FIVE-YEAR FIELD STUDY CONFIRMS THE PIMA STANDARD FOR ESTIMATING POLYISOCYANURATE INSULATION LONG-TERM THERMAL PERFORMANCE

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In 1989, the industry produced some experimental, permeably-faced polyisocyanurate (PIR) laminated board insulation blown with HCFC-141b, and a second batch blown with CFC-11, which has undergone continuous field thermal performance monitoring for 5.5 years (June 1989 until February 1995). From these boards, several thin-sliced specimens were prepared and laboratory k-factors periodically measured on these core foam specimens. This work was conducted as part of a six-year joint research project between the Society of the Plastics Industry (SPI), Polyisocyanurate Insulation Manufacturers Association (PIMA), National Roofing Contractors Association (NRCA), and the Department of Energy (DOE) Oak Ridge National Laboratory (ORNL). One of the major research products from this cooperative research effort was the development of an accelerated method for predicting full thickness lifetime thermal conductivities ("in-service R-values") of permeably-faced polyisocyanurate products. This paper compares the prediction of the field installed permeably-faced boards generated from the accelerated aging procedure to the actual measured field performance. The field applications consist of loose-laid boards under ethylene propylene diene terpolmer (EPDM) membranes in a low-sloped roof installed in the ORNL Roof Thermal Research Apparatus(RTRA). For the 5.5 years, each test roof was monitored hourly for temperature and heat flux. This data provides a time series of boundary conditions for a computer program PROPOR (Properties - Oak Ridge) to compute weekly thermal conductivities. PROPOR is an application of one-dimensional inverse heat transfer analysis. Every six months the test specimens were pulled from the roof and tested under steady state conditions in the laboratory according to American Society of Testing Materials (ASTM) C 518-91. This field validation of the accelerated aging procedure called the "PIMA Method" concludes that the thin slicing and laboratory k-factor measurements, within the first six months, accurately predict five years of full-thickness, in-situ thermal performance of HCFC-141b permeably-faced polyisocyanurate insulation boards.

A computer program was developed which uses the thin-slice data set of a specific manufacturer's insulation. The design service life and full-thickness product is input and the in-service R-value is estimated. This value will vary depending on results from the thin slice testing. This work is leading toward an acceptable industry standard to determine the in-service R-value, which is defined as the design thermal resistance of insulation over the normal life of a roof system containing foams which thermally age.

KEYWORDS

Conductivities, field testing, in-service R-value, insulation, polyisocyanurate and thermal aging.

BACKGROUND

Leading Up to Development of the PIMA Method

Polyurethane insulation boards (the predecessor of polyisocyanurate) became widely used in the U.S. following the 1973 Energy Crisis. During the early years of use, there were no consensus standards regarding the aging and conditioning of the boards prior to R-value testing. Some manufacturers reported R-values that were determined shortly after product production, while others reported values that were determined quite some time after production. This resulted in considerable variation in reported R-values. This inconsistency generated significant concern and controversy in the roofing industry.

In 1981, the Roof Insulation Committee of the Thermal Insulation Manufacturers Association (RIC/TIMA) promulgated a conditioning procedure.[1] This procedure specified that insulation samples were to be conditioned for 180 days (± 5 days) at 73.4°F, + 3.6°F (23°C ± 2°C), at 50 percent (± 5 percent) relative humidity. NRCA Technical Bulletin #11 (November 1981) recommended using the RIC/TIMA conditioning procedure. While this new procedure allowed manufacturers to report thermal resistance values on a standardized basis, the controversy on thermal performance did not end.

Researchers discovered that samples taken from roofs that had been in place for a few years had lower R-values than what would have been presumed, based on the RIC/TIMA procedure. Roofing contractors became particularly concerned, because it appeared that the labeled R-value of the insulation that they had installed did not accurately represent the performance of the product over time.

In response to the inconsistency between R-values based on RIC/TIMA conditioning compared to the R-values from existing roofs, in 1985, the Midwest Roofing Contractors Association (MRCA) recommended that an "in-service" R-value of 5.56 per inch thickness be used for polyurethane and polyisocyanurate insulation boards.[2] In 1987, MRCA and NRCA issued a Joint Technical Bulletin that recommended an in-service R-value of 5.6 per inch thickness.[3] This bulletin included a technical explanation and extensive list of references.

The MRCA/NRCA in-service R-value has been criticized by some manufacturers, and few manufacturers report this value (or any other in-service value).[4] NRCA recognized that some of the criticism is justified,[5] but until development of the PIMA Method, there was no other consensus on an appropriate value or method to determine an appropriate value.

By implementing the PIMA Method, the roofing industry will have a scientifically-based method for determining in-service R-value of permeably-faced polyisocyanurate insulation boards. After more than 20 years of R-value controversy and substantial expenditures for laboratory and field research, this issue should be resolved.

Work Leading to the Development of the PIMA Method

In April 1993, an extension to the Cooperative Research and Development Agreement (CRADA) ORNL 90-0028 was signed between the Society of Plastics Industry (SPI)-Polyurethane Division, the Polyisocyanurate Insulation Manufacturers Association (PIMA), National Roofing Contractors Association (NRCA) and the Oak Ridge National Laboratory (ORNL). The overall objective of this cooperative research project is to help accelerate the industry's transition from CFCs to HCFCs and eventually to more environmentally acceptable polyisocyanurate insulations in the future. The first tasks of this CRADA extension were to: complete a full five years of field testing of permeably-faced, closed-cell polyisocyanurate foams blown with CFC-11 and HCFC- 141b, prepare a procedure for the laboratory prediction of the long-term thermal resistance ("in-service R-value") of polyisocyanurate closed-cell foams and validate the accelerated thermal aging procedure.[6,7] Thermal aging is the change in thermophysical properties of rigid closed-cell PIR foam with time due to changes in the composition of the gas contained within the cells.

