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# ***Water Vapor Transmission and Moisture Accumulation in Polyurethane and Polyisocyanurate Foams***

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## RÉSUMÉ

On a étudié le transport de vapeur d'eau dans des mousses rigides de polyuréthane et de polyisocyanurate à l'aide de trois méthodes d'essai -- deux dans des conditions isothermiques et l'une en présence d'un gradient thermique. Les trois méthodes ont permis de dégager les coefficients de transmission de vapeur d'eau des matériaux. On observe que la valeur des coefficients augmente rapidement lorsque la température est supérieure à 20 °C. Dans une des méthodes isothermiques appelée «méthode du bac modifiée», mise au point à l'Institut de recherche en construction, seule la température doit être contrôlée, ce qui est contraire à l'autre méthode, ASTM (D-1631-80), c'est-à-dire la mesure de la teneur en humidité relative. La méthode d'essai par la mesure de la teneur en humidité relative est plus précise. Il a été démontré que la vapeur d'eau ne s'accumule pas dans les matériaux.

On a étudié le transport de vapeur d'eau dans des mousses rigides de polyuréthane et de polyisocyanurate à l'aide de trois méthodes d'essai -- deux dans des conditions isothermiques et l'une en présence d'un gradient thermique. Les trois méthodes ont permis de dégager les coefficients de transmission de vapeur d'eau des matériaux. On observe que la valeur des coefficients augmente rapidement lorsque la température est supérieure à 20 °C. Dans une des méthodes isothermiques appelée «méthode du bac modifiée», mise au point à l'Institut de recherche en construction, seule la température doit être contrôlée, ce qui est contraire à l'autre méthode, ASTM (D-1631-80), c'est-à-dire la mesure de la teneur en humidité relative. La méthode d'essai par la mesure de la teneur en humidité relative est plus précise. Il a été démontré que la vapeur d'eau ne s'accumule pas dans les matériaux.

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## Water Vapor Transmission and Moisture Accumulation in Polyurethane and Polyisocyanurate Foams

**REFERENCE:** Schwartz, N. V., Bomberg, M., and Kumaran, M. K., "Water Vapor Transmission and Moisture Accumulation in Polyurethane and Polyisocyanurate Foams," *Water Vapor Transmission Through Building Materials and Systems: Mechanisms and Measurement*, ASTM STP 1039, H. R. Trechsel and M. Bomberg, Eds., American Society for Testing and Materials, Philadelphia, 1989, pp. 63-72.

**ABSTRACT:** Water vapor transport through rigid polyurethane and polyisocyanurate foams was investigated using three test methods—two under isothermal conditions and one in the presence of a thermal gradient. All three methods yielded water vapor transmission coefficients of the materials. It is observed that the magnitude of the coefficients increases rapidly with temperature above 20°C. In one of the isothermal methods called a modified cup method, developed at the Institute for Research in Construction, only the temperature has to be controlled and this is considered a definite advantage over the other method, ASTM Test Methods of Water Vapor Transmission of Materials, (E 96-80) dry cup method, in which both temperature and relative humidity are to be controlled. Further, the modified cup method also allows the determination of moisture accumulated in the test specimen during moisture transport. It was conclusively shown that during isothermal transport processes no moisture accumulates in either the polyurethane or the polyisocyanurate specimens.

The accumulation and distribution of moisture in the presence of a thermal gradient was also investigated. Contrary to the isothermal process, the moisture transport in the presence of a thermal gradient acting in the same direction as the vapor pressure gradient results in the accumulation of large quantities of water in the foams. This phenomenon may be partly attributed to the temperature dependence of the water vapor transmission coefficients.

