

# Long-Term Performance of Closed-Cell Foam Insulation

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## ABSTRACT

*Closed-cell foams filled with high-molecular-weight blowing agents, e.g., CFCs, have the highest thermal resistivity of any conventional insulation. When it is first manufactured, one-half of the heat transfer is due to conduction through the gas in the cell interior. If the foam surface is not well sealed, air components diffuse into the foam over time and the blowing agent diffuses out. This aging process can cause a substantial reduction in the thermal performance of the insulation. The aging process of the foam can be predicted based on recent measurements by the authors of the diffusion coefficient for a range of polyurethane and polyisocyanate foams. These measurements and subsequent predictions will be used to evaluate various techniques to rapidly determine the long-term aging behavior of foams. The time required, as well as the accuracy of the techniques, will be dealt with. The advantages of advanced facers or seals for the principal surfaces of the foams will be demonstrated, e.g., a carbon dioxide-filled foam board protected by an ideal facer is shown to give a time-averaged behavior equivalent to a CFC- or HCFC-filled foam whose surfaces are unprotected.*

## INTRODUCTION

Closed-cell foams have the lowest thermal conductivity of any insulation currently available other than vacuum insulations. The heat transfer through the insulation is due to conduction through the cell gas, conduction along the struts and cell walls of the solid polymer, and thermal radiation through the foam interior. Convective heat transfer is negligible in the cell interiors. For a freshly made foam filled with a blowing agent and excluding air, the gas conduction is roughly one-half the total heat transfer. Conduction and radiation are approximately equivalent, and each is equal to about one-fourth of the total heat transfer. These proportions can change with the foam density, the cell size, and the percent of the polymer in the cell walls.

Over time, the conductivity of the foam increases due to the diffusion of air components into the foam and the diffusion of blowing agents out of the foam. Since air has a thermal conductivity about three times as large as the blowing agent vapor, as the proportion of air in the cell interior rises, the effective conductivity of the foam increases by an corresponding amount. This is referred to as the *aging process* of foam. Because the gas transfer is a diffusion process rather than bulk flow, the diffusion of

each gas species is independent of the other gas species. Thus, there is a separate time constant for the diffusion of oxygen, carbon dioxide, nitrogen, and the blowing agent. For a 2.5-cm-thick unfaced foam sample, the diffusion of air components typically lasts one year, while the diffusion of the blowing agent lasts approximately 20 times longer. As the thickness of the foam sample is increased, the times increase with the square of the thickness.

The challenge is to find a reliable technique to quantify the aging rate of foam in a short time. Ideally, the accelerated aging technique should give accurate values for the conductivity changes over the lifetime of the foam. This should be done with the shortest practical test times. In addition, it would be most helpful if the aging results would yield a prediction of the aging of the same foam composition for different thicknesses and under different exposure conditions, especially different temperature levels and gradients.

There are several accelerated aging techniques either in use or under consideration. In this paper we will consider the advantages and drawbacks of several of the more well-known accelerated aging techniques. This will be based on the relationships governing the aging rate of foams and the diffusion properties measured by the authors. Results will be presented comparing measured aging results for full-thickness samples with predicted aging rates based on the experimental technique and numerical analysis developed by the authors and previous investigators.

## GAS DIFFUSION THROUGH FOAM

The mass flux of a single species of gas through the foam can be written in terms of Fick's first law of diffusion,

$$J = -D \frac{\partial c}{\partial x}, \quad (1)$$

where

- $J$  = rate of transfer of the given gas species,  
 $c$  = concentration,  
 $x$  = space coordinate indicating the direction of diffusion, and  
 $D$  = diffusion coefficient.

For a foam, if the distance for diffusion is large compared to an individual cell diameter, the foam can be considered a homogeneous medium with  $D$  and  $c$  expressed

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as effective quantities. The concentration can be related to the partial pressure of the given gas species within a given cell interior by Henry's law,

$$S_{sp} = \frac{c_{sp}}{p}, \quad (2)$$

where

$c_{sp}$  = species concentration within the solid polymer,  
 $p$  = partial pressure of that species in the vapor adjacent to the solid.

Similarly, for the foam considered as a homogeneous medium, an effective solubility can be written in terms of the effective concentration, the mass of the gas species in the solid polymer, plus the cell interior per unit foam volume. The effective solubility is

$$S_{eff} = \frac{c_{eff}}{p} = \frac{c_s}{p} \delta + (1-\delta) \frac{c_{sp}}{p}, \quad (3)$$

$$S_{eff} = \frac{\delta}{RT} + (1-\delta) S_{sp}, \quad (4)$$

where the ideal gas laws were used for the gas species within the cell interior. The effective permeability is taken as the product of the effective solubility and the diffusion coefficient.

Equation 1 can now be rewritten as

$$J = -P_{eff} \frac{\partial p}{\partial x} = -D_{eff} S_{eff} \frac{\partial p}{\partial x}. \quad (5)$$

Ostrogorsky and Glicksman (1987) have shown that the effective permeability can be related to the permeability of the solid polymer,

$$(Pe)_{eff} = \frac{\epsilon \langle l \rangle}{t} Pe_{sp}, \quad (6)$$

where

$t$  = cell wall thickness,  
 $\langle l \rangle$  = average distance between cell walls in the direction  $x$ , and  
 $\epsilon$  = parameter that accounts for the enhancement of permeation due to the nonparallel orientation of cell walls.  $\epsilon$  is shown to be two for randomly oriented cell walls. Ostrogorski showed that Equation 6 can be rewritten as

$$(Pe)_{eff} = \left( \frac{\epsilon^2}{f_w} \right) \frac{P_{sp} - P_g}{P_{foam} - P_g} Pe_{sp}. \quad (7)$$

Thus the effective permeability varies inversely with the foam density and the fraction of solid polymer in the cell walls,  $f_w$ . Note that the effective permeability is not a direct function of the cell size, although the cell size could affect  $f_w$ .

