

# USE OF THE DISTRIBUTED PARAMETER CONTINUUM (DIPAC) MODEL FOR ESTIMATING THE LONG-TERM THERMAL PERFORMANCE OF INSULATING FOAMS

Mark T. Bomberg  
Member ASHRAE

Mavinkal K. Kumaran

---

## ABSTRACT

*An integrated methodology for evaluation of long-term thermal performance of cellular plastics includes measurements of thermal resistivity of thin layers as a function of time. Then, two equivalent procedures may be used to predict aging of full-thickness insulation boards. If the foam is unfaced and sufficiently homogenous, a simple arithmetic operation, known as the scaling technique, can be used to calculate foam aging for layers of different thickness. When the cell structure of skin and core layers is significantly different or the foam is provided with facers, then the scaling technique is not appropriate and an extrapolative model of aging must be used.*

*Such an extrapolative model, called the distributed parameter continuum (DIPAC) model, is the subject of this paper. The basic material characteristics needed as the input for the model, such as cell gas concentration, oxygen and*

*nitrogen diffusivity, blowing agent solubility, and extinction coefficient, are determined either directly or indirectly from measurements of the changes in thermal resistance of the thin surface and core layers.*

*To check the DIPAC model predictions, roofing insulations such as polyisocyanurate, extruded polystyrene, phenolics, and modified resol foams were exposed on a test roof. Thermal properties of these insulation boards have been monitored under field conditions for a period of 2.5 years. Furthermore, some specimens of tested foams were periodically removed from the roof and measured under laboratory conditions.*

*The results indicate that the DIPAC model can become an important tool for evaluating long-term thermal performance (LTTP) of cellular plastics.*

---

## INTRODUCTION

To evaluate long-term thermal performance of cellular plastics, the aging process must be accelerated. Acceleration can be achieved either by exposure to elevated temperature or by use of thin layers of the foam. The first approach changes the permeability and solubility coefficients of different gases to such a degree that foam performance measured under elevated temperature may be difficult to correlate with the field performance of the material. Hence, only the thin layer approach is used in the work reported here.

Depending on foam uniformity, the aging of thin layers is related to the aging of full boards either by means of the scaling technique or by using a model of aging. When unfaced foam is homogenous enough to permit a simple arithmetic operation known as the scaling technique, the technique can be used to calculate foam aging for layers of different thickness. When, however, the cell structure of skin and core layers is significantly different or the foam is provided with facers, then the scaling

technique is not appropriate and models of aging (models of heat and mass transfer) must be used.

The objective of this paper is to verify model predictions for different types of roofing insulations. Outside test structures were constructed at a site in Ottawa and specimens of different foam products were exposed to the environment for almost three years. During the exposure period, specimens were periodically removed to measure their thermal resistance under laboratory conditions. Furthermore, a number of specimens had thermal resistance continuously monitored under field conditions, and replicate samples of products used in the roof and wall exposures were also evaluated in the laboratory.

This research included improvement of a previously developed model of aging (Bomberg 1988). Some changes provided a choice of using different equations for dealing with a given variable, e.g., thermal conductivity of cell gas. Other changes involved adding new considerations, for example, introduction of Flory-Huggins theory to calculate the activity coefficient and the resultant solubility

---

Mark T. Bomberg and Mavinkal K. Kumaran are senior research officers at the Institute for Research in Construction, National Research Council of Canada, Ottawa, ON.

of a blowing agent in the polymer. In effect, a more complete model, denoted here as the distributed parameter continuum (DIPAC) model, has emerged. Since the DIPAC model uses experimental data obtained on slices aged under controlled laboratory conditions to develop a prediction of performance under the service conditions for a full foam board, we call it an extrapolative model. This paper applies the DIPAC model to predict aging of different foams and compares the results of calculations with measured data.

## MATERIALS AND PROCEDURES USED FOR THERMAL TESTING

The work involved eight types of either experimental or commercial foams tested under both field and laboratory conditions. The foams were four extruded polystyrene (XPS) foams, coded as C, D, F, and G products; one polyisocyanurate (PIR) foam, coded as the O<sub>2</sub> product; one phenolic (PhR) foam, coded as the B product; and one modified resol foam (PhR), coded as the L product. These seven foam products were delivered to the test site by their manufacturers. The last foam, a PIR product, was taken from a warehouse. The PIR product had been extensively tested in the laboratory (Bomberg 1988) and on a built-up roof (Muhlenkamp and Johnson 1983).

Measurements of thermal resistance were performed on specimens either stored in the laboratory or built into the roof of an exposure box. In the latter case, they were exposed to weather conditions on one side and constant internal conditions on the other side (Bomberg and Kumaran 1994). The roof exposures used in this investigation include a conventional roof (CR) and a protected membrane roof (PMR). Both exposures utilized a single-ply black EPDM membrane.

Specimens of different foam products, either those placed in the conventional roof, the protected membrane roof, or the laboratory, were periodically removed from their respective locations and tested for thermal resistance using ASTM test method C 518. Thermal resistance measurements used for validation of the aging model were performed on large specimens; those used for generating material characteristics were performed on partly encapsulated slices and smaller specimens. Two pieces of laboratory equipment were used—a standard 600-mm-size heat flowmeter (HFM) apparatus and a four-station HFM, which permits simultaneous but separate testing of four 300-mm by 300-mm slices.

Both the laboratory measurements and model predictions were compared with the thermal resistance measured in situ. The tested specimens were positioned precisely on top of 25-mm-thick, high-density glass fiber, 600-mm by 600-mm reference, previously tested in an HFM apparatus and provided with surface

thermocouples. The output from these thermocouples was evaluated using a new test method developed for testing transient thermal performance of insulations (see below).

## THE DIPAC MODEL OF AGING

The objective of the DIPAC model is to calculate, as a function of time, the heat flux through a foam slab exposed to a specific temperature difference. The slab is treated as if it were made up of a number of layers that are subject to calculations performed in a sequence of time steps.