**KEY WORDS:** water vapor transmission, testing, water vapor permeance, thermal gradient, polyurethane foam, polyisocyanurate foam, moisture accumulation

Cellular plastic foams, among thermal insulating materials, are generally considered to be the least permeable to water vapor. But it is known that exposure of closed-cell cellular plastic foams to simultaneous thermal and moisture gradients has a detrimental effect on the long-term thermal performance and on the dimensional stability of these materials. Yet, apart from the work reported by Paljak [1], the information on moisture movement and accumulation in closed-cell plastics is very limited. Paljak determined the water vapor transmission (WVT) coefficients of four cellular plastics, namely, two expanded polystyrene bead boards, an extruded polystyrene board, and a polyurethane board, and investigated the accumulation of thermally driven moisture in the materials. The polyurethane board, though having a lower permeance, initially showed a higher rate of moisture accumulation than the

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two expanded polystyrene boards. However, after approximately 100 days, the rate started to decrease and by 200 days became insignificant. In contrast to the behavior of the polyurethane board, all three polystyrene boards continued to increase their moisture content even after 300 days.

Other workers [2-6] mainly aimed at a comparison of the performances of different materials and subsequent identification of laboratory test methods for the evaluation of moisture ingress to the materials. Very little attention was paid to understanding the physics of moisture movement through cellular plastics.

Recently, at the Institute for Research in Construction, the transport of water vapor in the presence of a thermal gradient through glass fiber insulation was extensively investigated [7-10]. An experimental method was identified [7,8] to determine two empirical coefficients that describe the moisture transport. These coefficients were subsequently used [9,10] in a numerical analysis of simultaneous heat and moisture transport through glass fiber insulations. To examine a possible extension of the preceding method to cellular plastics, a systematic investigation of moisture transport through these materials was undertaken, and a set of experimental results from the investigation is reported here. The experimental methods used were formulated to determine WVT coefficients under isothermal conditions and in the presence of thermal gradients. In addition, the rate of moisture accumulation and the distribution of the accumulated moisture were investigated. The measurements were done on two rigid cellular plastic boards, namely, a polyurethane (PUR) with density  $32 \text{ kg/m}^3$  and a polyisocyanurate (PIR) with density  $37 \text{ kg/m}^3$ .

### Experimental Methods and Results

The transport of water vapor through the preceding materials was investigated using three different experimental techniques that are described in this section.

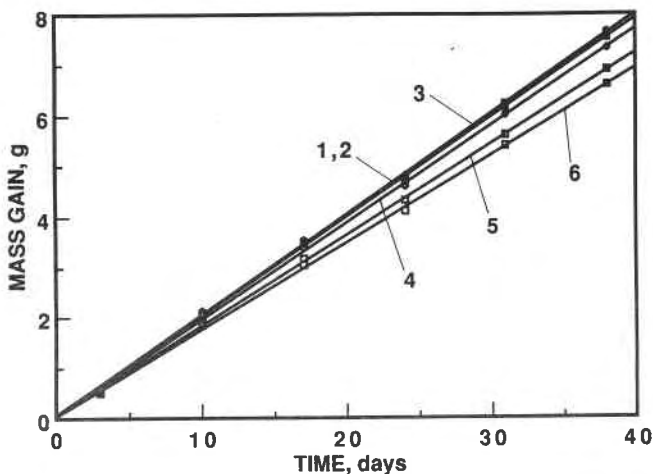


FIG. 1—Results from the dry-cup measurements at  $21.5^{\circ}\text{C}$ ; Lines 1, 2, and 3 represent PUR and Lines 4, 5, and 6 represent PIR.

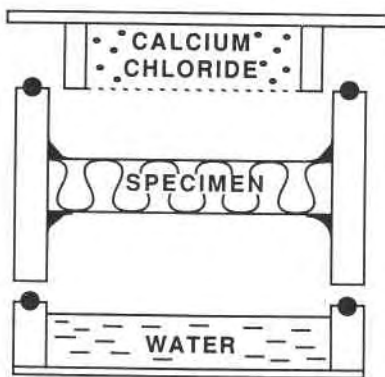


FIG. 2—Schematic of the modified cup method; represents O-rings used for sealing the containers air tight.