Representing the foam as a homogeneous continuum, conservation of mass leads to Fick's second law,

$$\frac{\partial c_{eff}}{\partial t} = -\frac{\partial J}{\partial x} = P_{eff} \frac{\partial^2 p}{\partial x^2}. \quad (8)$$

Using Equation 3,

$$\frac{\partial p}{\partial t} = D_{eff} \frac{\partial^2 p}{\partial x^2} = \frac{P_{eff}}{S_{eff}} \frac{\partial^2 p}{\partial x^2}. \quad (9)$$

To find the partial pressure within the foam cells as the foam ages, Equation 9 must be solved for each gas species for a prescribed set of initial conditions and boundary conditions. When the foam is first produced, the concentration of the blowing agents is known and the partial pressure of the air components is zero, although there may be carbon dioxide in the fresh foam. As the foam ages, the partial pressure of the air components at the outer surfaces of the foam generally remains constant and equal to the ambient values while the concentration of the blowing agent at the outer surface is zero.

Initial conditions for Equation 9 are

$$\text{at } t = 0, \quad p_i = p_{o_i} \quad (10)$$

and the boundary conditions are

$$\text{at } t = 0, \quad p_i = P_{o_i}, \quad (11)$$

where  $2L$  is the foam thickness.

Nondimensionalizing Equation 9,

$$\frac{\partial \bar{p}_i}{\partial \tau} = \frac{\partial^2 \bar{p}_i}{\partial \bar{x}^2}, \quad (12)$$

where

$$\bar{p}_i = \frac{p_i - P_{amb_i}}{p_{o_i} - P_{amb_i}}$$

$$\bar{x} = \frac{x}{L},$$

$$\tau = \frac{D_{eff} t}{L^2} = F_0.$$

The dimensionless time  $\tau$  is known as the Fourier number or Fourier modulus. Equation 12 applies to any foam thickness,  $L$ , and in dimensionless terms gives identical solutions. The time necessary to reach within, say, 10% of the final state corresponding to  $\bar{p}=0.1$  at a given location in terms of  $x/L$  is solely a function of  $\tau$  (see Table 1). For a given value of  $\tau$  as  $L$  decreases or  $D_{eff}$  increases, the physical time necessary to reach a certain state decreases.

## ACCELERATED AGING TECHNIQUES

### Temperature Increase of Full-Sized Sample

The most common accelerated aging test currently used is carried out with a full-width sample of the foam (Bau-

**TABLE 1**  
**Partial Pressure of Gas Species**  
**for One-Dimensional Diffusion**  
**Through a Plane Slab of Thickness 2L**

Fourier Modulus ( $D_{eff} t / L^2$ )	Center of Slab $\bar{p}$	Mean Value for Entire Slab $\bar{p}$
0	1	1
0.5	0.36	0.25
1	0.1	0.07
$\infty$	0	0

mann 1982). A fresh foam sample is kept for a fixed number of days at an elevated temperature. The elevated temperature increases the rate of diffusion. The thermal conductivity of the sample is measured over the time interval. Foams having a smaller increase of thermal conductivity are assumed to age more slowly over their entire life. The accelerated aging test allows a quantitative rating to be assigned to each product.

This technique has been used by industry and is familiar to workers in the field. Since the full thickness of the sample is used along with the facers on the foam, variations in the foam density from the centerline to the surface, as well as the details of the facer conditions, are retained.

There are numerous drawbacks and concerns about the full-thickness technique. Using typical values of the foam diffusion coefficient reported by Brehm and Glicksman (1989) and shown in Table 2, the time necessary to achieve full aging<sup>1</sup> for the CFC-11 blowing agent when the foam sample is kept at 60°C is five years for a 2.5-cm-thick foam sample and 20 years for a 5-cm-thick sample (see Table 3). Tests carried out for much shorter times show only the preliminary effects of the blowing agent diffusion. For nitrogen diffusion into the test sample, full aging for a 5-cm-thick sample requires 1.7 years while a 2.5-cm-sample requires five months. Furthermore, the increase of the diffusion rate with temperature is different for the air components and the blowing agent. Thus, the measured change of the thermal conductivity with time at the elevated temperature, which is due to the diffusion of both the air and the blowing agent, does not directly correspond to the history of the sample aging at room temperature.

