Long-Term Thermal Resistance of Polyisocyanurate Foam Insulation with Gas Barrier

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ABSTRACT

Closed-cell polyisocyanurate (polyiso) foam insulation with gas barriers or impermeable facers is used in various building envelope applications. The impermeable gas barrier on both sides of polyiso foam insulation board is designed to maintain the long-term thermal resistance (LTTR) of the insulation at a higher level. Recently, researchers at the Institute for Research in Construction (IRC)/National Research Council (NRC) of Canada, in association with the Canadian Polyisocyanurate Council, have been working to develop a standard test methodology that would help to quantify the design LTTR value of polyiso foam insulation boards with impermeable facers. This paper presents selected results from laboratory tests, field observations, and numerical modeling. Comparisons among these results indicate that the extent of thermal aging of impermeably faced polyiso foam boards can vary in different products. A concept of combined lateral and normal diffusion has been introduced in the numerical modeling to help prediction of the long-term thermal behavior of impermeably faced polyiso products. However, comparisons between the experimental and numerical modeling results indicate that the ratio of lateral to normal (L/N) diffusion rate is not the same for full thickness boards as for thin slices.

INTRODUCTION

Closed-cell foam insulation offers high thermal resistance per unit thickness, primarily due to the low thermal conductivity of the gas used as the blowing agent during the manufacturing of the foam. The aging of closed-cell foam insulation can occur due to inward diffusion of external air and outward diffusion of the blowing agent gas. Hence, the long-term thermal performance of closed-cell foam insulation depends greatly on the mechanisms and the rates of inward and outward diffusion of the air and blowing agent, respectively.

One of the most widely used closed-cell foam insulation is polyisocyanurate (referred to commonly as *polyiso*). Polyiso insulation products are made with facers in the form of a rigid board. These facers can be permeable or impermeable. The introduction of impermeable facers on the surface of polyiso rigid board is aimed at enhancing the long-term thermal resistance (LTTR) properties of the foam insulation. The LTTR of a foam product is defined, in the CAN/ULC S770-98 Standard for Determination of Long-term Thermal Resistance of Closed-cell Thermal Insulating Foams (S770-98), as the value measured after a five-year storage in a laboratory environment. This standard provides means for LTTR prediction based on accelerated aging of the insulation. This standard test procedure, however, is not appropriate at this time for estimating the LTTR value of impermeably faced polyiso rigid board insulation products. To address the issue of the LTTR of impermeably faced polyiso foam insulation, a joint research project was undertaken at the Institute for Research in Construction (IRC), National Research Council (NRC) of Canada, in association with the Canadian Plastics Industry Association (CPIA).

This paper presents the aims and objectives of the aforementioned project, research activities, and selected results obtained from laboratory tests, field tests, and numerical modeling.

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RESEARCH BACKGROUND

During the service life of the closed-cell foam insulation, high molecular weight, blowing agent gas diffuses out of the cell or dissolves into the polymer matrix and, at the same time, comparatively lightweight air components (primarily nitrogen and oxygen) from the external environment start to enter into the closed-cell foams. The blowing agent will diffuse out at a rate that is generally between one and two orders of magnitude lower than the rate of air diffusion into the foam (Alsoy 1999). These phenomena result in a continuous reduction of thermal resistance (i.e., aging) of the foam over a period of time, resting to a long-term equilibrium value. The rate of this aging process depends on the type of polymer used, foam structure, temperature, chemical composition of the blowing agent, and initial cell gas pressure (Isberg 1988).

A limited number of long-term performance studies on commercially available polyiso and polyurethane impermeably faced boardstock are available in the literature. The results of a five-year aging study on polyiso has been documented by Sherman (1979). Using the same polyiso test materials as in the five-year study, the results of an eleven-year aging study were reported by Hagan and Miller (1990). A ten-year aging study on polyurethane also was conducted by Sherman (1980).

The complex multi-component inward and outward gas diffusion process, which reduces the thermal resistance of polymer foam as a function of time, was first depicted in the 1960s by a simplified isothermal, multi-component diffusion model developed by Norton (1967). A number of limitations (Bomberg 1988) associated with Norton's approach, arising from simplified assumptions, were later addressed by researchers from MIT (Schuetz and Glicksman 1983; Ostrogorsky and Glicksman 1986; Glicksman et al. 1986) in the early 1980s. Researchers at IRC/NRC also worked during the second half of the 1980s and the early 1990s to develop a model that not only incorporates the basic approach of Norton and MIT but many improvements, including an extrapolative technique applicable to closed-cell foam insulation with facers (Bomberg 1988; Bomberg and Kumaran 1995). The model is known as the distributed parameter continuum (DIPAC) model.

However, the aforementioned models require an extensive range of input parameters such as: gas diffusion coefficients, accurate determination of cell-gas composition at various stages, appropriate characterization of the blowing agent gas storage/solubility in the foam polymer, thermal conductivity of the various components of the gas and the foam polymer, characterization of various heat transfer mechanisms, cell-gas pressure distribution, temperature profile, etc. It is time consuming and expensive to obtain all these data for any particular insulation product. Furthermore, it is inherently difficult to measure these in the laboratory. Hence, in such a situation, to achieve a reliable assessment of the LTTR of closed-cell foam insulation it is necessary to integrate the results from laboratory experiments, field observations, and modeling (Bomberg and Brandreth 1990). This is the approach adopted in this ongoing study as described in the following sections.