The most important simplifying assumptions made in development of the model are:

1. Material properties and boundary conditions remain unchanged during each time step.
2. Material properties used in a time step are those calculated in previous time step.
3. There is no coupling between heat and mass transfer phenomena except for the correction introduced by the approximate treatment of condensation and evaporation of the blowing agent (BA) (Bomberg 1988).

For each time and space step, six separate transfer equations are solved to determine the composition of the cell gas. As the cell gas composition changes, so does the thermal conductivity of the cell gas. Adding other components of heat transfer (solid-phase conduction, radiation, interaction between solid-phase conduction and radiation), which are assumed to be time independent, the heat flux in each layer of the foam may be calculated.

To this end, the model calculates for each time step and each layer:

1. temperature;
2. partial pressure of oxygen, nitrogen, carbon dioxide, and one or two BAs;
3. saturation partial pressure of each BA;
4. condensation or evaporation of each BA that occurs to maintain equilibrium with its pressure;
5. heat flux caused by the BA change of phase;
6. equilibrium solubility of BA as a function of partial pressure, temperature, and period of aging;
7. transfer between dissolved and gaseous fraction of BA to maintain solubility equilibrium; and
8. thermal conductivity of cell gas mixture.

Thus, except for the addition of items 6 and 7, the other elements of model formulation and solving procedures remain similar to those described in the earlier work (Bomberg 1988). The solubility function was introduced as a source/sink term to the one-dimensional mass conservation equations to bring it to the following form:

$$S_1 \frac{(P_i^{n+1} - P_i^n)}{\Delta t} = \frac{Pe_i^n [0.5 (P_{i-1}^{n+1} - 2P_i^{n+1} + P_{i+1}^{n+1})]}{(\Delta x)^2} + \frac{Pe_i^n [0.5 (P_{i-1}^n - 2P_i^n + P_{i+1}^n)]}{(\Delta x)^2} + m_o \quad (1)$$

where  $P$  is the partial pressure of a gas in the slab, Pa;  $S_1$  is the specific gas storage, kg/(m<sup>3</sup>·Pa); and  $Pe$  is the gas permeability coefficient, kg/(s·m·Pa). The gas permeability coefficient may vary depending on location in the cross section, i.e., may vary with the coordinate  $x$ . Finally,  $m_o$  is the sink-source term for this gas, calculated for a unit of volume of the foam, kg/(m<sup>3</sup>·s). Equation 1 gives the gas partial pressure at each node at time step ( $n + 1$ ), using the values of material characteristics ( $Pe$ ,  $S_1$ , and  $m_o$ ) from the previous time step, i.e., at time step  $n$ .

Finally, to reduce the time of calculations for daily variations of temperature, there is a choice in equation-solving procedures. In addition to matrix inversion, a Thompson's algorithm for tridiagonal matrix solution (Pantakar 1980) can be selected.

### INPUT: MATERIAL CHARACTERISTICS AND INITIAL AND BOUNDARY CONDITIONS

This section reviews only those techniques for determination of material characteristics that are new or different from those described in an earlier paper (Bomberg 1988).

### Density Distribution in the Cross Section

Four 5- to 10-mm thick, 300-mm by 300-mm square specimens are cut from each surface and from the core of the foam. These specimens are mainly used for thermal resistance testing; however, as densities of test specimens are determined as auxiliary information, the density distribution across the slab thickness is also derived by interpolating the data from four specimens cut from these three locations.

### Specific Mass Extinction Coefficient for IR Radiation

The radiative component of heat transfer is defined by the following equation:

$$k_r = 16\sigma T^3(1 - \exp(-Kx)) / (3K\rho) \quad (2)$$

where  $\sigma$  is the Stefan-Boltzmann constant,  $T$  is the absolute temperature,  $K$  is the mass extinction coefficient,  $x$  is the distance from the material surface, and  $\rho$  is the specimen density.

Equation 2 describes the radiative component of thermal conductivity as a function of specimen thickness. Note that for optically thick specimens (large value of  $x$ ), Equation 2 gives an average radiative contribution

as defined by the Rosseland's approximation (Bomberg 1988; Ostrogorsky and Glicksman 1986).

### Effective Diffusion Coefficient of Nitrogen and Oxygen

Measurements of the diffusion coefficients of nitrogen and oxygen were performed with a constant-volume sorption apparatus that is described in Schwartz et al. (1989) and Brehm and Glicksman (1989). For nitrogen, being the dominant gas in the air, the diffusion coefficient is always determined for the surface and core layers. The oxygen diffusion coefficient is determined only for the core layer. The same ratio is then used to assign the distribution of oxygen diffusion coefficient across the different layers of the board (Ostrogorsky and Glicksman 1986; Schwartz et al. 1989).

The temperature dependence for the diffusion coefficients is needed for the model calculations. The diffusion coefficients are, however, measured at room temperature. Generally, for a given foam, the temperature dependence of the diffusion coefficient for nitrogen and oxygen are similar and can be estimated from data in the literature (Ostrogorsky and Glicksman 1986; Schwartz et al. 1989; Destephen 1993).