*ASTM Test Methods of Water Vapor Transmission of Materials (E 96-80),  
Dry Cup Method*

About 300 g of calcium chloride was placed in a glass crystalizing dish, 150 mm diameter and 75 mm deep. The edges of the test specimen, with the same diameter as the dish, were sealed and then mounted air-tight on the dish with sealing wax. The assembly was then placed in a chamber maintained at a temperature of  $21.5 \pm 0.5^\circ\text{C}$  and a relative humidity of  $50 \pm 2\%$ . The mass gain of the assembly was recorded periodically. Three specimens each of PUR and PIR were used for these measurements and the results are shown in Fig. 1.

*Modified Cup Method*

The test assembly for this method is shown schematically in Fig. 2. The method combines the features of both the ASTM dry and wet cup methods. A cylindrical container (144 mm

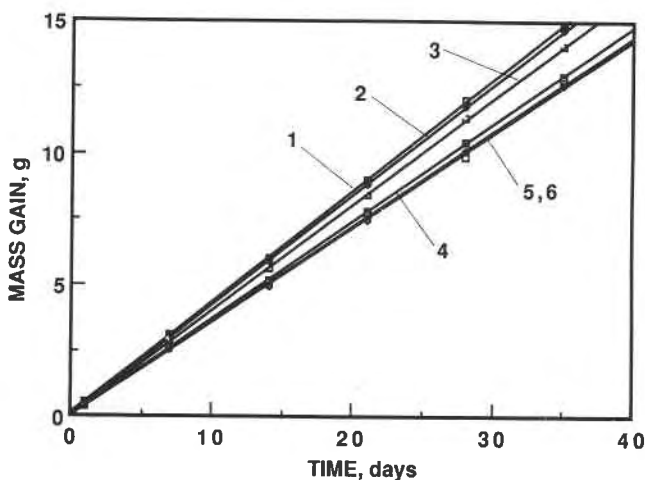


FIG. 3—Results from the modified cup measurements at  $21.5^\circ\text{C}$ ; Lines 1, 2, and 3 represent PUR and Lines 4, 5, and 6 represent PIR.

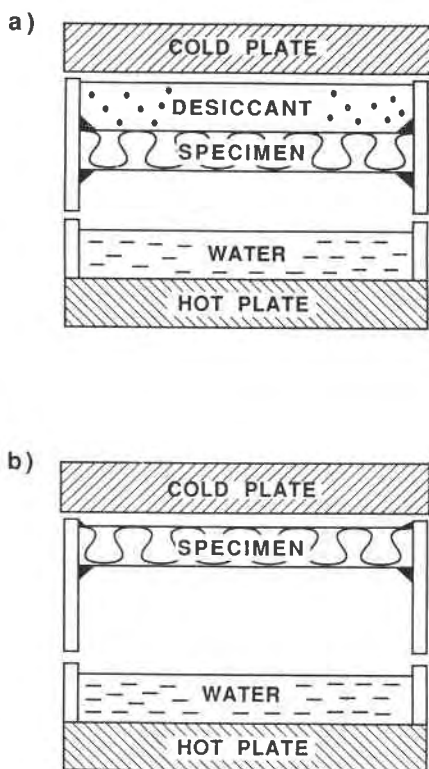


FIG. 4—Schematic of the thermal gradient method; (a) the specimen is separated from the cold plate through a layer of desiccant and (b) the specimen and the cold plate are separated by a film of polyvinylidenechloride.

diameter), in which the specimen has been sealed with silicone rubber, was placed between containers with water and calcium chloride, respectively. The desiccant was separated from the specimen through a highly permeable layer of spunbonded polyolefin (approximately 40 times more permeable than the test specimens). The assembly was held in place by two aluminum plates bolted together. It was then placed in a chamber maintained at  $21.5 \pm 0.5^\circ\text{C}$ . The assembly was separated periodically, and the desiccant and specimen containers were individually weighed. Then it was reassembled and the experiment continued. The measurements were done on three specimens of PUR and three specimens of PIR. The mass gained by the desiccant during the experiment is shown in Fig. 3. None of the specimen containers gained any measurable mass.