### Room Temperature Aging of Thin Samples

A more recent proposed technique (McElroy et al. 1991) uses thin samples that are aged at room temperature. These samples have a large surface area that allows them to be used in a conventional thermal conductivity apparatus. The thermal conductivity of individual slices is measured with time, or the slices taken from a full-width sample are

<sup>1</sup>Full aging is assumed to be established when the centerline concentration is within 10% of the value at a very long time. This condition corresponds to a Fourier modulus of unity.

reassembled and the overall thermal conductivity is measured. The aging time of the sample is related to that of the full slab by the Fourier modulus,

$$Fo_{sample} = \frac{D_{eff} t_{sample}}{L_{sample}^2} = \frac{D_{eff} t_{slab}}{L_{slab}^2} = Fo_{slab}. \quad (13)$$

Thus a thin sample and a thick slab will have an identical gas composition when the Fourier moduli of the two samples are the same. Note that since the sample is aged at the operating temperature of the slab, the effective diffusion coefficients are unchanged for each gas species and the aging time of the sample can be related to that of the full slab,

$$\frac{t_{sample}}{t_{slab}} = \frac{L_{sample}^2}{L_{slab}^2}. \quad (14)$$

Thus thin slices will age faster than a full-sized sample.

Using the measured diffusion coefficients given in Brehm and Glicksman (1989), the time to reach fully aged conditions can be estimated for the thin slices (see Table 3). For a 1-cm sample aged at 20°C, the nitrogen composition

**TABLE 2**  
**Diffusion Coefficients for Gases**  
**from Transient Sorption Measurements**

Gas	Temperature [°C]	$D_{eff}$ [ $10^{-8}$ cm $^2$ /s]
CO <sub>2</sub>	40	193
	60	351
	80	609
O <sub>2</sub>	40	46.4
	60	88.8
	80	211
N <sub>2</sub>	40	6.84
	60	12.3
	80	21.1
R-11	40	.326
	60	.959
	80	2.34

#### Data on Foam Used in Table 2

Foam Density ( $\rho_f$ )	32.2 kg/m <sup>3</sup>
Solid Polymer Density ( $\rho_p$ )	1150 kg/m <sup>3</sup>
Void Fraction ( $\delta$ )	0.9744
Average Distance between Cell Walls ( $\ell$ )	154 μm
Average Cell Wall Thickness ( $t_w$ )	0.8 μm
Percent Polymer in Cell Walls ( $P_w$ )	40.6%

**TABLE 3**  
**Effect of Sample Thickness on Time for Centerline Concentration  
of Given Gas to Reach within 10% of Final Value**

Thickness	R-11		$N_2$	
	20°C	60°C	20°C	60°C
5 cm	100 yrs	20 yrs	5 yrs	1.7 yrs
2.5 cm	25 yrs	5 yrs	15 mos	5 mos
1 cm	4 yrs	0.8 yrs	2.4 mos	0.8 mos
0.5 cm	1 yr	0.2 yrs	0.6 mos	0.2 mos

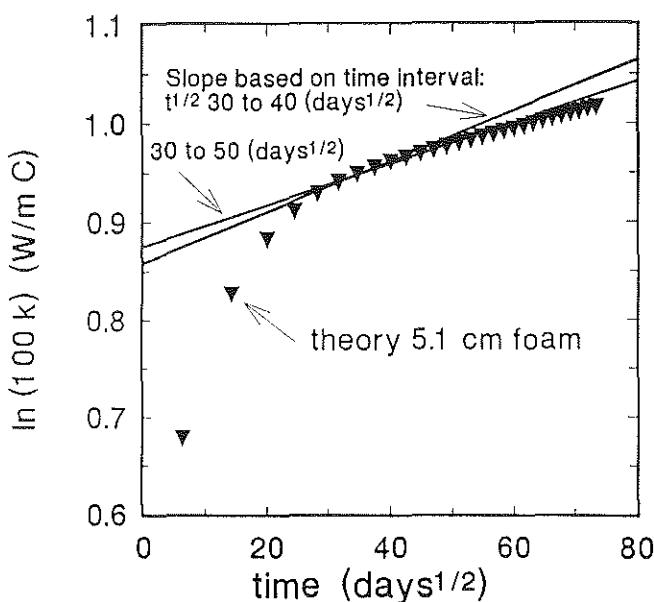
reaches fully aged conditions in about 2.4 months. The other air components reach fully aged conditions in even shorter times. In the same sample, however, R-11 requires four years to reach fully aged conditions. If a 0.5-cm sample could be accurately cut, the time for R-11 aging would be reduced to one year. The width of such a sample corresponds to only 10 to 15 cell diameters. If the cells at both surfaces are damaged by the cutting process, then the effective thickness of the sample would change by 15% to 20%. That is, at both surfaces there is a row of open cells that would immediately come to equilibrium with the surrounding air. The diffusion of R-11 or another blowing agent would be confined to the interior volume of the sample, excluding the broken cells. The time for aging would be given by Equation 15, but the thickness should be the effective interior thickness. However, the conductivity measurement would include the effects of the air-filled surface layers.