### Effective Diffusion Coefficient of Blowing Agent

The effective diffusion coefficient for the blowing agent is calculated using the DIPAC model by matching the model results to the measured changes in thermal resistance over the aging period. This technique can be applied to foams manufactured with one captive blowing agent and permits the establishment of the BA diffusion coefficients for both core and surface layers (see Figure 1). Because all input data for the DIPAC model must be known (or assumed), it usually involves a few iterations to estimate the diffusion coefficients. These iterations start from the time of manufacture to correctly represent the storage and transfer processes undergone by the BA, nitrogen, and oxygen. The temperature

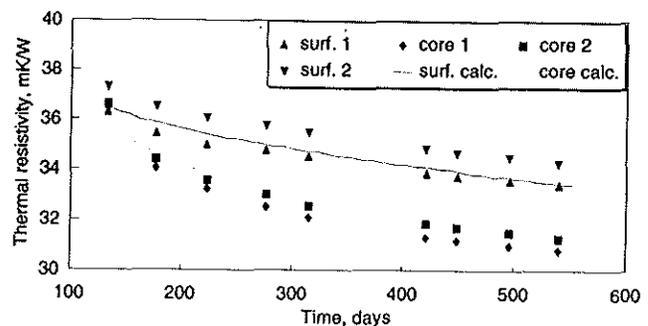


Figure 1 Aging curves (thermal resistivity vs. aging period) for 7-mm-thick layers cut after about 140 days of aging from the core and surfaces of XPS product D.

dependence of the BA diffusion coefficient is estimated from data reported by earlier workers (Ostrogorsky and Glicksman 1986).

In the example shown in Figure 1, the BA diffusion coefficients for the surfaces and core are determined as follows. The slices were cut after 140 days of full-board aging. Hence, the initial BA concentration distribution in the full board had to be calculated. Using an initial guess of the BA diffusion coefficients for both the surface and core layers as input to the DIPAC model, a distribution of BA pressure was estimated after a 140-day period of full board aging. From this distribution, the BA pressure in each of the surface and core layers was extracted. Then the DIPAC model was used to calculate the aging curve for each of these layers and compare them with those already experimentally determined. These calculations were repeated until the agreement between calculated and measured aging curves for each of the layers was satisfactory. With other input data independently determined, the close agreement between measured and calculated aging curves, as shown in Figure 1, implies a correct estimate of the BA diffusion coefficient.

### Solid-Phase Conduction with Image Analysis Characterization of Cells

The DIPAC model permits use of either the cube model (Schuetz and Glicksman 1983) or the serial-parallel model with input from image analysis (IA) to calculate solid conduction. The latter model recognizes three parallel heat-flow mechanisms: conduction through cell gas, conduction through the continuous polymer, and contribution from mass transfer (latent heat transfer). To use the serial-parallel model of heat transfer through the polymeric matrix, a thinning routine (Schwartz and Bomberg 1989) is used to divide the polymer matrix into the continuous and the discontinuous parts.

### BA Solubility as a Function of Time and Temperature

Since the amount of blowing agent dissolved in the polymer matrix appears to change over long exposure periods (Bomberg et al. 1990), it may be convenient to divide the BA solubility into two components—one describing the contribution of the void space, the other that in the polymeric matrix. The first component of solubility is defined, for a unit volume, as the partial derivative of mass,  $m$ , with respect to gas pressure. For an ideal gas (Schuetz and Glicksman 1983), it becomes  $S_1 = 1/(R_m T)$ .

Equation 1 introduced a sink/source term related to a specific gas storage in the polymer matrix (the second component of solubility),  $m_o$ , which traditionally has been assumed negligible (Ostrogorsky and Glicksman 1986). This sink/source term denotes the gas that may either be absorbed by the polymer surface or may

penetrate into the polymer matrix. To describe how the temperature and pressure of BA affect its solubility, the Flory-Huggins equation (Flory 1953) was used. This equation, here Equation 3, generally is accepted for correlation of blowing agent solubility data and is used to generalize the interaction between the solute (BA) and the solvent (polymer) over a wide range of temperature and pressure conditions from a few measured values (Gorski et al. 1986),

$$\ln(a_i) = \ln(\phi_1) + (1 - \phi_1) + \chi(1 - \phi_1)^2 \quad (3)$$

where  $a_i$  is the activity coefficient,  $\phi_1$  is the volume fraction of the solvent, and  $\chi$  is the Flory-Huggins interaction parameter.

There was, however, another parameter introduced in conjunction with Equation 3. This parameter, called the polymer index,  $p_{ind}$ , is used to modify the relation between the polymer mass and the solubility process. Such a modification can be caused by the presence of crystalline segments that may reduce the fraction of amorphous polymer dissolving the blowing agent or by the presence of electro-osmotic forces on the polymer surface that would increase the surface absorption of the gaseous BA. For an amorphous polymer, e.g., polystyrene and blowing agent with a normal boiling point close to room temperature, the polymer index is equal to one. For a polymer with a significant fraction of highly organized segments, e.g., polyurethane, it is less than one. Nevertheless, being an empirical quantity, for some blowing agents the polymer index was found to be higher than one, even for an amorphous polymer.

Having estimated the equilibrium BA solubility in the polymer matrix, one more parameter,  $\xi$ , is needed to relate the rate of BA entry into the polymeric matrix to elapsed time,  $t$ . Based on the work by Destephen (1993), it is defined as

$$\xi = C \exp((t_{max} - t)/t_{max}) \quad (4)$$

where  $C$  is an experimentally determined constant.

In effect, the sink/source term,  $m_o$ , is calculated as a product of the equilibrium solubility,  $S$ , and the change in the  $\xi$ -parameter during the actual time step,  $\Delta\xi$ :

$$m_o = \Delta\xi \cdot S. \quad (5)$$

The sink/source term defined by Equation 5 becomes zero when aging time reaches the value of  $t_{max}$ .

### BA Concentration

The measurements of the BA concentration in the cell gas were performed by a manufacturer. The foam was crushed under a solvent environment and gas chromatography was applied (Ascough 1989).