AIMS AND OBJECTIVES

The broad objective of this project is to contribute to the development of a comprehensive test procedure that can be used to predict the LTTR of polyiso foam insulation products with impermeable facers.

More specifically, there are two major tasks involved in this project: (1) laboratory and field tests on specimens and (2) analysis of the test observations/data with a numerical modeling tool (DIPAC).

It is envisaged that by combining the output from the above two tasks, a methodology could be developed that can be applied to estimate the LTTR characteristics of polyiso with impermeable facers.

MATERIALS UNDER CONSIDERATION

Three polyiso foam rigid insulation boards (Product A, B, and C) were considered in this study and were obtained from three different North American sources, each one differing from the other in terms of the blowing agent or the manufacturing process. However, these products have very similar physical properties, as given in Table 1. In all cases the 1.2 m by 2.4 m panels had a nominal thickness of 25 mm and were delivered to the laboratory approximately seven days from the date of manufacturing.

EXPERIMENTAL PROGRAM

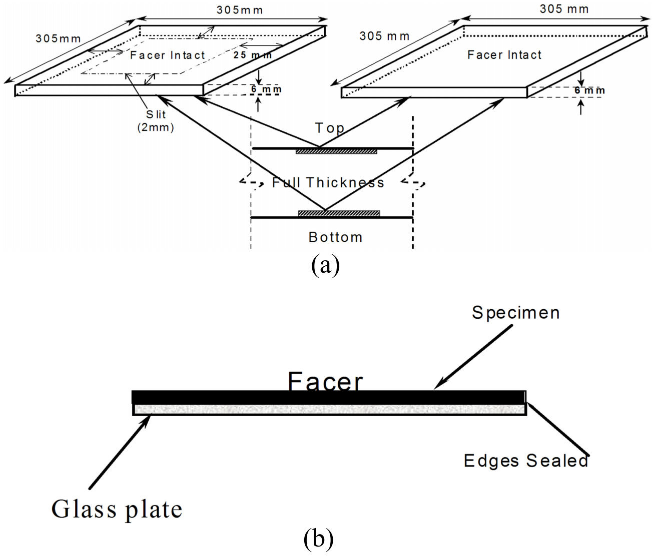
The test program and modeling work were designed to complement each other. Laboratory and field tests were

Table 1. Physical Description of Materials

Product / Material ID	Average Thickness (mm)	Density (kg/m^3)	Full Board Size (mm × mm)	Remarks
A	24.8	35.9	1220 × 2440	Aluminum foil faced and restrained rise product with HCFC as the blowing agent.
B	25.6	36.9	1220 × 2440	Aluminum foil faced and restrained rise product with a zero-ozone depletion potential new blowing agent.
C	24.8	34.3	1220 × 2440	Aluminum foil faced and free rise product with HCFC.

Table 2. Details of Laboratory Test Specimens

Specimen Type	Dimension		Total No. of Specimen	Comments
	Area (mm^2)	Thickness (mm)		
Full-thickness	610 × 610	≅25	6	
Thin-Slice—Test 1	305 × 305	6	4	(a) Two each from top and bottom surface Two with slit on the facer and two without it (Figure 1a) Totally encapsulated with glass plate and epoxy coating on edges (Figure 1b)
Thin-Slice—Test 2	305 × 305	6 or 12	4	Core slices (Figure 2a) without facers One-sided aging for 6 mm thin slices (Figure 2b) Two-sided aging for 12 mm thin slices
Thin-Slice—Test 3	Same as Thin-Slice —Test 1	Same as Thin-Slice —Test 1	Same as Thin-Slice—Test 1	Same as Thin-Slice—Test 1
Thin-Slice—Test 4	Same as Thin-Slice —Test 2	Same as Thin-Slice—Test 2	Same as Thin-Slice—Test 2	Same as Thin-Slice—Test 2



(a)

(b)

Figure 1 *Specimens for Thin-Slice—Test 1.*

carried out on full-thickness and thin-slice specimens. While thin-slice specimens were aged and tested only in the laboratory, full-thickness specimens were aged and tested both in the laboratory and in the field.

Laboratory Tests

Two types of specimens are considered in laboratory tests for all three products. Tests were done on (1) full-thickness specimens and (2) thin-slice specimens. Table 2 and Figures 1 and 2 describe the size and other related information about the specimens. Both full-thickness and thin-slice specimens were aged in the laboratory as described below.

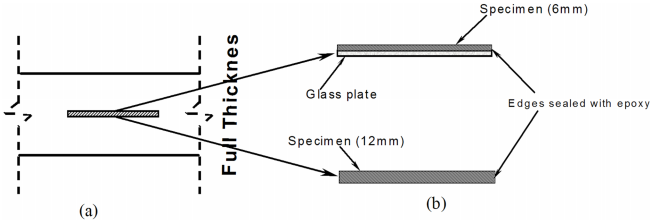


Figure 2 *Specimens for Thin-Slice—Test 2.*

Aging of Full-Thickness Specimens. Six full-thickness (≅ 25 mm) specimens (610 mm × 610 mm) were cut from three different boards for each product from various locations of the boards. Initial heat transmission properties of these specimens were determined in the laboratory within ten days of arrival at the laboratory using a heat flow meter apparatus according to the ASTM Test Method for Steady-State Thermal Transmission Properties by Means of Heat Flow Meter Apparatus (C 518). These specimens were exposed to a laboratory environment of 24±2°C (temperature) and 50±5% RH (relative humidity) and were retested after about twelve months or more of exposure.