To reduce the time necessary to carry out slicing experiments of foam samples, it has been proposed (McElroy et al. 1991) to extrapolate the data at intermediate times to obtain the aging behavior of a longer time. To aid in the extrapolation, the measured conductivity of the thin slices is plotted as the log of the conductivity versus the square root of time divided by the thickness (the latter follows from the Fourier number). To test the uncertainties inherent in the extrapolation, a theoretical aging behavior was derived from the diffusion coefficients reported by Ostrogorsky and Glicksman (1987) and Ostrogorsky's (1985) numerical solution to the diffusion equations for each gas species. Figure 1 shows the theoretical results at discrete time intervals for a 5.1-cm-thick foam sample. (Note: A 1-cm foam sample would follow the same points, with time in days reduced by a factor of 25.) Two least-squares linear curve fits are shown in Figure 1 for results between  $t^{1/2}$  of 30 to 40 ( $\text{days}^{1/2}$ ) and 30 to 50 ( $\text{days}^{1/2}$ ), respectively. The difficulty with using the extrapolation technique becomes evident. If conductivity data only existed out to a time of 40 ( $\text{days}^{1/2}$ ), the first linear curve fit corresponds well to the data up to that time but gives poor extrapolated results at a longer time. Note that with a log scale, disagreements are compressed. For successively longer test times, the extra-

pulation does improve progressively. However, it is not clear a priori how long the slicing test must be carried out to achieve a satisfactory extrapolation. The results of Figure 1 would suggest a required test in excess of 100 days with a 1-cm-thick sample to achieve satisfactory extrapolation. Note that the success of the extrapolation also depends on the choice of the lowest time data to include in the linear regression; if it is taken at the intersection of a second linear curve fit for a shorter time, larger errors may ensue.

#### Elevated Temperature Aging of Thin Slices

The methods described above will provide aging results for the effects of air diffusion into the foam in a reasonable testing period. However, both techniques require very lengthy periods before any appreciable effects of blowing agent diffusion can be determined. Ideally, a combination



**Figure 1** Aging of foam predicted and extrapolated, based on two different time intervals for least-squares fit.

of thin samples and elevated temperature will result in the shortest test times to obtain aging data. Such an aging test procedure has been developed by the authors.

Thin samples of foam are tested at elevated temperatures. The effective diffusion coefficients for each air component and for the blowing agent are measured individually. The foam is first conditioned at an elevated temperature to remove other gas species. The foam sample is placed in a closed volume and the pressure of the given gas species surrounding the sample is suddenly changed. The pressure versus time behavior is compared to the solution to the diffusion equation (Equation 9), with suitable boundary conditions (see Brehm and Glicksman [1989] for details). The value of the effective diffusion coefficient can be obtained by the best fit between the time history of the experimental pressure and the predicted history.

The diffusion test samples can have a relatively small diameter, e.g., 6 to 7 centimeters, allowing thin samples to be accurately cut. For the room temperature slicing technique described in the previous section (where the thermal conductivity is measured), much larger sample diameters are needed, increasing the difficulty to obtain thin samples without substantial surface damage.

The diffusion of gases is considered to be a thermally activated process. It can be expressed by the following Arrhenius type equation:

$$D_{\text{eff}} = D_o \exp\left(-\frac{E_d}{R} \frac{1}{T}\right) \quad (15)$$

where

$D_o$  = a constant that scales the magnitude of the diffusion coefficient,

$E_d$  = activation energy for diffusion, and

$R$  = specific gas constant.

If the effective diffusion coefficient of a gas in a foam is measured at different temperatures,  $D_o$  and  $E_d/R$  can be evaluated. Values at other temperatures can then be calculated:

$$D_{\text{eff}}(T) = D_{\text{eff}}(T_1) \exp\left(\left(\frac{E_d}{R}\right)\left(\frac{1}{T_1} - \frac{1}{T}\right)\right). \quad (16)$$

In this way, measurements of gas permeability at elevated temperatures are extrapolated to room temperature. If the cell gas composition is predicted, the thermal conductivity of the gas can be calculated.

With the diffusion coefficient for each gas species determined, Equation 9 can then be solved to find the distribution of the partial pressures throughout the sample for any given time. The gas composition can be related to the thermal conductivity of the mixture using the Wassiljewa equation, with the coefficients found from the Linsey-Bromley correlations (Reitz et al. 1984; Reid et al. 1977).

The effective thermal conductivity of the foam is the sum of the gas conduction, solid conduction, and radiation. Changes in the effective conductivity with time are solely due to the changes in the gas conductivity.

This method requires a two-step procedure to predict the aging—measurement of the diffusion coefficients followed by computation of the aging prediction. The use of thin samples at elevated temperatures makes this the most rapid procedure to determine foam aging. Once the diffusion coefficients are measured versus temperature, the results can be used to predict the aging of a foam of any thickness and experiencing any arbitrary temperature exposure. The computational procedure can also deal with two-dimensional diffusion, e.g., edge diffusion, as well as samples with a density gradient from the surface to the centerline.

The diffusion coefficients must be remeasured when the foam chemistry is changed or when changing blowing conditions yield a different fraction of material in the cell wall (see Equation 7). The numerical computer procedure to calculate foam aging has been written (Ostrogorsky 1985) and is available to other researchers.

## RESULTS

Results of the technique using elevated temperature aging of thin samples will be compared to measured aging of full-thickness samples. Comparisons will be made for results reported by Baumann (1982), Wiedermann (1988), and Szabat and Baumann (1989). For the first two comparisons, effective diffusion coefficients were based on measurements made on thin specimens of representative foam samples, not samples taken directly from the full-thickness samples. In the comparison with the data of Szabat and Baumann, thin specimens were taken from the full-thickness boardstock for which aging data were obtained.