The preceding measurements were repeated at mean temperatures of 10, 32, and  $51^\circ\text{C}$ . The results were similar to those at  $21.5^\circ\text{C}$  except that the PUR specimens started to distort at  $51^\circ\text{C}$ . Measurements were hence abandoned on the PUR specimens at  $51^\circ\text{C}$ .

#### Temperature Gradient Method

The experimental setup for this method is shown schematically in Fig. 4. The specimen container, made of plexiglas, was sandwiched between a cold plate at  $5^\circ\text{C}$  and a pool of water in contact with a hot plate at  $50^\circ\text{C}$ . The specimens, 130 mm square, were sealed to the inside of the containers. On the cold side of the specimen there was either a layer of

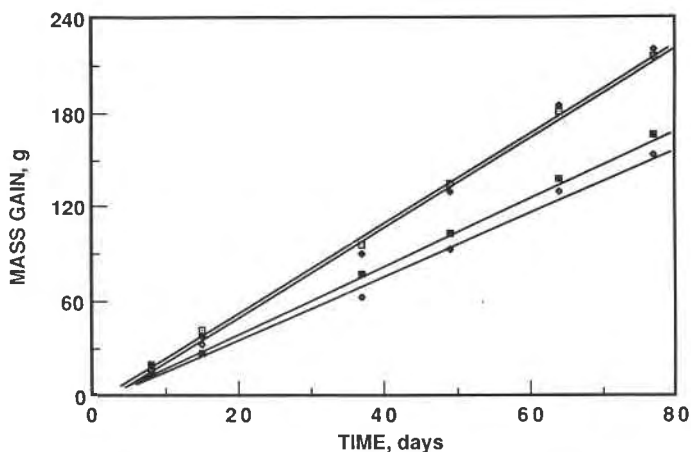


FIG. 5—Mass gained by the desiccant in the experimental setup in Fig. 4a;  $\square$  and  $\diamond$  represent PUR and the other two PIR.

molecular sieves or a layer of polyvinylidenechloride (saran) film of low permeance; the former arrangement allowed a through transport of moisture across the specimen while the latter prevented any through transport. The specimen containers were periodically removed from the assembly and the moisture gain by the specimen container and that by the desiccant, if applicable, were determined. The corresponding moisture distribution in the specimens was also determined using a gamma-spectroscopic method [11,12].

Two specimens each of PUR and PIR were investigated in the presence of the desiccant. The moisture gain by the desiccant is shown in Fig. 5 and that by the specimen in Fig. 6. The distribution of moisture in the specimens at two stages of the experiment is shown in Figs. 7a and b. The moisture gain by two PUR specimens and two PIR specimens in the presence of the polyvinylidenechloride film is shown in Fig. 8. The distribution of moisture in the preceding specimens at two different stages of the experiment is shown in Fig. 9.

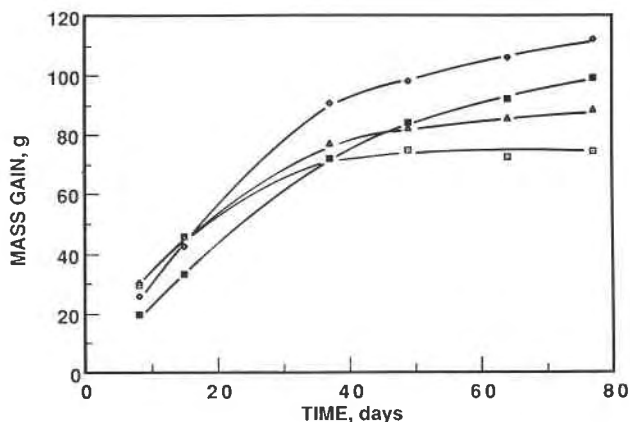


FIG. 6—Mass gained by the specimens in the experimental setup in Fig. 4a;  $\diamond$  and  $\blacksquare$  represent PUR and the other two PIR.