**TABLE 1 Characteristics of XPS Product D Used in the DIPAC Model Calculations (Bomberg and Kumaran 1995)**

Material Characteristics	Surface	Core	Surface	Comments
Density, kg/m <sup>3</sup>	27.5	28.7	27.5	10-mm slices
$D_{eff}$ BA, m <sup>2</sup> /s	0.50E-12	0.15E-11	0.50E-11	see above
$D_{eff}$ N <sub>2</sub> , m <sup>2</sup> /s	0.11E-09	0.60E-09	0.11E-09	measured
Extinction coeff., kg/m <sup>2</sup>	47	47	47	measured
Initial fraction BA	0.76	0.79	0.76	measured
Solubility period, days	80	80	80	estimated
Polymer Index (solubility)	1.0	1.0	1.0	estimated
Interaction coefficient	0.8	0.8	0.8	measured
IA parameters: $A_n, A_r, F_1$	***	1.43; 1.34; 0.20	***	measured
O <sub>2</sub> , $D_{eff}$ at 297 K	***	0.60E-09	***	measured
N <sub>2</sub> , $D_{eff}$ at 297 K	***	0.11E-09	***	measured
BA, $D_{eff}$ at 297 K	***	0.15E-11	***	calculated
O <sub>2</sub> , $D_{eff}$ at 323 K	***	0.30E-08	***	estimated
N <sub>2</sub> , $D_{eff}$ at 323 K	***	0.55E-09	***	estimated
BA, $D_{eff}$ at 323 K	***	0.15E-10	***	estimated

### An Example of Input Data for the DIPAC Model

Table 1 indicates whether the material characteristics were measured on the actual foam or were estimated from the literature.

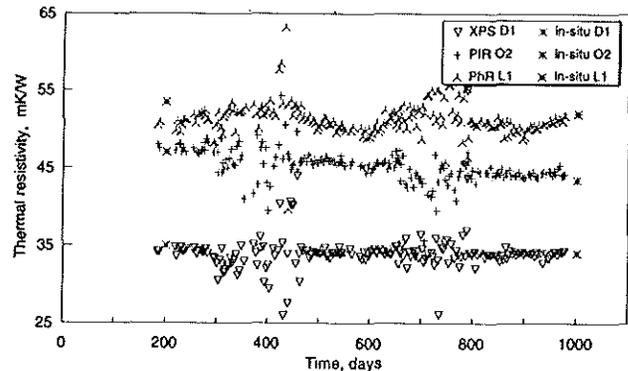
### A METHOD TO MEASURE THERMAL RESISTANCE IN SITU

A number of factors affect the performance of thermal insulating materials under field conditions that cannot be easily predicted or tested in the laboratory. Since it is difficult to predict how much foam insulation is affected by daily and seasonal temperature variations, particularly when these processes affect aging and weathering of the foam, thermal resistance was also measured in situ, while the foam was exposed to actual weather effects.

A method developed for in situ testing, called the "heat flow comparator (HFC) method," is presented in Bomberg et al. (1994a). Thermocouples were placed on each surface of the reference and test specimens to measure temperatures that then were used as the boundary conditions in the heat flow calculations. Both specimens are treated as homogeneous, and their thermal properties (thermal conductivity and specific heat) are assumed to be linear functions of temperature. Use of Kirchoff's potential function as postulated by Kirchoff in 1894 (Stephenson 1992) instead of thermal conductivity linearizes the equation system for the range of temperature in which the linear relation of thermal conductivity on temperature holds.

The heat flux across the boundary surface between the reference and the tested specimen is calculated using a numerical algorithm to solve the heat transfer equation through the reference specimen. By imposing the requirement of heat flux continuity at the contact boundary between test and reference specimens, corresponding

values of thermal conductivity and heat capacity of the tested specimen are found with an iterative technique. The HFC computer code calculates heat flux at the interface and finds a match within sensitivity and truncation errors of the numerical method. Even though thermal properties of the test specimen are initially guessed, the process of simultaneous optimization of a few hundred data points (one test series lasts over a period of a few days) results in the most probable set of material properties. The overall uncertainty of the field measurements was estimated to vary between 4% and 7%, of which 3.5% was attributed to the uncertainty in properties of the reference specimens (Bomberg et al. 1994a).



**Figure 2** Thermal resistivity of XPS product D<sub>1</sub>, PIR product O<sub>2</sub>, and modified resol product L<sub>1</sub> measured in situ and adjusted to the laboratory test conditions.

Figure 2 shows results of thermal resistivity calculations performed with the HFC computer code, which are adjusted to 24°C for the sake of comparison.

Despite scatter in the results, one may see an overall aging trend in Figure 2. This trend will be described with linear approximation as a change between 200 and 1,000 days of aging. Extruded polystyrene product D<sub>1</sub> ages slowly, reducing its thermal resistivity from about 35 m·K/W at 200 days to about 34 m·K/W at 1,000 days. PIR product O<sub>2</sub> shows a slightly higher rate of aging, namely, the thermal resistivity is reduced from 47 m·K/W at 200 days to about 43.5 m·K/W at 1,000 days. Modified resol foam, product L<sub>1</sub>, shows aging from about 53.5 m·K/W at 200 days to about 52 m·K/W at 1,000 days. A similar plot (not shown here) for phenolic foam product B indicates reduction of thermal resistivity from about 53.5 m·K/W at 200 days to about 50.5 m·K/W at 1,000 days.

## COMPARISON OF MEASURED AND CALCULATED THERMAL RESISTANCE

Using material characteristics established with techniques discussed above as input to the DIPAC model, one may "predict" aging of full boards and compare them with data measured on boards exposed to various environmental conditions. (All material characteristics used in DIPAC calculations reported in this paper can be found in an NRC report [Bomberg and Kumaran 1995]). To establish long-term thermal performance of a foam product, one must determine a statistically valid initial thermal resistance. In the work reported here, three randomly selected specimens from three production batches of each tested material (a total of nine specimens) were normally used for this purpose.

### Thermal Resistance of Extruded Polystyrene as a Function of Time

An XPS product, "C," was exposed on a conventional roof and in the laboratory and intermittently tested at standard test conditions (mean temperature of 24°C and temperature difference about 22°C). To examine if the tested specimen represents the average product performance, the initial thermal resistivity was measured on nine specimens, selected from three different batches as mentioned above. The mean value of thermal resistivity was 38.1 m·K/W, with a standard deviation of 0.12 m·K/W. Thus, the aging curve shown in Figure 3 may be considered as representative of product C.