For the comparisons to the data of Wiedermann and Szabat and Baumann, the initial effective conductivity of the samples was calculated. The solid polymer and radiative thermal conductivity were calculated based on measured average foam properties using the equations developed by Schuetz (1982). The expression for the solid polymer contribution to the thermal conductivity is

$$k_s = \left[ \frac{2}{3} - \frac{(100 - P_{cw})}{300} \right] (1 - \delta) k_{sp}, \quad (17)$$

where

$k_{sp}$  = thermal conductivity of the solid polymer,

$\delta$  = foam void fraction, and

$P_{cw}$  = percent of solid polymer in the cell walls.

The expression for the radiative component, taken from Glicksman and Torpey (1987), is

$$k_R = \frac{16}{3} \frac{d}{3.68} \left( \frac{\sigma T^3}{\rho_f} \right)^{\frac{1}{2}} \quad (18)$$

where

$\sigma$  = Stefan-Boltzmann constant,  
 $d$  = diameter of the foam cell,  
 $\rho_{sp}$  = density of the solid polymer, and  
 $\rho_f$  = foam density.

In the simulations presented in this work, a  $k_{sp}$  of 0.27 W/m·K and a  $\rho_{sp}$  of 74 lb/ft<sup>3</sup> will be assumed.

### Foam Geometry: Fraction of Solid Polymer in Cell Wall

The product of the foam density and the percent of solid polymer in the cell walls characterize the aspect of foam structure that affects foam aging.

The fraction of material in the cell walls is defined as

$$f_w = \frac{S_v t_{cw}}{(1-\delta)}, \quad (19)$$

where

$S_v$  = surface-to-volume ratio of the foam cells,  
 $t_{cw}$  = thickness of the cell wall,  
 $\delta$  = foam void fraction.

The greater the percentage of material in the cell walls, the greater the resistance to mass transfer. The percentage of material in the cell wall,  $P_{cw}$ , is simply  $100 f_w$ .

### AGING PREDICTION

The aging model developed by Ostrogorsky (1985) was originally verified by comparing predictions of thermal aging with long-term thermal conductivity measurements. The bases for the aging model are measurements of gas permeability in the foam, foam density, cell size, and cell wall thickness. Ostrogorsky's predictions were based on steady-state measurements of foam permeability to air gases and R-11. The measurements were made at elevated temperatures and extrapolated to the temperature of the long-term aging. In this comparison of aging at 24°C, reproduced in Figure 2, predicted and measured values agree to within 6%.

### Igloo

A very thick foam structure was fabricated with R-11 blown foam in 1961; it is referred to as *igloo*. It has shown unusually high  $k$ -factor retention. To determine if the aging characteristics are due to the structure of the foam or are due to unusual polymer chemistry, the natural aging of this foam is compared to theoretically predicted values from the computer simulation.

The 7.25-cm-thick igloo was constructed by spraying foam in layers over a cardboard-like form. A cross section of the foam is composed of alternating layers of foam separated by a film of solid polymer (see Figure 3).

In the aging model, the igloo foam was treated as a homogeneous material. Measurements of cell wall thickness and average distance between cell walls were used in the calculation of percent of material in the cell walls to represent an approximation of the foam's average properties. The sample has a high average density. The permeability of the igloo material was not measured directly. Instead, the permeability of the solid polymer, measured by Ostrogorsky, was used with Equation 7 to calculate the effective permeability of the igloo foam. Measured and calculated values are listed with properties of Ostrogorsky's foam in Table 4.

In 1988, Wiedermann measured the thermal conductivity and cell gas pressure 1.5 cm from the foam face of the igloo. Figures 4 and 5 compare the simulation with these measurements. The simulation and measurement results are also listed in Table 5. The simulation assumes 0.6 bar R-11 as the initial cell gas pressure, 15°C average temperature seen by the igloo over its history, and solid polymer diffusivity the same as the foam measured by Ostrogorsky.

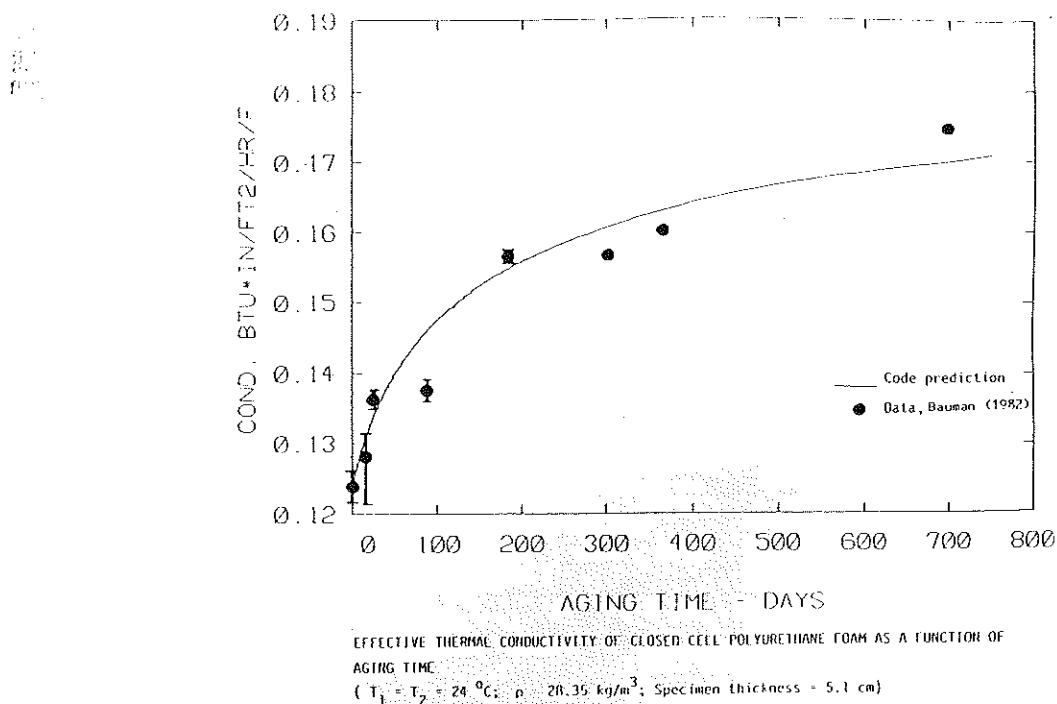
It is the first time that naturally aged foams this old have been compared to the aging model. Results indicate that the slow aging of the igloo can be attributed to the density and structure of the foam rather than to lower polymer permeability.