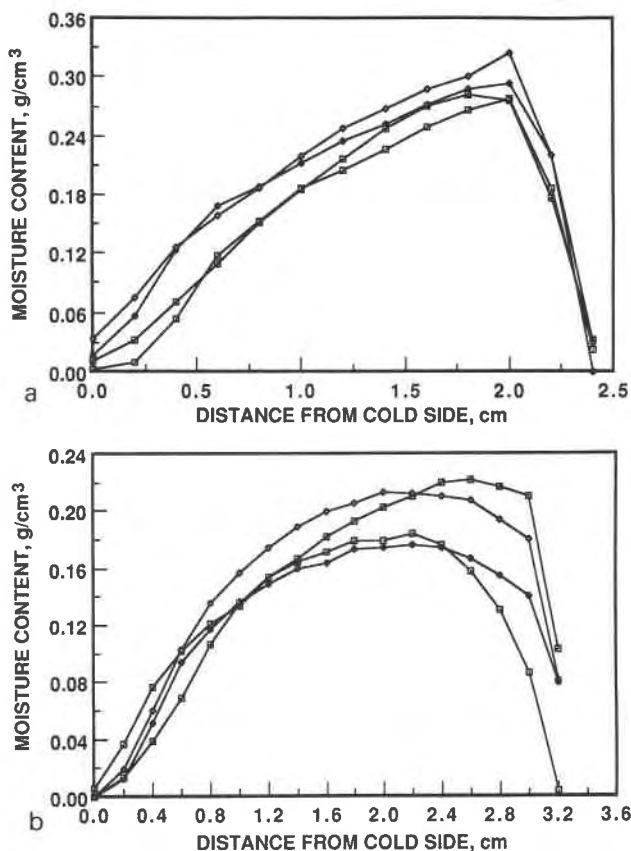


FIG. 7—Moisture distribution in the specimens in the experimental setup in Fig. 4a; (a)  $\blacksquare$  and  $\square$  represent PUR specimens on the 37th day and the other two on the 64th day, and (b)  $\blacklozenge$  and  $\square$  represent PIR specimens on the 37th day and the other two on the 64th day.

## Discussion

It is seen from Figs. 1, 3, and 5 that the net moisture transfer across the two materials is always a linear function of time, irrespective of the boundary temperatures and vapor pressures imposed in the three test methods. In the three methods employed here, the water vapor pressure gradient across the test specimens is known—rather precisely in the dry cup and in the modified cup methods but only approximately in the temperature gradient method (the surface temperatures of the specimens not being measured). This information allows the calculation of water vapor permeance of each test specimen from the data in Figs. 1, 3, and 5. The values so calculated are given in Table 1. The experimental data were processed through a linear least-squares analysis. In doing so, for each sample of material, all available data (12 to 18 pairs of data) on all the specimens investigated at any given boundary condition were weighted equally. Thus, the numbers in Table 1, though statistically representing average values for both samples, do not reflect the uncertainty introduced by material inhomogeneity. At times, this uncertainty can be large. For example, Zehendner [13] has reported that the permeance of 40-mm-thick specimens of PUR of density  $30 \text{ kg/m}^3$  varies

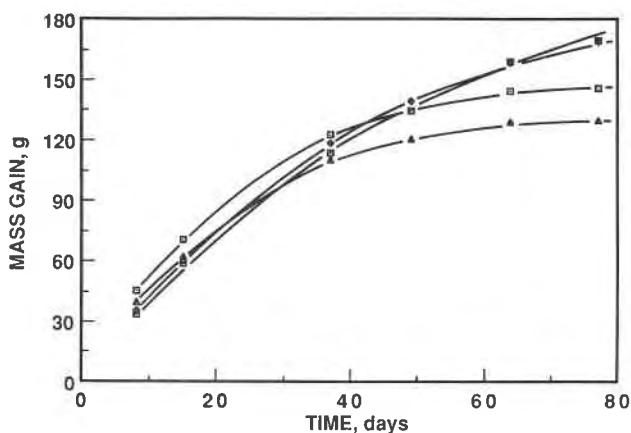


FIG. 8—Mass gained by the specimens in the experimental setup in Fig. 4b;  $\triangle$  and  $\square$  are PIR specimens and the other two are PUR specimens.