Aging of Thin-Slice Specimens. Four sets of tests were conducted with thin-slice specimens for each of the three products. As shown in Table 2, these tests are identified as Test 1, Test 2, Test 3, and Test 4. The details of test specimens are given in Table 2 and Figures 1 and 2.

In Test 1, two 6-mm-thick slices were cut from each surface (Figure 1a) (total of four) of the board and placed on an epoxy-coated glass substrate (Figure 1b). The edges of each specimen were sealed with epoxy coating to facilitate one-sided aging of the polyiso foam through the foil facer only. Two of these four specimens had the facer surface intact on the exposed side, whereas the other two had a slit about 2 mm wide on the facer surface of about 25 mm from the edge (Figure 1a).

The presence of the slit on the facer allows a two-dimensional diffusion pattern, i.e., accounts also for diffusion parallel to the facer surface.

For Test 2, all of the thin slices were taken from the core of the polyiso board (Figure 2a). Naturally, these core foam slices were without any facer. Two of the slices were 6 mm and the other two were 12 mm. The core slices of 6 mm thickness were subjected to one-sided aging on the glass plate and edges sealed with epoxy coating (Figure 2b). However, the 12-mm-thick core slices were being tested without any kind of treatment on the two major surfaces, i.e., two-sided aging (Figure 2b).

Test 3 and Test 4 were repeat tests of Test 1 and Test 2, respectively. Thin-slice specimens were exposed in the laboratory and tested for heat transmission properties at different stages of aging, using a heat flow meter apparatus according to ASTM C 518.

In addition, for model benchmarking, special tests were conducted on the thin-slice specimens, not reported in this paper, to define the thermal resistivity (r-value) as a function of material thickness and temperature.

Field Test in the IRC/NRC Test Hut

Any long-term performance evaluation process should be benchmarked with field exposure tests. In this research program, all three full-size polyiso rigid boards were installed in a purpose-built test hut at the IRC/NRC campus in Ottawa. The indoor environment of the test hut was controlled and exterior weather data were also available. Full-size boards of Product A and Product B were installed on the east wall of the test hut and Product B and Product C boards on the west wall. In this way, the field performance of all three polyiso products could be monitored and also the difference in performance due to wall orientation (east or west) could be identified. Each of the four insulation boards was instrumented with two heat flow sensors. The detailed descriptions of the field tests and instrumentation are available in an earlier publication (Mukhopadhyaya et al. 2002).

MODELING TOOL

The distributed parameter continuum or DIPAC model, developed at IRC/NRC, can be and has been used in the recent past as a tool for evaluating the LTTR of foam insulation. It solves for the partial pressure of the blowing agent as a function of time within the insulation board and calculates conductivity to determine overall r-value as a function of time. Several publications are now available where the fundamentals of the DIPAC one-dimensional model have been discussed at length (Bomberg 1988; Bomberg and Kumaran 1995). However, the DIPAC one-dimensional model does not have an effective provision for accommodating the lateral diffusion component of the blowing agent, i.e., the flow of gas parallel to the facer.

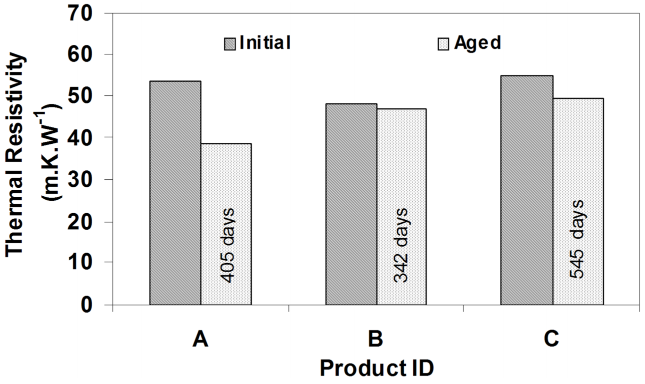


Figure 3 *Average thermal resistivity of full-thickness, impermeably faced polyiso foam insulation.*

The DIPAC two-dimensional model has been specifically developed for this project to incorporate the lateral diffusion component of the blowing agent into the model. The DIPAC two-dimensional model considers three different layers cut parallel to the facer. The external layers represent foam with properties different from those in the central or core layer. This permits introduction of the lateral gas diffusion through the external layers. Furthermore, each external surface is provided with a contact resistance used to simulate an impermeable facer. The objective of the DIPAC two-dimensional model is to calculate the heat flux through a slab, provided with a facer on each side, as a function of aging time and boundary conditions. To achieve this, the facers and the slab are divided into a given number of layers and the aging time is counted as a number of time-steps. Some of the material characteristics used in these calculations, e.g., density, extinction coefficient for infrared radiation, or effective gas diffusion coefficient, may vary across the slab for some products. Therefore, all of the material characteristics used for the input are measured at three locations—at the middle and at each surface of the slab. Using a specified interpolation function, one may calculate material characteristics for each layer.