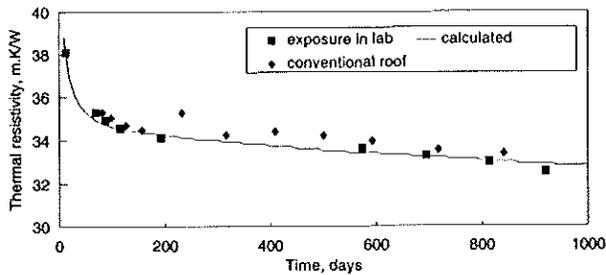


Figure 3 Measured and calculated from the DIPAC model, aging curves for full-thickness XPS product C.

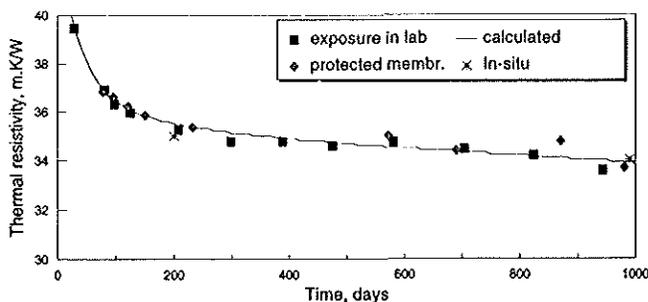


Figure 4 Measured and calculated from the DIPAC model, aging of boards of the XPS product D.

Figures 3 and 4 show aging of extruded polystyrene (XPS) products C and D, indicating that differences between foam exposed on the roof and stored in the laboratory are small. (Product D is characterized by the initial thermal resistivity of 39.2 m·K/W determined on nine tests, with the standard deviation of 0.32 m·K/W.) The agreement between thermal resistivity calculated from the DIPAC model and the values measured in the laboratory and in situ is excellent.

Figure 5 shows aging of extruded polystyrene (XPS) product F, exposed on a protected membrane roof (PMR) and in the laboratory. These tests were initiated within a few days after manufacture. The mean thermal resistivity for this product was 44.4 m·K/W. The standard deviation was 1.12 m·K/W. (The standard deviation was larger because during the period of initial tests, the R-value changed about 5%.) There is also a good agreement of tests and the DIPAC model prediction.

The XPS product G differed from the above three because it used two blowing agents. Hence the model calculations were more complex. One must have independent information on at least one of the BA diffusion coefficients. In this case, one of the diffusion coefficients was estimated from aging of the same product manufactured with a single blowing agent. Then the procedure described above was used to estimate the other diffusion coefficient.

Furthermore, DIPAC calculations performed for thin-slice aging showed that the measured initial concentrations of the two blowing agents were erroneous. Fortunately, correct information on an identical but thinner XPS product was available, and this information was substituted in the model calculations for product G. The results are shown in Figure 6.

Figure 6 shows aging of the XPS product G, exposed on a conventional roof and in the laboratory and intermittently tested at standard test conditions. The initial thermal resistivity of 45.0 m·K/W was determined, with a standard deviation of 0.51 m·K/W. Even if the agreement between measured and predicted data is not as good as in the three previous cases, it still may be considered as satisfactory.

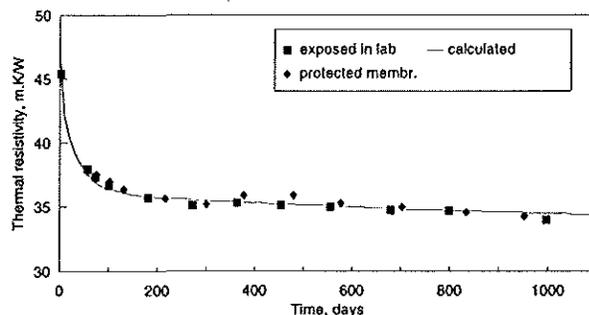
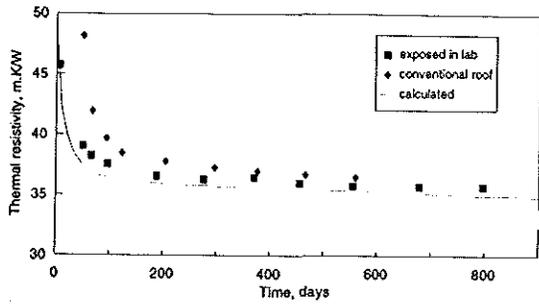


Figure 5 Measured and calculated from the DIPAC model, aging curves for full-thickness XPS product F.

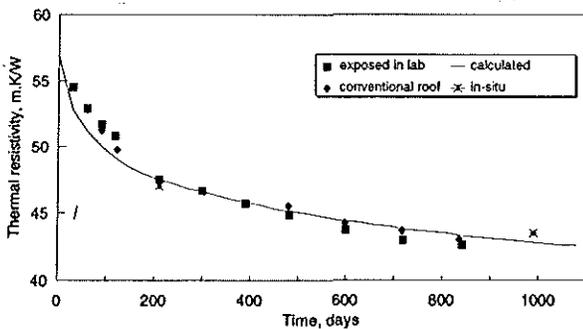


**Figure 6** Measured and calculated from the DIPAC model, aging curves for full-thickness XPS product G.

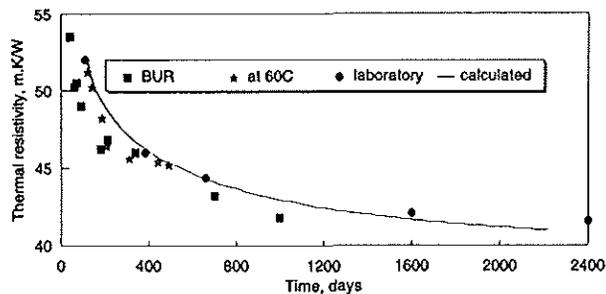
### Thermal Resistance of Polyisocyanurate Foams as a Function of Time

Figure 7 shows the aging of polyisocyanurate (PIR) product O<sub>2</sub>. This foam product had a value of mean thermal resistivity of 54.2 m·K/W (and a standard deviation of 0.36 m·K/W). This product was exposed on the conventional roof and in the laboratory. Intermittent tests at standard test conditions show small differences between the foam exposed on the roof and stored in the laboratory and a satisfactory agreement with the DIPAC model prediction, particularly after 200 days of aging.

