineering), and a Ph.D. degree from the University of Toronto in Mechanical Engineering in 1957. From 1952 to 1960, he taught engineering subjects and carried out research on the drying of agricultural products at the Ontario Agricultural College. In 1960 Dr. Hedlin joined the staff of the Division of Building Research, National Research Council of Canada at the Prairie Regional Station in Saskatoon, Saskatchewan, and has carried out research on humidity measurement, moisture absorption characteristics of some building materials, and on flat roofing. At present he is Officer-in-Charge of the Division's Prairie Regional Station.