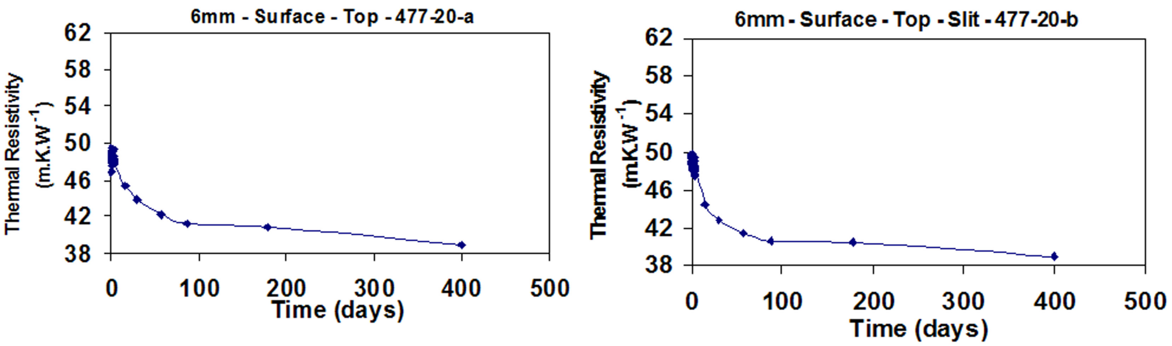
EXPERIMENTAL OBSERVATIONS

Laboratory and field tests have generated large amounts of useful information. However, only selected results are presented in the following paragraphs in a systematic manner.

Laboratory Aging of Full-Thickness Specimens

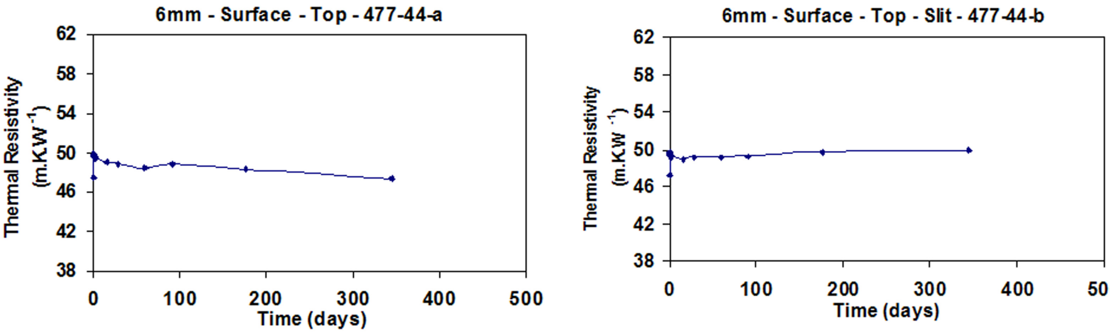
The average values for the initial and aged (Product A, 405 days; Product B, 342 days; Product C, 545 days) thermal resistivity of the three products are shown in Figure 3. The initial results obtained from six specimens for each product also show that all observations are within about ±2% of the average thermal resistivity values reported in Figure 3. Almost similar trends for the variation of the results were also observed after the specified aging period.

Due to aging the average thermal resistivity of Products A, B, and C were reduced by 28%, 2%, and 10%, respectively.



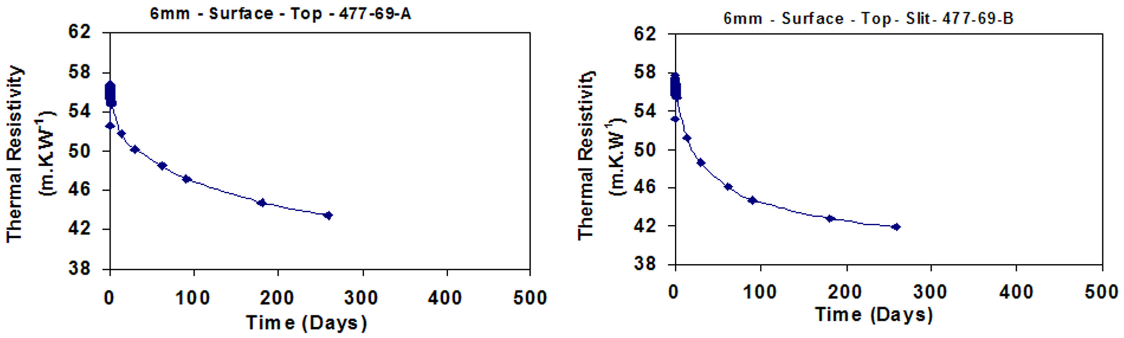
(a) Without slit on the facer (Product A)

(b) With slit on the facer (Product A)



(c) Without slit on the facer (Product B)

(d) With slit on the facer (Product B)



(e) Without slit on the facer (Product C)

(f) With slit on the facer (Product C)