Figure 8 shows aging of the polyisocyanurate product OC (nominal density 37 kg/m<sup>3</sup>; mean thermal resistivity in time of receiving 52.1 m·K/W with a standard deviation of 11 tests was 0.57 m·K/W). This product was not exposed on the experimental roof; however,



**Figure 7** Measured and calculated from the DIPAC model, aging curves for full-thickness PIR product



**Figure 8** Measured and calculated from the DIPAC model, aging of boards of the PIR product OC.

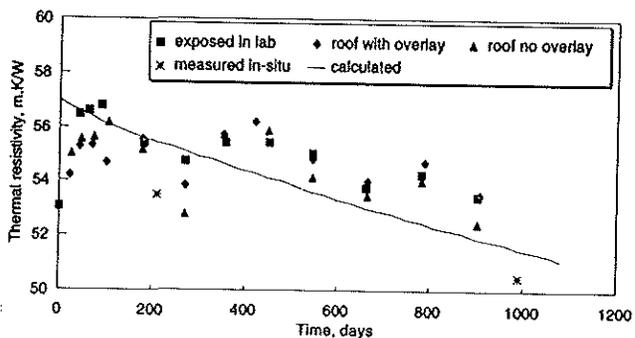
there was a history of its laboratory testing and field performance on an experimental, built-up roof (BUR) in a northeastern U.S. location (specimens from a built-up roof were tested under standard conditions for a period of three years [Muhlenkamp and Johnson 1983]). At the test site, this product was exposed at an elevated temperature (60°C for one year) (Bomberg 1988) and in the laboratory for about seven years.

The date of this product's manufacture was unknown. Using the mean value of thermal resistance upon receiving it and other material characteristics determined on this PIR product, the DIPAC model estimated the period of aging prior to the initial R-value testing as approximately 150 days. As shown in Figure 8, there are some intermittent differences between tests performed on foam exposed to standard or elevated temperatures; there is, however, a satisfactory agreement between measured and predicted long-term thermal performance for this PIR foam product.

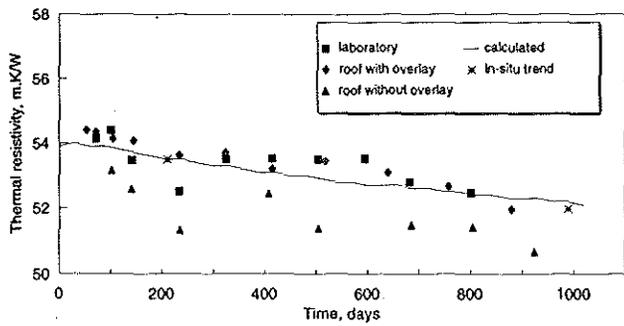
### Thermal Resistance of Phenolic and Modified Resol Foams as a Function of Time

Figure 9 shows aging of phenolic (PhR) product B<sub>1</sub>. This product was exposed on the conventional roof and in the laboratory with and without fiberboard overlay. The mean value of initial thermal resistivity was 54.95 m·K/W with a standard deviation of 1.33 m·K/W.

Despite a significant scatter in thermal resistivity (measured under standard laboratory conditions), there is no significant difference between the performance of foam exposed on the roof and that stored in the laboratory. The increase of thermal resistivity shown for all specimens of the phenolic product B over a period of a few months may be assumed as related to the drying of moisture introduced during the manufacturing process. Moisture distribution in the specimens exposed in the roof varies with the season, and one may expect seasonal differences in thermal resistivity of these specimens. Figure 9 shows that specimens exposed in the roof without fiberboard overlay indicate slightly larger oscillations in thermal resistivity than the oscillations shown by the specimens protected with the fiberboard



**Figure 9** Measured and calculated from the DIPAC model, aging curves for full-thickness PhR product B.



**Figure 10** Measured and calculated from the DIPAC model, aging curves for full-thickness PhR product L<sub>1</sub>.

overlay and the scatter in experimental results obtained on the PhR specimens exposed in the laboratory

Because the current version of the DIPAC model does not include effects of moisture, one may compare the measured and calculated values only when the foam is likely to have been dried out, for example, after one year of exposure. At this stage the agreement between measured and predicted results is considerably improved.

Finally, Figure 10 shows aging of modified resol product L<sub>1</sub>. The mean value of the initial thermal resistivity is 53.98 m·K/W, with a standard deviation of 0.25 m·K/W. Similar to the previous case, there is significant scatter in thermal resistivity but no systematic difference between performance of foam exposed on the roof and that stored in the laboratory.

A comparison between the measured and predicted results is more difficult to make for the phenolic (Figure 9) and modified resol (Figure 10) foam products, but the magnitude of aging predicted by the DIPAC model appears to be correct.

## DISCUSSION OF USE OF THE DIPAC MODEL

Using a popular analogy of the weakest link that limits the strength of the whole chain, the utility value of the long-term thermal performance (LTTP) methodology depends on the reliability of different techniques used to generate the material characteristics for the DIPAC model. These techniques were reviewed when validating the predictive LTTP methodology. To validate the methodology, the model predictions were compared with measurements performed on specimens exposed to controlled laboratory and field conditions. All important types of polymers and different blowing agents were represented in this comparative study to make the evaluation methodology applicable for different combinations of polymers and BAs and to make this review indicative of both the advantages and limitations of the proposed approach.