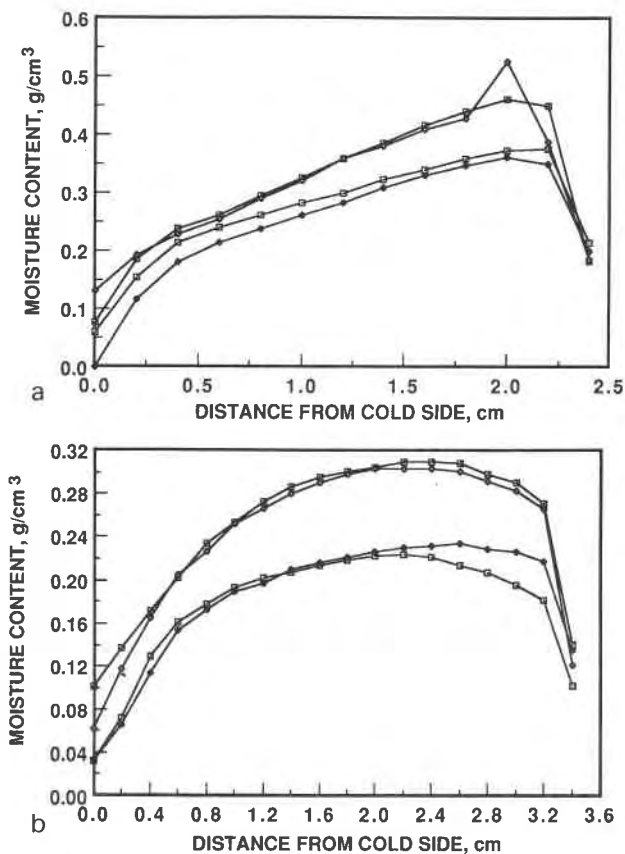


FIG. 9—Moisture distribution in the specimens in the experimental setup in Fig. 4b; (a)  $\square$  and  $\diamond$  represent PUR specimens on the 37th day and the other two on the 64th day and (b)  $\diamond$  and  $\square$  represent PIR specimens on the 37th day and the other two on the 64th day.

TABLE 1—The water vapor permeance,  $\mu$ , of PUR and PIR at various temperatures; the numbers in parentheses indicate the standard error, expressed in percent, as estimated from the least-squares analysis.

Temperature, °C	Test Method	$\mu \times 10^7$ , g/(m <sup>2</sup> · s · Pa)	
		PUR	PIR
10	modified cup	1.14(2.2)	1.02(1.1)
21.5	dry cup	1.12(0.7)	1.03(2.3)
21.5	modified cup	1.16(1.2)	1.01(1.0)
27.5 <sup>a</sup>	thermal gradient	1.80(2.1)	1.31(3.3)
32.0	modified cup	2.09(0.1)	1.62(5.3)
51.0	modified cup	***	2.66(5.0)

<sup>a</sup> This is an approximate mean temperature of the specimens.

between  $0.7$  and  $1.3 \times 10^{-7}$  g/(m<sup>2</sup> · s · Pa), all measurements having been done at 23°C. The present measurements were restricted to two or three specimens and hence no realistic estimate of the range of values of permeance of the materials can be made. But even with this limited number, variabilities up to 18% were observed, between specimens.

The permeance of each material was determined at 21.5°C using the dry cup and the modified cup methods. It can be seen from Table 1 that, well within the standard errors, these values are identical. It may then be suggested that the modified cup method is a preferred one for isothermal measurements for two reasons:

1. only the temperature of the chamber is to be controlled, whereas both the temperature and relative humidity are to be controlled in the dry cup method; and
2. it provides information on moisture accumulated in the specimen during the vapor transport, whereas the dry cup method gives information on the net vapor transport only.