Figure 4 *Change of thermal properties in thin surface slices (Test 1).*

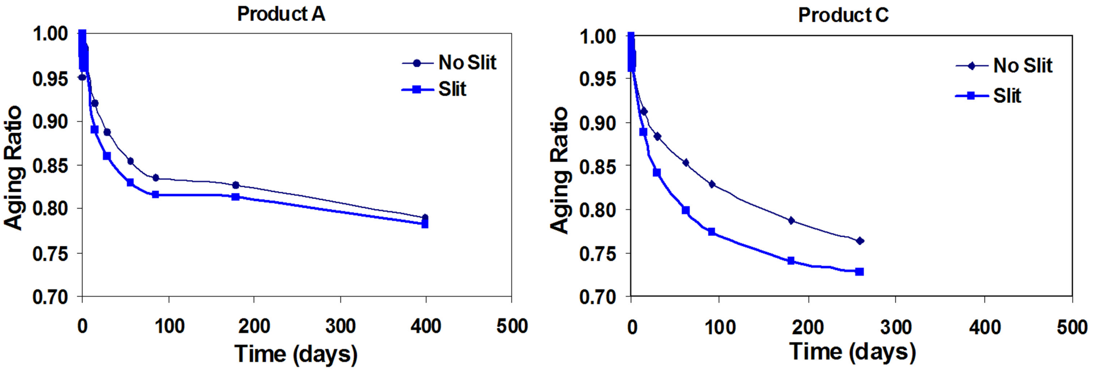
The change of thermal resistivity due to aging effect on Product B was small (≈ 2%) and within the expected range of experimental variation.

Laboratory Aging of Thin-Slice Specimens

As mentioned earlier, two types of thin slices were tested in this research program. Surface slices were in Tests 1 and 3 and core slices in Tests 2 and 4.

Observations from Surface Slices (Tests 1 and 3). Typical aging (i.e., reduction in thermal resistivity with time) curves of thin surface slice specimens, with and without a slit on the facer, can be seen in Figure 4. These results were obtained from Product A, Product B, and Product C. These thin slices were exposed to the ambient laboratory condition. The exposure duration was for a period of nine months or more.

These aging curves clearly show rapid aging at the beginning of the exposure and then a reduction in the aging rate to a near stable value for Products A and C. In the case of Product B, however, these changes are less evident. The different aging characteristics of Products A, C, and B imply that aging char-



(a) Slit and No Slit - Thin Slice - Product A

(b) Slit and No Slit - Thin Slice – Product C

Figure 5 *Aging due to lateral flow of blowing agent parallel to facer: (a) Product A and (b) Product C (Test 1).*

acteristics of one polyiso product can vary from another and it is necessary to investigate more than one polyiso product, as has been done in this project. There is also an indication that the presence of a slit on the facer in Products A and C results in a higher rate of aging in the initial stage.

This phenomenon is more evident if the results are presented in terms of aging ratio (i.e., the ratio of the thermal resistivity at any specified time to the initial thermal resistivity), as shown in Figures 5a and 5b. One possible explanation for the increased initial aging rate of the faced specimen is that ingress of air (an inert gas) will change the molar composition of the cell gas and thereby reduce the effective thermal conductivity of the foam. Another possible explanation is the lateral diffusion of cell gases parallel to the facer. In addition, it is also possible that the facer is not effectively impermeable. In general, these observations of Tests 1 and 3 indicate that experimentally it is possible to identify the effect of the lateral flow of the blowing agent on the aging process of impermeably faced polyiso insulation foam board when the aging process is rapid (Products A and C).

Observations from Core Slices (Tests 2 and 4). Figure 6 shows the typical aging curves of core slices from Tests 2 and 4 for Product A, Product B, and Product C. These figures indicate that, as would be expected, the initial (up to 15-20 days) aging process was rapid but thereafter it slowed down significantly. The aging process almost stabilized, or slowed down to a negligible rate, at the end of the test period for all three products. Figure 7 shows the typical plot of aging ratio vs. time for the two core slices of Products A, B, and C. The two-sided aging of a 12-mm-thick core slice was initially faster than the one-sided aging of the 6-mm-core slice for all three products. However, tests on core slices showed much faster aging than the surface slices in Tests 1 and 3, signifying that the impermeable facer influenced the rate of aging (Figure 7).

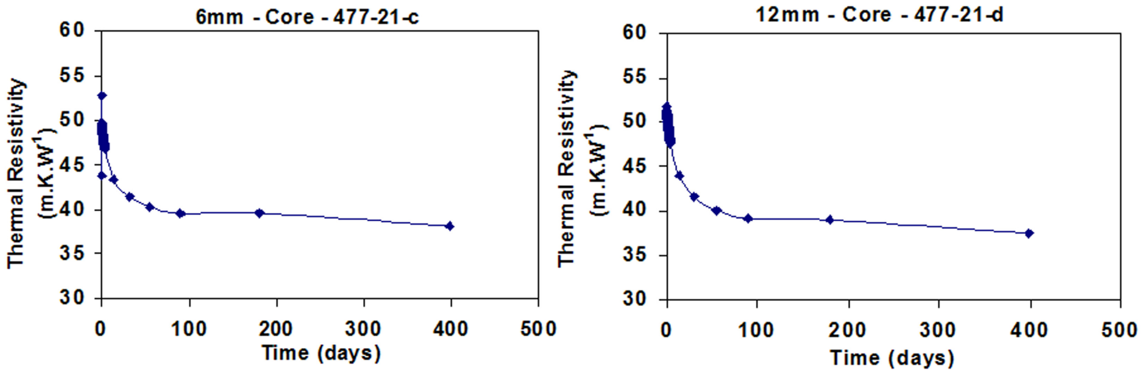
APPLICATION OF MODELING TOOL—DIPAC 2-D

Experimental results clearly indicate that Products A and C aged significantly in terms of thermal resistivity while exposed to laboratory condition. Both thin slices and full-thickness boards showed a similar trend. Hence, the experimental results obtained from Products A and C would be interesting for further investigation and analysis using DIPAC 2-D. However, only the analyses of the results obtained from Product C using DIPAC-2D are presented in the following paragraphs (given length requirement for this paper).