### Foam Blown with R-141b

A sample of laminated board stock of an R-141b blown MR-Terate 203-Multranol 9171 PIR was supplied by Szabat and Baumann. Results from transient sorption measurements of the diffusion coefficient of air components and refrigerants in this foam are presented in a previous paper (Page and Glicksman 1990).

The thermal conductivity of this foam was measured over time in two unfaced foam board samples by Szabat and Baumann (1989). One of these boards was aged at room temperature, the other at 70°C. The results of the measurements and the predicted aging based on diffusion coefficient measurements at 25°C are plotted in Figure 6.

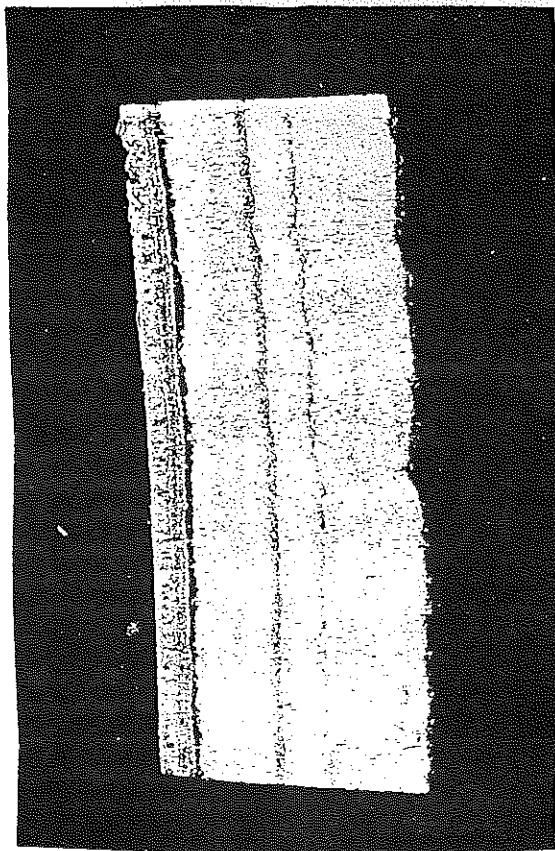
The measured results by Szabat and Baumann at 70°C indicate that the time to reach a given effective conductivity is approximately one-half the time to reach the same conductivity for the 25°C case. This disagrees with all of the data we have obtained for diffusion coefficients of the air components and the blowing agent. For example, based on our measurements of the nitrogen diffusion coefficient for this foam, the time should decrease by a factor of more than 3.5 when the temperature is increased from 25°C to 70°C. This is inconsistent with measurements we have made for all other foams. The modest increase seen by



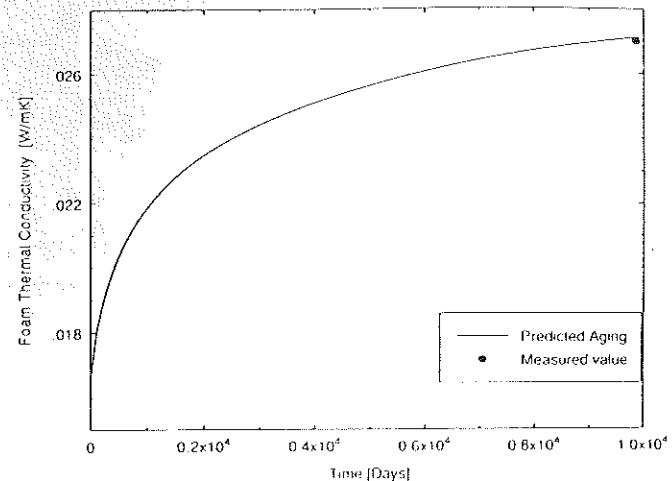
**Figure 2** Prediction of thermal conductivity vs. time compared to thermal conductivity measurement of naturally aged foam at 24°C.

Szabat and Baumann at 70°C is inconsistent with our findings.

Measurements were made simultaneously of the air diffusion coefficients for a sample of an R-11-blown foam under test at a national laboratory. The physical properties of the foam are shown in Table 4. Figure 7 shows a comparison of the predicted conductivity versus time using the aging model. The conductivity value is adjusted by changing the sum of solid conduction plus radiation so that the theory and data agree at small times. The experimental



**Figure 3** Cross section of the igloo.



**Figure 4** Prediction of igloo thermal conductivity vs. time compared to thermal conductivity measurement of igloo naturally aged at 15°C.