The extrapolative model of aging is a key element of this procedure to predict long-term thermal performance of all types of cellular plastics. This model uses data obtained on thin layers tested under laboratory condi-

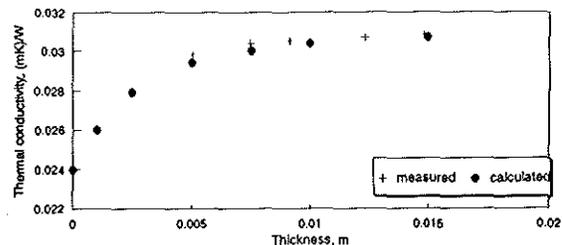
tions and extrapolates them to estimate the performance of full boards under other, but well defined, environmental conditions. While the previous section showed that agreement between measured and predicted results ranged from excellent to acceptable, this section will address the uncertainty of the input data.

Reliability of DIPAC model predictions depends on the precision of the input data. The following difficulties were encountered when generating material characteristics: errors in the measured initial BA concentration, particularly when two blowing agents were used, and limitation of the test method to measure diffusion coefficients (could not be used below  $1 \times 10^{-12} \text{ m}^2/\text{s}$ ). Furthermore, some material characteristics, such as age of the sample received for testing or the initial BA concentration, were missing. Yet, in the same way as used for determination of BA diffusion coefficients, the DIPAC model can be used to verify other input data. Two examples illustrate use of this verification facility incorporated in the DIPAC model.

## Verification of Invariable Components of Heat Transfer

Figure 11 shows thermal conductivity of XPS product C as a function of specimen thickness measured on a heat flowmeter. The extinction coefficient of this XPS product was measured (Booth and Grimmes 1994) and used as input to the DIPAC model in calculating the results shown in Figure 11. Because the radiative mode of heat transfer is determined by the shape of the  $\lambda = \lambda(x)$  curve, comparing the prediction from the DIPAC model with the measured data permits verification of other invariant components of heat transfer.

The agreement between measured and calculated results shown in Figure 11 implies that all invariable components of the foam's thermal conductivity, namely, the thermal conductivity of solid polymer, the path extension factor and fraction of discontinuous polymer (characterization of cells with image analysis technique), cell gas conduction, and the extinction coefficient for radiation, were input correctly.



**Figure 11** Thermal conductivity of XPS product C as a function of specimen thickness, measured in the HFM apparatus and calculated from the DIPAC model using a measured value of the extinction coefficient.

## Verification of Cell-Gas Composition at a Given Stage of Aging

To check cell-gas composition, one may use measurements of thermal resistivity (conductivity) as a function of the specimen temperature (so-called thermal ramp). This technique was used for XPS product G (see Figure 12), for which all material characteristics were measured, but the value of the initial BA concentration was questionable.

The test specimen has completed stage one of aging (full ingress of air components), so the only unknown variable affecting temperature dependence of thermal resistivity was the cell-gas composition. The agreement between measured and calculated results shown in Figure 12 implies that cell-gas composition was estimated correctly (note that two blowing agents were present in the cell gas). As the thermal ramp test relates to a specific stage of aging, this measurement can also be used for verification of the change in the cell-gas composition (Kumaran et al. 1989).

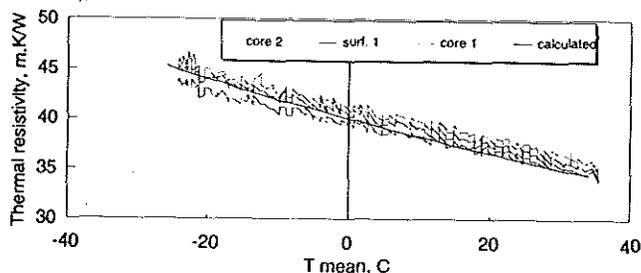


Figure 12 Thermal resistivity of XPS product G as a function of mean specimen temperature.

## CONCLUSIONS

The results verified use of the DIPAC model for evaluating long-term thermal performance of cellular plastics on specimens of eight different HCFC blown foams placed in the outdoor exposure facility for a period of almost three years. During the exposure period, these specimens were periodically removed to measure their thermal resistance under laboratory conditions. Thermal resistance was also continuously monitored under the field conditions and the replicate samples of these products were also exposed and evaluated in the laboratory conditions. The agreement between measured and predicted results varied from "excellent" to "acceptable," depending on accuracy of the input data. In some cases, either input data were missing (diffusion of oxygen and nitrogen through phenolic foams) or were so inaccurate that they had to be replaced by an estimate from the DIPAC model. For example, BA concentration for products G, B, and L was estimated from matching the aging curves of surface and core layers. Even in those cases, the agreement between measured and predicted results may be considered as satisfactory.

It appears that the DIPAC model can become an important tool for evaluating long-term thermal performance (LTTP) of cellular plastics. To this end, however, one must better address three important aspects of long-term thermal performance methodology: the impact of moisture, efficiency of gas barriers, and improvement in laboratory testing of thin layers.

Our knowledge is insufficient to answer questions on long-term structural integrity and durability of some rigid foams under actual field conditions. More information on moisture accumulation and its effect on structural integrity is needed to answer these questions. As moisture can impact the structural integrity of the polymeric matrix, inclusion of moisture transport would allow assessment of materials under specific field applications and further improve the predictive capability of the designer or specifier.

To slow the aging process, foam may be protected with a gas barrier. The effect of an impermeable facer may, however, be greatly reduced by lateral diffusion in a thin layer of the foam adjacent to the facer. Even though this layer is only a few cells thick, the rate of gas diffusion parallel to the barrier may greatly exceed the rate of diffusion in the direction of the foam rise and reduce thermal performance of the foam system. Different reasons may be associated with the phenomenon of diffusion parallel to the impermeable gas barrier, the rollover of the cells during the lamination process, or the collapse of cell walls under a shear stress introduced by the facer. The efficiency of gas barriers in retarding the aging process must be carefully tested (Bomberg et al. 1994b).