Analyses of Results Obtained from Polyiso Product C

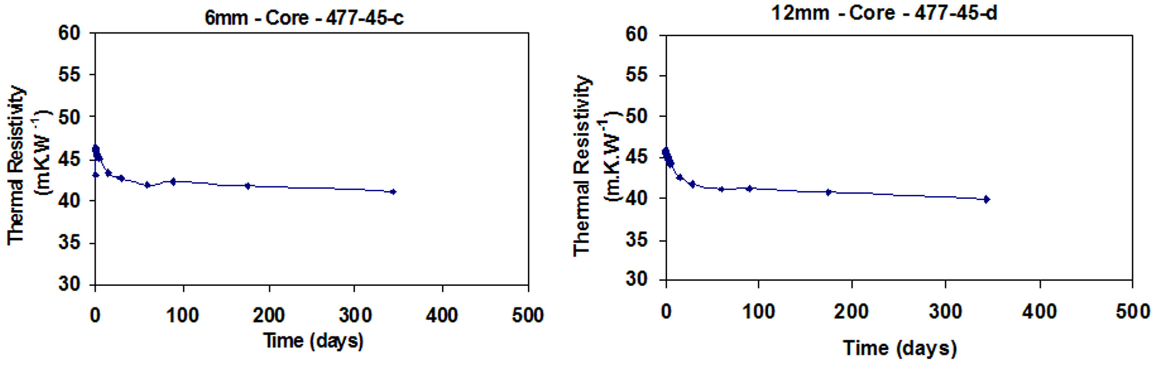
Product C is a free-rise product, and the differences in thermal resistivity between the core and surface layers are expected to be small. To establish the initial thermal resistivity of the full-board thickness and that of thin slices, measurements were taken immediately after receiving the product at the laboratory. This product was received by IRC/NRC on July 6, 2001, and initial thermal measurements were obtained within one week of receiving the shipment.

Aging of Core Slices. Figure 8 shows measurements performed on polyiso product C compared with DIPAC model predictions. The input parameters for the model related to the diffusion and solubility of oxygen, nitrogen, and blowing agent. The industrial partners in the research consortium provided these values. Fine-tuning of the input data was made to fit the measured results. It is to be noted that the time-dependent solubility process is superimposed on the effect of oxygen and nitrogen diffusion. This process is assumed to last for about 150 days. Since both of these variables are approximated, one cannot rely entirely on the fit, such as shown in Figure 8, to ensure that each of these properties is adequately accounted for. Nevertheless, having checked the overall effect of aging on the core slices and achieved approximate corre-



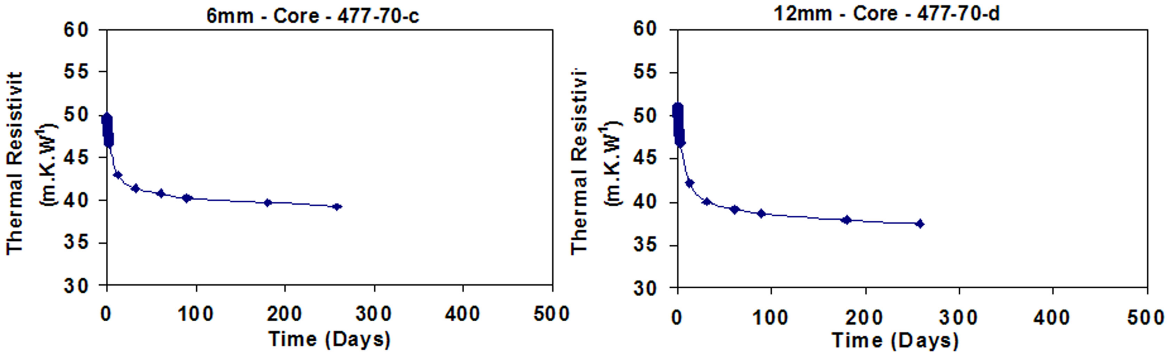
(a) 6mm core slice (1-sided aging, Product A)

(b) 12mm core slice (2-sided aging, Product A)



(c) 6mm core slice (1-sided aging, Product B)

(d) 12mm core slice (2-sided aging, Product B)



(e) 6mm core slice (1-sided aging, Product C)

(f) 12mm core slice (2-sided aging, Product C)