This paper compares the field data collected in a low-sloped roof on the RTRA at the Oak Ridge National Laboratory in Oak Ridge, Tenn., from 1989 to 1995, to the laboratory test procedure which was developed under this CRADA. The laboratory test procedure uses ASTM Test Method C 518 for periodic determinations of the thermal resistance of specimens of reduced (i.e., sliced) thickness for a period of about 180 days to observe the effects of aging. A set of thermal resistance results for specimens aged under controlled laboratory conditions is used to predict the lifetime thermal resistivity (R/inch) of the foam product under actual use.[8-14] The time-averaged (integrated) thermal resistance is defined as the thermal resistance of a material of given thickness averaged over a specified time period.

The laboratory test specimens were prepared from the center of full-thickness products in order to have a cell gas content that is representative of the foam product at the time of manufacture. The material for this comparison was 1.5-inch (38 mm) thick polyisocyanurate insulation boards blown with a HCFC-141b and a second batch blown with CFC-11 manufactured in June 1989. For laboratory conductivity testing, specimens were prepared for both types of boardstock: full thickness, 1.3 inches (33 mm) thick, and four thin specimens, 0.3 inches (10.1 mm) thick. Each thermal resistance test was done at a mean temperature of 75 ± 4°F (24 ± 2°C) on specimens conditioned at 75 ± 4°F (24 ± 2°C) and 50 ± 5 percent relative humidity before and during the test sequence. Only five data points spanning an aging period of 190 days were available for the thick specimen and for the stack of four thin specimens. The 1995 proposed PIMA Standard calls for at least eight data points.[14] This analysis of the accelerated aging prediction of these foams attempts to follow as close as possible the procedure which was refined after the initiation of this extensive laboratory and complementary field study at ORNL.

At the time of production, the cells of this type of closed-cell plastic foam contain the highest percentage of blowing agent and the lowest percentage of air components. A blowing agent is a gas with a lower thermal conductivity than air. During the service life of a rigid closed cell PIR foam, air components diffuse into the cells, and the blowing agent diffuses out of the cells or partially dissolves (solubilizes) in the solid polymer matrix. Since the inward diffusion of air components is generally much faster than the outward diffusion of the captive blowing agent, the aging process proceeds in two stages. During the first stage, the cell gas composition changes at a significant rate because of the rapid diffusion of air components into the cell and the outward diffusion of all rapidly diffusing blowing agents. These composition changes cause the thermal conductivity of the material to change. This stage of aging is defined as the primary stage. Carbon dioxide is an example of a rapidly diffusing blowing agent which is sometimes generated during foam manufacture. Its outward diffusion rate will usually exceed the entry rate of air components during the primary stage. As the diffusion of air components nears completion, the thermal conductivity of the material changes more slowly. The thermal conductivity continues to change, however, due to continuing outward diffusion from the cells of the blowing agent. This stage is defined as the secondary stage. The estimated age of a rigid closed cell plastic foam (when the aging process switches from the primary to a secondary stage) is called the transfer point. Note that because of this aging process, the in-service R-value will be a function of the design service life (for instance, a foam will have a higher in-service R-value if the design life is 10 years compared to 20 years).

The results of this CRADA[10-12] and the development of the ASTM standard test method[13] yielded a procedure that would accelerate the change in the thermal resistance of the closed-cell plastic foams which change due to cell gas concentrations. Polyisocyanurate, extruded polystyrene, spray polyurethane and phenolic foams all age; expanded polystyrene does not change. The focus on cell gas concentrations is based on the fundamental underlying assumptions that: The apparent thermal conductivity of a rigid closed-cell plastic foam, k, can be approximately expressed as the sum of the apparent thermal conductivities due to radiation k_r, due to gas mixture k_g and due to solid polymer k_s[10,15-21]

$$k = k_r + k_g + k_s$$

It is assumed that the values of k_r and k_s do not change significantly.[10] Thus the aging process is studied exclusively by focusing on the cell gas thermal conductivity. The cell gas conductivity is a function of partial pressure of the cell gas components which change with time. The driving parameters controlling the change in partial pressure of the gas components are their effective diffusion coefficients, specimen thickness and time.[15] Solubility changes are not addressed. Since time cannot be sped up, either the diffusion coefficients have to be increased or the thickness reduced. Under this CRADA, we tried speeding up the diffusion coefficients by increasing the conditioning temperature of the test specimens. The amount of acceleration achievable by raising the aging temperature was found to be limited. We found that the temperature increase does not equally change the diffusion coefficients of all the cell gases involved in the aging process. This left the only viable accelerated aging option, to reduce specimen thickness.

The accelerated procedure is based on the assumption that a thin slice removed from the core of the foam board will age at a rate that is proportional to the square of the ratio of the thickness of the product to that of the thin slice. For example, the thermal resistance predictions of a 1.5-inch (38.1 mm) thick board, after fourteen years, are equal to the thermal resistance of a 0.4-inch (10.1 mm) thick specimen after one year [$(1.5/0.4)^2 = 14$].