Table 1 lists values for permeance at different temperatures between 10 and 51°C. These values are plotted in Fig. 10. It is seen that for both materials, the permeance increases rapidly with temperature above 21.5°C and that this increase appears to be linear. Figure 10 also shows that the permeance calculated from the data available from the thermal gradient method, though less precise, also shows the general pattern of increasing permeance with temperatures above 21.5°C. The present investigation indicates that the permeance of both materials is independent of temperature in the range 10 to 21.5°C. This has to be confirmed by doing more measurements in this temperature range.

The information on the accumulation of moisture can be generalized as follows. If the vapor transport occurs under isothermal conditions, there is no moisture accumulation. But if the process occurs in the presence of a thermal gradient that acts in the same direction as the pressure gradient, depending on the duration, large quantities of liquid water can be trapped in the warmer regions of the material. As seen from Figs. 6 and 8, the preceding phenomenon occurs whether there is through transport or not. Probably, right from the beginning of the experiment, moisture accumulation starts from the warmer regions and builds up continuously until a steady state, determined by the boundary conditions, is achieved. Thus, as illustrated in Figs. 7 and 9, even after 37 days into the experiment, at each location the moisture content was continuously increasing. In the case of the PUR

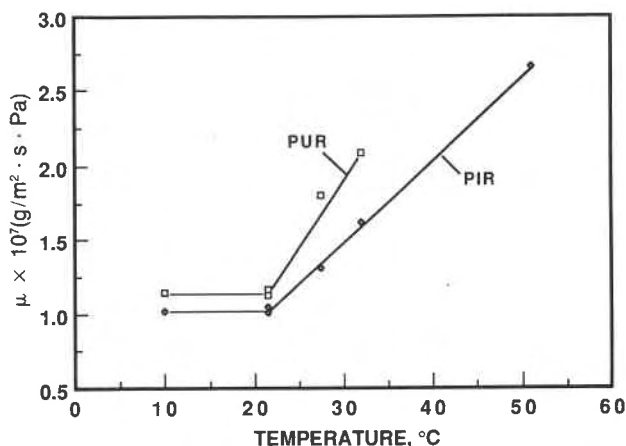


FIG. 10—The dependence of the water vapor permeance,  $\mu$ , of the materials on temperature,  $T$ ;  $\square$  represents PUR and  $\diamond$  represents PIR. The shaded data pair are from the thermal gradient method and as indicated in the text, these data, though less precise, also conform to the general behavior.

specimens, after 64 days there was no further increase in the moisture content, and the distribution of moisture measured on the 64th day probably corresponded to the steady-state distribution. But with the PIR specimens, the distribution was changing slowly towards a steady state, even after nine weeks. It can be seen from Fig. 9 that there are regions that are half filled with liquid water at the steady state. Indeed, such a situation will have significant influence on the thermal performance of the material.

As observed by Paljak [1], during the initial stages of the process, the total moisture accumulation in the specimens starts at a higher rate and with time it becomes insignificant. In fact, with PUR, a steady state is established within approximately 40 days, in the presence of the desiccant. Further investigation of this phenomenon is in progress. The information currently available indicates that the duration of the moisture pickup depends on the boundary temperatures. Obviously, the distribution of the accumulated moisture also will be determined by the boundary conditions.

The temperature dependence of the permeance may partly account for the moisture accumulation in the presence of the thermal gradient. Water vapor enters any given location of the specimen from a warmer region at a higher rate and leaves to a colder region at a lower rate. Hence, an amount of moisture that corresponds to the difference in the two rates should accumulate at the location. An accurate knowledge of the temperature dependence of the permeance may thus be used to estimate the rate of moisture accumulation as well as the distribution of the accumulated moisture. This aspect needs to be further investigated.

Perhaps the most intriguing observation from the present investigation is the following. The moisture accumulated in the test specimens under simultaneous temperature and vapor pressure gradients does not affect the net rate of moisture transport through them. This leads one to believe that there are some unique physicochemical processes associated with the transport of moisture through polyurethane and polyisocyanurate foam insulations. Further research resources are to be expended for a thorough understanding of these physicochemical processes.

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