**TABLE 4**  
**Characteristics of Foams**  
**Joint Government-Industry Research Project, Bayer Igloo and Ostrogorsky**

Sample	21	Igloo	Szabat	A*
Isocyanate	MDI	—	MR	MDI
Polyol Base	†	—	T	—
Blowing Agent	R-11	R-11	R-141b	R-11
$\rho_f$ [lb/ft <sup>3</sup> ]	1.92	4.93	1.76	1.77
$\delta$	0.977	0.936	0.981	0.979
$\langle \ell \rangle$ [mm]	 ⊥	0.24 0.16	— 0.15	0.235 0.226 — 0.34
$t_{cw}$ [ $\mu\text{m}$ ]	0.3	0.55	0.84	0.37
$P_{cw}$ [%]	17	12	39.1	10

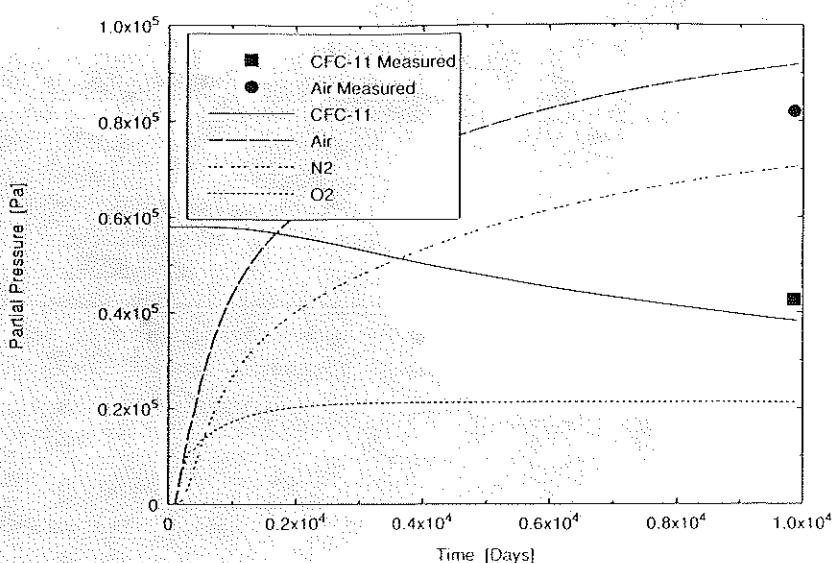
\*Foam measured by Ostrogorsky (1985).

† Polymer chemistry from joint government-industry research project (Blanpied and Knis 1990).

‡ R-123/R-141b blends.

— = Perpendicular facer.

|| = Parallel facer.



*Figure 5. Prediction of partial pressure vs. time at node 1.5 cm under surface of foam.*

results (McElroy et al. 1991) for several different thicknesses plotted versus a modified Fourier number agree closely with the model. The theory predicts that each thickness will give identical values when plotted in this fashion.

#### Diffusion Barriers

All of the aging predictions presented so far have all of the foam surfaces exposed to the atmosphere. This is the proper condition for most foam boards today, even those

with facings. Present products generally have inadequate adhesion between the facing material and the foam. Even if the facing is impermeable, the gases can easily move in a lateral direction under the interface from the edge to the center of the boards (Ostrogorsky and Glicksman 1987).

If a board could be reliably made with an impermeable barrier tightly attached to both the upper and lower faces, aging would be confined to diffusion from the exposed edges of the panel, substantially reducing the rate of aging. Figure 8 illustrates the predicted behavior of such a board blown solely with carbon dioxide. The time-averaged

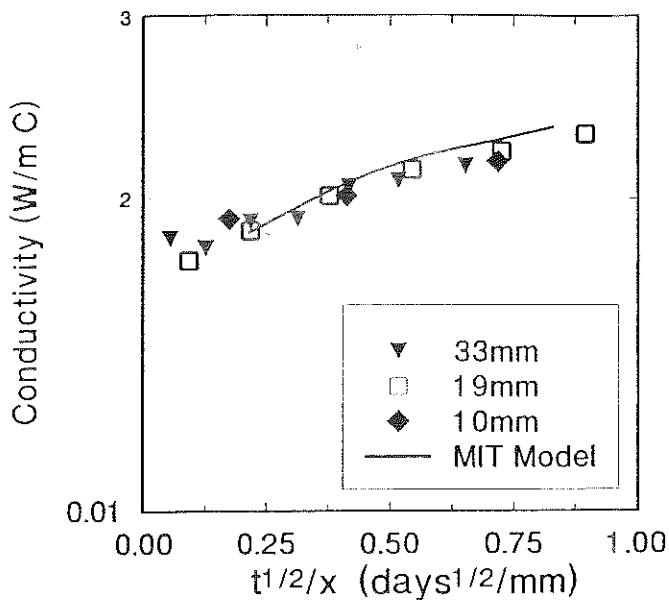
**TABLE 5**  
**Igloo Aging Prediction and Measured Values**  
**after 27 Years at 15°C**

Conductivity [W/m · K]	Simulation Prediction	Measurements (Wiedermann 1988)
$k_S$	0.0062	—
$k_R$	0.0023	—
$k_{foam}$	0.0271	0.027
<b>Cell Gas Partial Pressure* [kPa]</b>		
R-11	39	42.7
Air	91	82