The nonlinear increase in k with time/(thickness)^2 can be described by two linear regions by plotting the natural logarithm (ln) of k versus (time)$^{1/2}$/thickness. The data are fitted using a least square's method to a straight line for the primary and secondary aging stages. This procedure assumes the thermal conductivity (k) can be described by an exponential dependence on diffusion coefficient (D), time (t) and thickness (h).

$$Y = A + B\,Z \qquad (1)$$

$$\ln k = \ln k_0 + (Dt)^{1/2}/h, \qquad (2)$$

Where k_0 is the initial thermal conductivity, A is $\ln k_0$, Y is ln k, Z is $t^{1/2}/h$, and B is $D^{1/2}$. The fitted equations for Region 1 and Region 2 are used to estimate k for a foam of a specific thickness at various times and the time-averaged lifetime thermal resistivity (1/k).

A laboratory measured thermal conductivity of a thin-sliced test specimen from work conducted as part of this CRADA,[10,11,12] showed two linear regions of logarithms of k with the quantity (diffusion coefficient x time)$^{1/2}$/thickness. This thermal data expressed in terms of scaled time (time$^{1/2}$/thickness) provides estimates of the thermal resistance or time-averaged thermal resistance for full-thickness boards of actual field installed boards. The latter observation and the development of ASTM Standard C 1303[13] set the stage for a round robin with 13 participating laboratories which found they could predict lifetime R/inch values to within 2 percent of each other.[14]

This accelerated procedure is an extremely useful tool to the building community. Material producers have faced a major formulation change in their product lines due to the ban in the production of CFCs and will be facing further changes with the future elimination of HCFC substitutes. The short time period given to industry to comply with the ban does not offer the luxury of developing data that requires long-term tests to support new products which need to be introduced to the marketplace. Similarly, users of these products require long-term thermal performance data on closed-cell plastic foams to make informed design recommendations and purchasing decisions. The PIMA Method of accelerating aging produces a prediction of the long-term thermal performance of a closed-cell plastic foam. The test results shown in this paper illustrate that field and laboratory data agree on the long-term performance of both CFC- and HCFC-blown products. The procedure is shown to predict the long-term thermal performance of CFC polyisocyanurate (PIR) products within 5 percent and HCFC products within 2 percent. This is considered acceptable accuracy.

There are two basic differences between ASTM Standard 1303 and the PIMA Method. The ASTM Standard C 1303 is more general, it does not specify as tightly the testing sequence time schedule because different foams age at different rates, and it also requires a thickness correction for the damaged cells resulting from sample preparation. Since the PIMA Method uses relatively thick slices, the correction for damaged cells is not significant.

OBJECTIVE

The objective of this paper is to validate the PIMA Method of accelerated aging polyisocyanurate insulation, using the laboratory thermal conductivity data collected on thin sliced specimens, and the five years of thermal conductivity in-service roof data collected on permeably-faced experimental PIR boards manufactured in June 1989.

ACCELERATED AGING

Summary of the Proposed 1995 PIMA Standard

The PIMA Standard for estimating the long-term thermal resistance of unfaced, rigid, closed-cell, polyisocyanurate foam insulation predicts the R-value as a function of time. The proposed standard uses ASTM Test Method C 518 for periodic determinations of the thermal resistance of specimens of reduced thickness for a period of 180 days to observe the effects of aging. The set of thermal resistance results for specimens aged under controlled laboratory conditions may then be used to estimate the in-service thermal performance of the foam product. A computer program was developed which uses the thin slice data set of a specific manufacturer's insulation. The design service life and full product thickness is input and the in-service R-value is estimated. This value will vary depending on results from the thin slice testing. The in-service R-value will not be the same for all polyisocyanurate due to different characteristics of the foam unique to each manufacturer.[14]

Soon after manufacturing, the specimens are prepared from the center of a full-thickness product in order to have a cell gas content that is representative of the product at the time of manufacture. A minimum of five thermal resistance specimens per sample will be prepared: a full-thickness specimen, typically 1.5 ± 0.2 inches (38 ± 5 mm) that is representative of the product, and four thin specimens, 0.39 ± 0.04 inches (10 ± 1 mm) thick. The effective specimen thickness of the thermal resistance specimen is determined to 1 percent (within 0.01 inches or 0.2 mm) using a vernier caliper or the C 518 apparatus. Guidelines on sample preparation are provided in the Appendix of this paper. Each thermal resistance test is obtained at a mean temperature of 75 ± 4°F (24 ± 2°C) with a temperature difference of 40°F (22°C) to 50°F (28°C). The specimens will be conditioned at 75 ± 4°F (24 ± 2°C) and 50 ± 5 percent relative humidity before and during the test sequence. Because of the thinness of the aging specimens, the four identical layers are stacked and always oriented the same for each thermal conductivity measurement. At least eight data points spanning an aging period of 180 days will be obtained for each type of specimen. The test times should be selected to yield data for both aging regions, as described below:

As mentioned earlier, the nonlinear increase in k with time/(thickness)^2 can be described by two linear regions by plotting the natural logarithm of k versus (time)$^{1/2}$/thickness. The data are fitted using a least square's method to a straight line for Region 1 and Region 2. This procedure assumes the thermal conductivity (k) can be described by an exponential dependence on diffusion coefficient (D), time (t) and thickness (h).

$$Y = A + B\,Z \qquad (1)$$

$$\ln k = \ln k_0 + (Dt)^{1/2}/h \qquad (2)$$

Where k_0 is the initial thermal conductivity, A is $\ln k_0$, Y is ln k, Z is $t^{1/2}/h$, and B is $D^{1/2}$. The fitted equations for Region 1 and Region 2 are used to estimate k for a foam of a specific thickness at various times and the time-averaged thermal resistivity (1/k).