Finally, because a special four-station HFM apparatus was built for thermal testing of thin foam layers, this research did not evaluate the precision of thermal resistance determination on thin layers that is attainable with traditional HFM equipment. Performing such evaluation would benefit potential users of the DIPAC model.

## ACKNOWLEDGMENTS

The work reported here is part of a joint research project between the Society of the Plastics Industry and the National Research Council of Canada.

Many thanks go to the technical officers of the Thermal Insulation Group at NRC: to John Lackey, who calibrated all reference specimens for field testing; to Roger Marchand, who developed interface and set the data acquisition system; and to Nicole Normandin, who patiently collected on disks more than 2 million temperature readings per year. They also performed all the laboratory measurements that are reported in this paper.

The measurements of the BA concentration in the cell gas were performed by DuPont Canada. Measurements of the thermal conductivity of XPS product C were performed at the Granville R&D Center, Dow Chemical NA.

## REFERENCES

- Ascough, M.R. 1989. Determination of blowing agent concentration in cellular plastics. Int. Workshop on Long-term Thermal Performance of Cellular Plastics. The Society of Plastics Industry (SPI) Inc. of Canada.
- Bomberg, M. 1988. A model of aging for gas-filled cellular plastics. *J. Cellular Plastics* 24: 327-347.
- Bomberg, M.T., and M.K. Kumaran. 1994. Laboratory and roofing exposures of cellular plastic insulation to verify a model of aging. Third Symposium on Roofing Research and Standards Development, *ASTM STP 1224*, T.J. Wallace and W.J. Rossiter, Jr. eds. Philadelphia, Pa.: American Society for Testing and Materials.
- Bomberg, M.T., and M.K. Kumaran. 1995. Procedures for predicting long-term thermal performance of foam insulations. Internal Report. Ottawa, ON: National Research Council, Canada.
- Bomberg, M.T., M.K. Kumaran, M.R. Ascough, and R.G. Sylvester. 1990. Effect of time and temperature on R-value of rigid polyurethane foams, pp. 420-431. Orlando, Fla.: Polyurethane 90 SPI Inc. *J. Thermal Insulation*, Jan. 1991: 241-267.
- Bomberg, M.T., Y.S. Muzychka, D.G. Stevens, and M.K. Kumaran. 1994a. A comparative method to determine thermal resistance under field conditions. *J. Thermal Ins. and Bldg. Envs.* 18: 163-181.
- Bomberg, M.T., M.K. Kumaran, M.R. Ascough, J.A. Creazzo, J.K. Zane, and A.H. Syrop. 1994b. Techniques to assess the role of various components in retarding aging of rigid, faced thermal insulating foams. *J. Cell Plast.* 30: 106-124.
- Booth, J.R., and J.T. Grimmes. 1994. Validation of a technique to partition conductive and radiative heat transfer using a heat flow meter apparatus, pp. 783-793. *Proceedings 22nd Int. Thermal Conductivity Conference*, Technomic Publ. Co.
- Brehm, T.R., and L.R. Glicksman. 1989. A new sorption technique for rapid measurement of gas diffusion and solubility in closed-cell foam insulation. *Polyurethanes*, pp. 547-552. The Society of Plastics Industry (SPI) Inc.
- Destephen, M.R. 1993. Diffusion and solubility of gases in polymeric foams. Ph.D. thesis. Cookeville: Dept. of Chemical Engineering, Tennessee Technological University.
- Flory, P.J. 1953. *Principles of polymer chemistry*. Ithaca, N.Y.: Cornell University Press.
- Gorski, R.A., R.B. Ramsey, and K.T. Dishart. 1986. Physical properties of blowing agent polymer systems—I: Solubility of fluorocarbons blowing agents in thermoplastic resins. *J. Cellular Plastics* 22: 21-51.
- Kumaran, M.K., M.T. Bomberg, R.G. Marchand, J.A. Creazzo, and M.R. Ascough. 1989. A method for evaluating the effect of blowing agent condensation on sprayed polyurethane foams. *J. Thermal Insulation* 13: 123-137.
- Muhlenkamp, S.P., and S.E. Johnson. 1983. In-place thermal aging of polyurethane foam roof insulations. Paper 11, 7th Conf. on Roofing Technology, April 14-15. National Bureau of Standards/National Roofing Contractors Association.
- Ostrogorsky, A.G., and L.R. Glicksman. 1986. Aging of polyurethane foams, the influence of gas diffusion on thermal conductivity, pp. 1-98, ORNL/SUB/84-9009/2. cf. Ostrogorsky, A.G., Aging of polyurethane foams. 1985. Doctor of Science thesis (L.R. Glicksman, supervisor). Cambridge: Massachusetts Institute of Technology.
- Pantakar, S. 1980. *Numerical heat transfer and fluid flow*. New York: Hemisphere Publ. Co.
- Schuetz, M.A., and L.R. Glicksman. 1983. A basic study of heat transfer through foam insulation. Sixth International Polyurethane Conference. San Diego, Calif.: The Society of Plastics Industry (SPI) Inc.
- Schwartz, N.V., and M.T. Bomberg. 1989. Image analysis and characterization of cellular plastics. *J. Thermal Insulation* 15: 153-171.
- Schwartz, N.V., M.T. Bomberg, and M.K. Kumaran. 1989. Measurements of the rate of gas diffusion in rigid cellular plastics. *J. Thermal Insulation* 13: 48-61.
- Stephenson, D.G. 1992. The calculation of heat flux into a slab of homogeneous material that has thermal conductivity and volumetric heat capacity that are functions of temperature. *J. of Thermal Insulation* 15: 311-317.