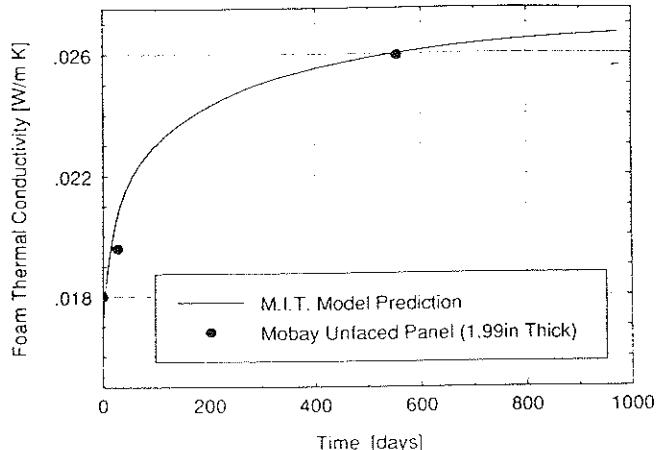
\* 1.5 cm from surface.

conductivity for the entire board is compared to the results for an R-11-blown board with poor barrier adhesion, e.g., identical to bare surfaces. For a 2.5 cm (1 in.) thick board that is 61 cm (2 ft) wide, the aging behavior of the carbon dioxide-blown insulation is almost identical to the R-11-blown insulation! For wider panels, the carbon dioxide-blown panel with ideal barriers is superior to a present-day R-11-blown panel.

There is a clear need to develop better barrier-to-foam adhesion systems. This will be facilitated by the development of a reliable and rapid quantitative technique to measure the resistance to lateral diffusion at the foam-facer interface. Such a technique will permit confident development of a barrier adhesion system without long-term tests of each concept.



**Figure 7** Aging of R-11 foam with different thickness, data vs. prediction.



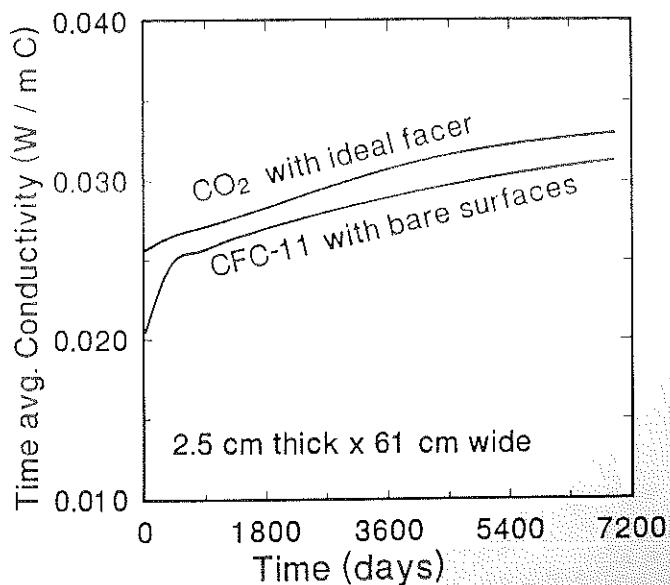
**Figure 6** Foam 18 aging at 25°C. Predicted and measured thermal conductivity vs. time.

## CONCLUSIONS

There are three general accelerated techniques to determine the long-term aging of foams. Aging of full-width samples at elevated temperatures allows a quantitative ranking of various foams.

Aging thin samples at room temperature allows for measurement of air diffusion effects in a reasonable time. Substantial blowing agent diffusion will require lengthy times—at least half a year—to accurately extrapolate to longer times.

Measurement of the diffusion coefficient of individual gas species at elevated temperatures with thin samples will give the most rapid tests for determining aging effects of air and blowing agents. The measured diffusion coefficients are



**Figure 8** Time-averaged thermal conductivity. Carbon dioxide blown foam with ideal impermeable barriers on both faces vs. R-11 foam without barriers.

then used in a computer model to predict the effective conductivity versus the age of full-width foams. Comparisons of the computer model with several different test results give generally good agreement.

If impermeable barriers are applied with good adhesion to foam boards so that lateral gas flow at the interface is eliminated, the time-averaged conductivity of the board will be substantially reduced. Alternatively, a foam blown with a higher conductivity gas such as carbon dioxide, while maintaining good diffusion barriers, will give performance equivalent to or better than a present-day board blown with R-11. Research is needed to develop a test technique to quantify the degree of lateral diffusion at the interface.

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## NOMENCLATURE

$C$	= concentration
$D$	= diffusion coefficient
$E$	= activation energy
$F_w$	= fraction of solid in cell wall
$F_o$	= Fourier modulus
$J$	= mass flux
$k$	= conductivity
$\ell$	= mean distance between cell walls
$L$	= foam thickness
$p$	= pressure
$P$	= permeability
$P_{cw}$	= percentage of solid in cell wall
$R$	= gas constant
$S$	= solubility
$T$	= temperature
$t$	= time
$x$	= coordinate

## Greek

$\rho$	= density
$\sigma$	= Stefan-Boltzmann constant
$\epsilon$	= geometry factor
$\tau$	= dimensionless time

## Subscripts and Superscripts

$f$	= foam
$eff$	= effective

$sp$	= solid polymer
$( )$	= dimensionless

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