1989 HCFC-141b and CFC-11 Blown PIR Foam Accelerated Aging Data Reported in PIMA Standard 95 Format

Thin Specimens—A PIMA member manufactured these experimental laminated boardstock blown with HCFC-141b and CFC-11 in June 1989. Three thicknesses of 2 x 2 ft. (0.6 x 0.6 m) specimens were produced by planing the facer and foam from 1.5-inch (38 mm) boardstock. To develop the regression coefficients used in the generation of the aging curve for this paper, we used data from two 1.3- and 0.39-inch (33 and 9.9 mm) thick specimens and data for the first 190 days after manufacturing, to be as consistent as possible with the 1995 Proposed PIMA Standard. Thin specimen preparation is discussed further in the Appendix of this paper.

ORNL Heat Flow Meter Apparatus (HFMA)—The thermal conductivities at 75°F (24°C) of the sliced, aging specimens were all measured on the ORNL HFMA.[22] This comparative heat flow metering technique is designed to meet ASTM C 518, Configuration B: transducers installed on both faces.[9] The ORNL HFMA is described in References 22-24. As specified by ASTM C 518-91, the HFT is calibrated with standard reference material (SRM) 1450b and 1451 to establish calibration factors as a function of specimen thickness and temperature before a measurement campaign. The apparatus uncertainty has been established to be less than ± 5 percent. The two-standard-deviation value (2 δ) from a comparison with other C 518 apparatuses was 2.2 percent for planed PIR boards.[25-26]

Thin Slice Thermal Conductivity Data—The thermal conductivities obtained in the laboratory for HCFC-141b foam are shown in Table A.1 of the Appendix. The complete set of conductivity data can be found in Reference 12. The data analysis followed the specified format for the 1995 PIMA Standard.[14]

Accelerated Aging Analysis—

Step 1. Both data sets were entered in a spreadsheet, which yielded the "X" variable which is the scaled time-thickness variable of (time)$^{1/2}$/thickness in the units of (days)$^{1/2}$/inch and the "Y" variable which are ln 100•k with k in the units of BTU•in/(h•ft^2•°F). The X and Y variables for the HCFC-141b foam are shown in Tables A.1 and A.2. The Appendix also contains an example of the tables used to conduct the analysis for deriving the prediction of lifetime thermal performance prescribed in the 1995 PIMA Standard using the HCFC-141b foam data discussed throughout this paper.

Step 2. The individual data sets were sorted in ascending order of the "X" variable which is (time)$^{1/2}$/thickness.

Step 3. The individual data sets were plotted as "Y" versus "X", or "ln 100•k" versus "days$^{1/2}$/inch." Doing so resulted in a "two-region" graph with Region 1 being the initial low k, high slope region and Region 2 being the high k, low slope regions. Figures 1 and 2 show the plots for both sets of specimens. Their is a transition zone between the two regions in which some judgment is needed to decide which if any region a point in this zone belongs.

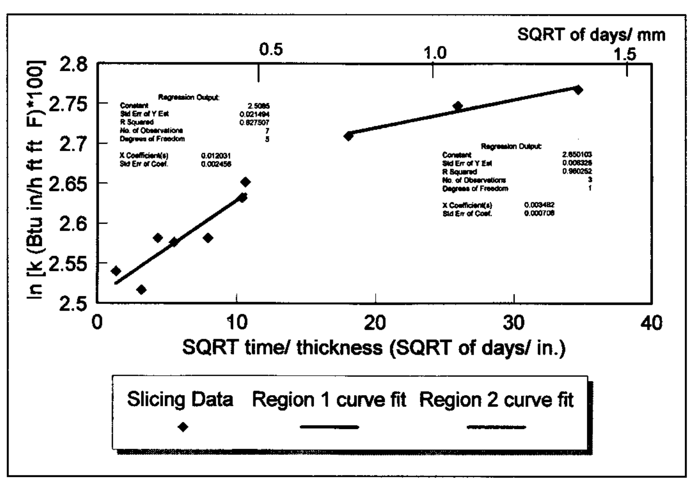

Figure 1. CFC-11 slicing data and regression fit for aging prediction.

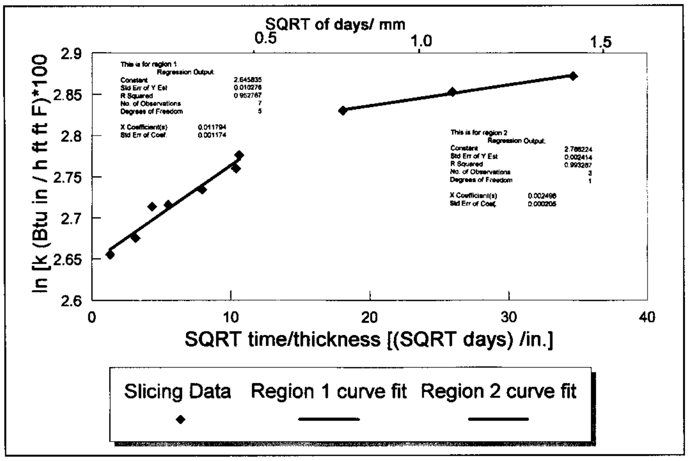

Figure 2. HCFC-141b slicing data and regression fit for aging prediction.