Figure 6 *Change of thermal properties in thin core slices (Test 2).*

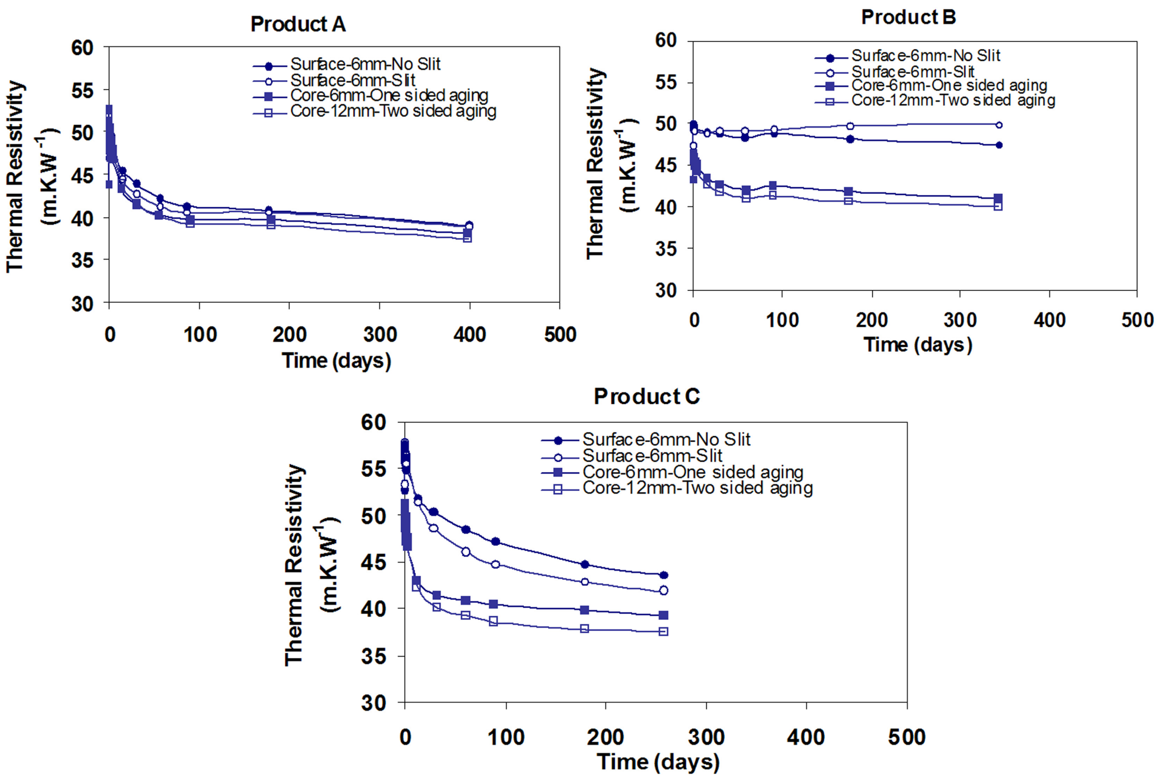


Figure 7 *Aging of surface and core slices (Test 1 and Test 2).*

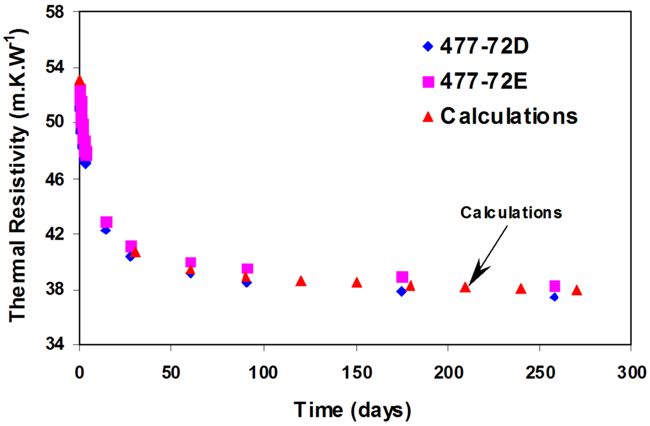


Figure 8 *Changes in thermal resistivity measured for 12-mm thick core slices with aging on both sides but having the perimeter sealed to simulate a one-dimensional diffusion process.*

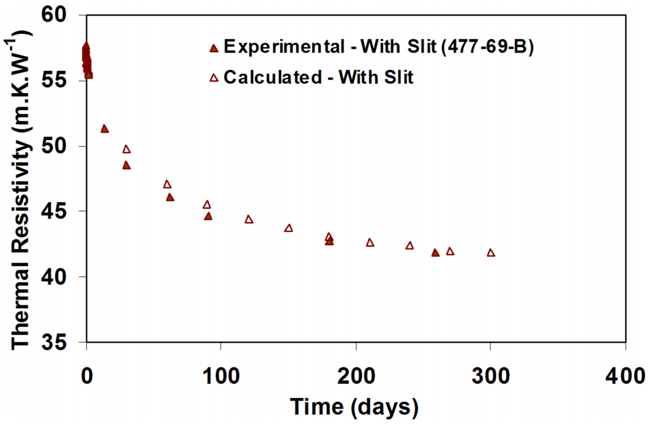


Figure 9 *Changes in thermal resistivity of 6-mm thick surface slices with slit in the top surface and perimeter sealed (calculated with L/N ratio = 100).*