Step 4. The individual data points in Region 1 and the individual data points in Region 2 were identified.

Step 5. The Region 1 and Region 2 data were fitted by means of a least square s method to the following functions:

Region 1: $\ln 100 \bullet k = A_1 + B_1 \text{ (days)}^{1/2}/\text{inch}$ (5)

Region 2: $\ln 100 \bullet k = A_2 + B_2 \text{ (days)}^{1/2}/\text{inch}$

The results of the fitting by means of a least square's method are provided for both graphs shown in Figures 1 and 2, as well as in Table 1.

Step 6. For each data set, the constants (A_1 and A_2) and slopes (B_1 and B_2) for Region 1 and Region 2 were used to calculate the average k for 10 years for 1, 1.5, 2.0 and 3.0 inches (25, 38, 50 and 75 mm) of product thickness and 20 years for 1, 1.5, 2.0 and 3.0 inches of product thickness. This calculation yielded the predicted lifetime (in-service) R/inch values shown in Table 2.

Region 1 contains seven individual data points and Region 2 contains only three individual data points. The fitting procedure yielded the values for A and B for Region 1 and Region 2 given in Table 1 for the two sets of specimens.

	Constants for HCFC-141b	Slopes for HCFC-141b	Constants for CFC-11	Slopes for CFC-11
Region 1	2.645835	0.011794	2.5085	0.012031
Region 2	2.786224	0.002498	2.650103	0.00348

***Table 1.** Constants and slopes for Region 1 and Region 2 for HCFC-141b and CFC-11 specimens.*

IN-SERVICE LOW-SLOPED ROOF THERMAL CONDUCTIVITY

ORNL Roof Thermal Research Apparatus (RTRA)

The field data was collected on the ORNL Roof Thermal Research Apparatus (RTRA) which is a 10 x 30 ft. (3 x 9 m) continuously conditioned building that can accommodate eight 4 x 4 ft. (1.2 x 1.2 m) test roofs. Two of these test roof slots were used for this project. Figure 3 shows a top view of

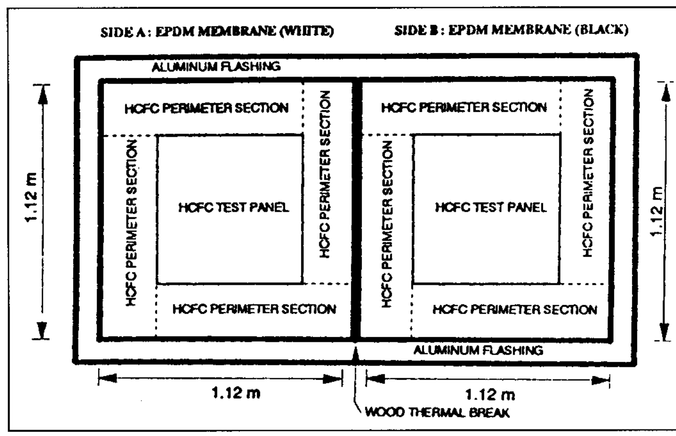

Figure 3. Top view of test roofs installed in the RTRA.

how these test roofs were installed in the RTRA. The central 2 x 2 ft. (0.61 x 0.61 m) section of each foam test specimen is physically separated from the remaining foam to check calibrations of the heat flux transducers and generate a periodic ASTM C 518 k-factor versus specimen mean temperature relationship. This data is used to report all field thermal conductivity at the same specimen temperature though the actual mean insulation board temperature in an in-service roof varies throughout the year. The Figure 4 shows a cross section of the two layers of 1.5-inch (38 mm) thick PIR foam insulation and a 0.045-inch (1.14 mm) EPDM membrane resting on a metal deck. A 2 x 2 inch (51 mm square) heat flux transducer (HFT) is mounted between the two layers of insulation in the center of the test specimen,[18] and copper-constantan thermocouples are used to monitor temperatures at interfaces (between the

Lifetime (yr.)	Foam type	1 in.	1.5 in.	2.0 in.	3.0 in.
10	CFC-11	6.15 [42.7]	6.48 [45.0]	6.67 [46.3]	6.95 [48.2]
10	HCFC-141b	5.59 [38.8]	5.80 [40.2]	5.93 [41.2]	6.11 [42.4]
20	CFC-11	5.79 [40.2]	6.20 [43.0]	6.43 [44.6]	6.71 [46.6]
20	HCFC-141b	5.35 [37.1]	5.62 [39.0]	5.77 [40.0]	5.95 [41.3]

***Table 2.** Integrated long-term resistivity ((h•ft²• °F)/Btu•in.) [m.k/w] for several full-thickness PIR products tested in this research project.*

membrane and the top foam layer, between the foam layers, and between the bottom foam layer and the metal deck). The RTRA has a complete weather station for continuous monitoring of ambient temperature conditions.

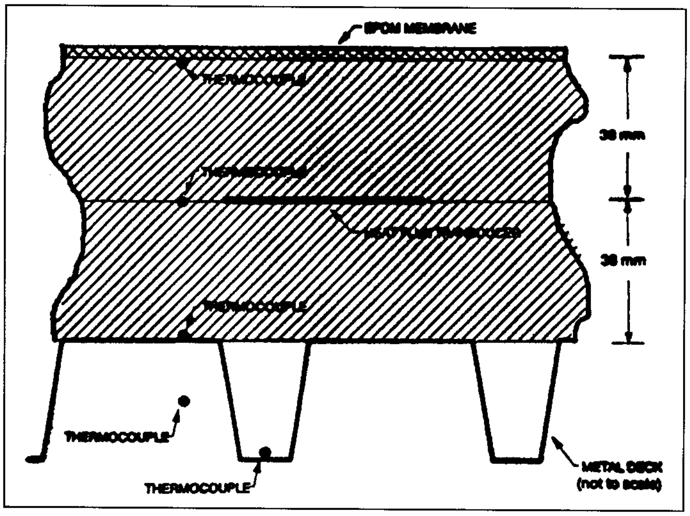

Figure 4. Cross section of two layers of PIR foam insulation and a EPDM membrane on a metal deck.

Five Years of HCFC-141b and CFC-11 Polyisocyanurate In-Situ Thermal Conductivity Data

Data Collection and Analysis Procedure—Temperature and heat flux data from the sensors installed in the test panels are automatically recorded at one-minute intervals and averaged into hourly values. A computer program PROPOR (Properties-Oak Ridge) is used to compute the thermal conductivity of the insulation.[28-29] This procedure was added to ASTM C 1155 Standard Practice for Determining Thermal Resistance of Building Envelope Components from In-Situ Data in 1995.[30] PROPOR is an application of one-dimensional inverse heat transfer analysis. Using a time

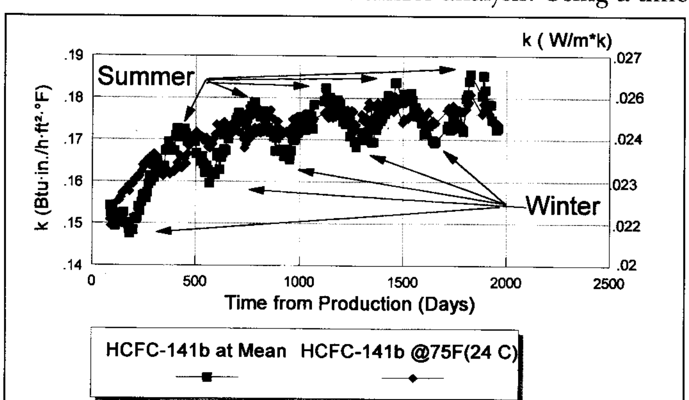

Figure 5. HCFC-141b field data—k-factor-mean and normalized to 75°F (24°C).

series of boundary conditions and initial estimates of thermal properties, PROPOR calculates the temperatures and heat fluxes at sensor locations using the conduction heat transfer equation for a homogeneous medium. The PROPOR output is used to report the k-factor at the mean insulation temperature experienced for each week for the two board combinations. The k-factor for PIR insulation varies with mean temperature. This is clearly shown in Figure 5 which is a plot of more than five years of weekly k-factors for the HCFC-141b foam measured on the RTRA at mean specimen temperature and at 75°F. Reporting at a single temperature tends to flatten the seasonal fluctuations. Although on an annual basis, it is interesting to note that the average top board (as shown in Figure 4) temperature under a black membrane was 72°F (22.2°C) for this test under Oak Ridge, Tenn., climatic conditions, as shown by the bar graph of five-year average annual specimen temperatures in the roof in Figure 6. The actual field temperatures are of course lower in the winter than in the summer. Since

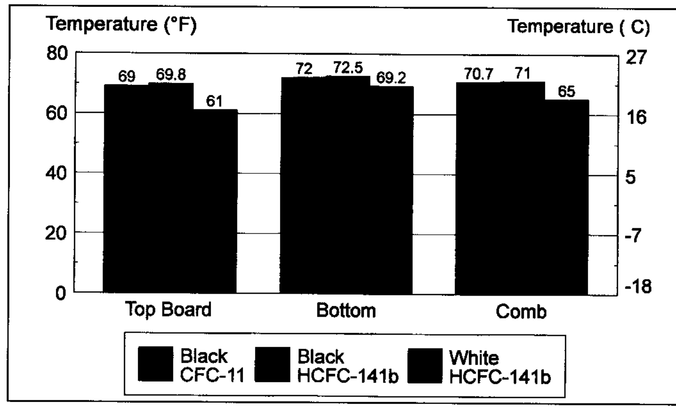

Figure 6. Five-year average temperature of polyisocyanurate on a roof in Oak Ridge, Tenn.

the PIMA Method calls for a specimen temperature measurement at 75°F (24°C), that is what the field data is adjusted to before comparing it to the accelerated aging prediction. The exact procedure for normalizing the field data to 75°F (24°C) is described in Reference 4. Periodically the field specimens were pulled from the RTRA to develop temperature adjustment factors. The data reported at 75°F (24°C) in this paper used laboratory measurements of k vs. temperature collected periodically through the five-year test period. Table 3 identifies the date of the laboratory data measurement used to adjust the field data for this paper.

Laboratory Data	Period of Field Data Collection
5/17/90	Oct. 1, 1989 - Sept. 30, 1990
11/15/90	Oct. 1, 1990 - March 30, 1991
5/13/91	April 1, 1991 - March 29, 1992
9/11/92	March 30, 1992 - Oct. 3, 1993
6/3/94	Oct. 4, 1993 - Feb. 1995

Table 3. Dates of laboratory k-factor adjustment data used to convert reported field data to a consistent temperature of 75°F for continuous comparison to the PIMA Method of accelerated aging prediction.