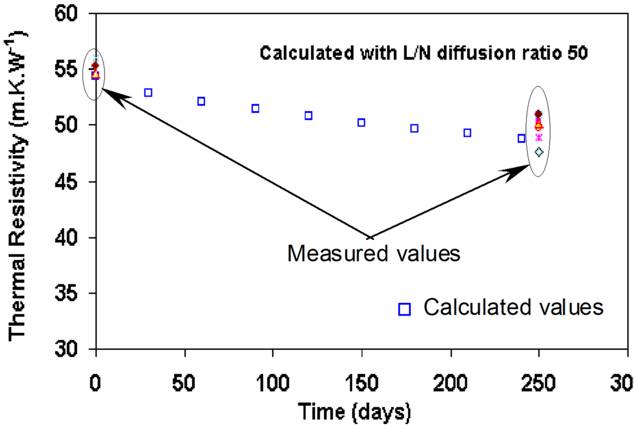


Figure 10 *Measured and calculated values of thermal resistivity for full-thickness specimens (L/N ratio 50).*

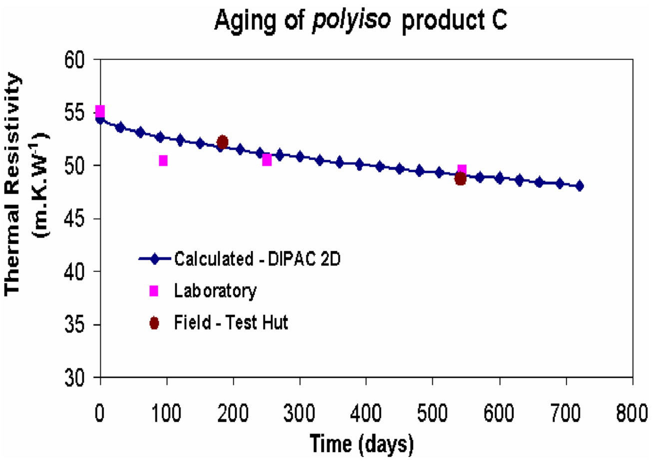


Figure 11 *Comparison of laboratory tests and field tests with calculated aging of product C (L/N ratio 15).*

spondence, one may proceed to examine the thermal performance of the surface layers.

Aging of Surface Slices. To ensure that only the effect of diffusion through or adjacent to the facer is measured, all surface slices were adhered with epoxy resin to glass plates. Two types of measurements were performed. The first one involved sealing the edge surfaces and making a slit on the facer, 25 mm away from the edges. The slit (or slot) was about 2 mm wide and resulted in outlining a square with 250 mm sides. The second type of measurements was performed with the facer untouched, i.e., with the full 300-mm-square specimen, and edges completely sealed.

The experimental observations (Figure 4) showed that thin-slice specimens, glued on a glass plate, with the facer intact aged considerably (around 20%) in terms of thermal resistivity. This cannot be due to aging through the sealed edges. This observation indicates the possibility of gas diffusion taking place through the impermeable facer. Further investigation is required to characterize this phenomenon. For modeling purposes, the facer is considered impermeable in this study. Figure 9 shows the comparison with DIPAC 2D model calculations and with the experimental results from the specimen that had a slit on the impermeable facer.

Aging of Full-Thickness Board. Figure 10 shows the aging in thermal resistivity of full-thickness specimens (610 mm × 610 mm). Thermal resistivity was measured over a period of 9 to 17 months of laboratory exposure and was compared with the calculated values. Using properties determined for core and surface slices and verified in two additional special tests (effect of specimen thickness and temperature) it is possible to calculate the change in thermal resistance of a full-thickness board. The model can be fine-tuned to match the full thickness measurements by setting the L/N ratio equal to 50 for Product C. However, for thin surface slice with a slit, for Product C, the L/N ratio required for agreement was 100.

Comparison—Laboratory Results, Field Observations, and DIPAC-2D Output

It was necessary to use an L/N ratio of 15 in the model in order to match the full-thickness field test data. Figure 11 shows the comparison between laboratory and field measurements of aging and that predicted by the DIPAC-2D model using an L/N ratio of 15.

SUMMARY OF OBSERVATIONS

The experimental and *DIPAC-2D* modeling results for one polyiso product (Product C) discussed in this paper used HCFC blowing agents with a high solubility, and impermeable facers. The diffusion and solubility functions for this product were similar to another polyiso product (Bomberg and Kumaran 1994) and three other polyiso products reported in previous proprietary, i.e., confidential, research (Bomberg and Kumaran 1991). In general, the following observations could be made from analyses of the results obtained from the DIPAC-2D model and examining experimental data.

First, while the laboratory measurements, field observations, and numerical calculations (i.e., DIPAC 2-D) appear to agree well, there is an inconsistency with the lateral diffusion coefficient. The lateral diffusion coefficient determined for different specimens (i.e., full thickness and thin slices with facer) are significantly different. It is an important issue that needs further research.

Second, a considerable amount of aging occurred in thin-slice specimens despite having untouched impermeable facers, as well as a glass plate at the bottom of the specimens and edges sealed completely with epoxy coating. This can be due either to imperfections of the gas barrier system or edge sealing.

Further investigation on these issues would be imperative for future progress toward the development of a methodology to predict the LTTR of polyiso board with impermeable facer.

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