HCFC-141b Compared to CFC-11—Figure 7 shows the weekly k-factors of the CFC-11 and HCFC-141b blown PIR for the two 1.5-inch (38 mm) boards stacked under a loose laid black EPDM for more than a five-year period. For these experimental HCFC-141b blown boards made in June 1989, the average in-situ k-factor over the five-year period after production was 9.6 percent higher (i.e., the R-value was lower) than that of the CFC-11 over the same period. The latest set of HCFC-141b blown PIR undergoing field testing in 1995 at ORNL has k-factors during the first six months after production about the same as those shown for the first six months of the CFC-11 boards plotted in Figure 7. The formulations used in the most recently received board is believed to be optimized for the HCFC-141 blowing agents where as the 1989 boards used a generic formulation based on 1989 technology.[31]

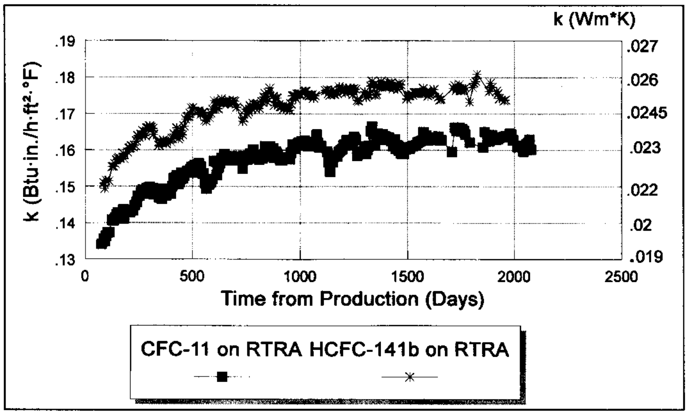

Figure 7. CFC-11 and HCFC-141b—k-factor normalized to 75°F (24°C).

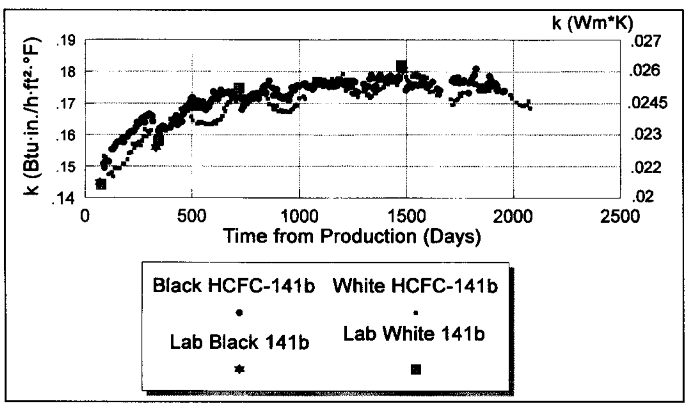

Figure 8. HCFC-141b black vs. white—k-factor normalized to 75°F (24°C).

Does Not Matter Whether the Membrane is Black or White—Figure 8 shows five years of weekly averaged k-factors for the HCFC-141b boards under a black and under a white EPDM membrane and periodic laboratory measurements on the same boards. The color of the roof membrane does not have a significant impact on the aging characteristics of the PIR. Over time the spread in apparent thermal conductivity, which can be seen in the first two winter seasons, diminishes. For the first three years, the two board stacks covered with the white membrane averaged 5.7°F(3.1°C) less than under the black. After a five-year period this difference remained exactly the same as shown in Figure 6. The actual k-factor of the HCFC-141b insulation stack under the more reflective membrane was 2.8 percent lower than the actual value for the HCFC-141b boards under the black membrane. This comparison was derived from the data shown in Table 4.

PIMA Method Field Validation

The field data is plotted on the same graph as the five thin specimen ASTM C 518 measurements for both the CFC-11 and HCFC-141b, respectively, in Figures 9 and 10. The non-

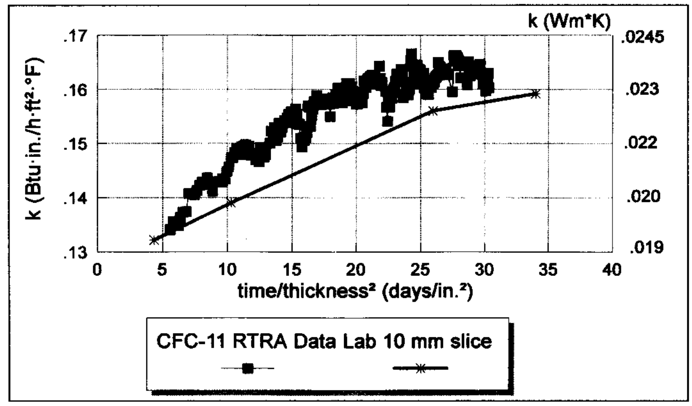

Figure 9. CFC-11 aging—field data vs. .39 in. (10 mm) lab data.

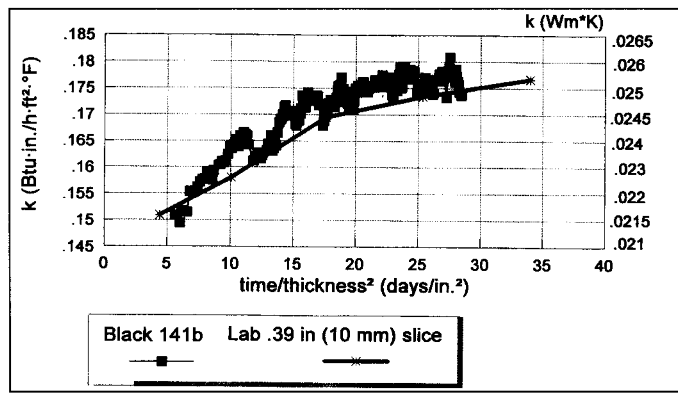

Figure 10. HCFC-141b aging—field data vs. .39 in. (10 mm) lab data.

linear increase in k with time/(thickness)² can be seen for this data. A second and more significant observation is the similarity between the laboratory k-factors and the field measurements. Note that the laboratory 0.39-inch (10 mm), thin-slice k-factor at about 676 (days/in.²) was taken 107 days after production, and the field data point was measured after 1,520 days. The scaling factor of 14 means that every day of specimen thin-slice aging equals 14 days of full 1.5-inch (38 mm) thick board aging. The laboratory thin-slice data are just slightly below the field measured thermal conductivity values. The slicing data for the HCFC-141 boards match the field data better, however, it is still slightly less than the full-thickness product. These data would suggest that there is not a densification or skin effect on this particular product with a 0.025-inch (0.63 mm) thick permeable organic/inorganic facer.[17] The actual thickness used to plot the field data was without the added thickness of the facer. If one chose to plot the field data with the full thickness, the field data would be slightly higher. This accelerated aging procedure is only representative of uniform foam. If a beneficial skin effect, densification or well-adhered impermeable facers were used on a PIR, the 1995 proposed PIMA Standard could predict a higher aged thermal conductivity than would be experienced in-service. Currently more than 90 percent of the PIR used in roofs have permeable facers.[32] It is the goal of ongoing work on this joint CRADA to develop superior PIR with impermeable facers which experience less thermal aging. However, for permeable faced products, it appears that the PIMA Method produces an accurate estimate of full-thickness product thermal performance. Discussion of the Precision and Bias (deviation) of the PIMA Standard can be found in the Appendix. The specimen preparation techniques and the dimension measurement procedures significantly influence the precision of this method as well as the precision of the thermal test method used. Precision data on the combined procedures are not yet available. The Bias (deviation) between the thin specimen aged R-values and the long-term, full-thickness five-year aged R-values found by Graves et al.[14] that the PIMA Standard over predicted the actual five-year integrated resistivity for HCFC-141b by 1.9 percent.

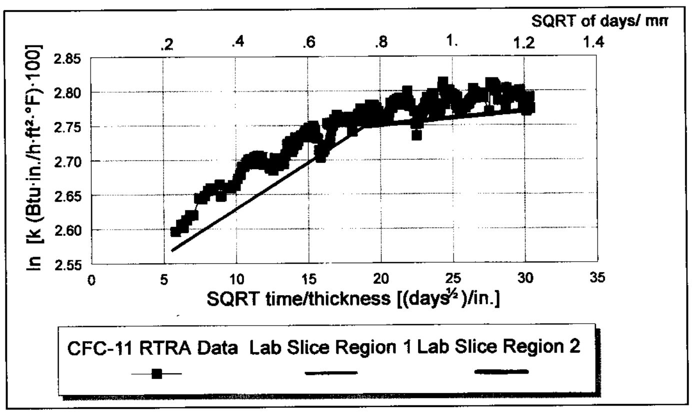

Figure 11. CFC-11 aging of 1.5 in. boards—field data vs. lab prediction 75°F (24°C).

Figures 11 and 12 are plots of the PIMA Method prediction of aging compared to more than five years of field data for CFC-11 and HCFC-141b blown PIR. Table 4 shows the measured compared to predicted time averaged thermal resistivity for the first five years, after production for the CFC-11 and HCFC-141b boards. After five years, the integrated resistivity for the CFC-11 accelerated aging procedure, following as closely as possible the prescribed PIMA Standard, was 3.9 percent higher than measured. For the HCFC-141b under the black and under the white membrane, the PIMA Standard prediction for integrated thermal resistivity was 1.5 percent and 0.2 percent higher than measured, respectively.

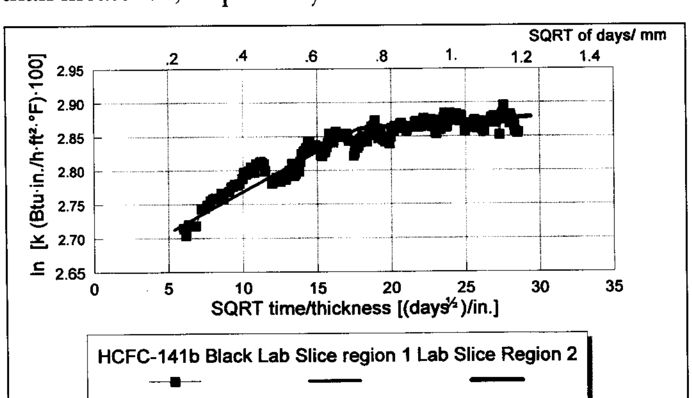

Figure 12. HCFC-141b under black aging—field data 1.55 in. (39 mm) vs. lab slice (75°F, 24°C).

An extensive effort was spent collecting periodic k vs. temperature data on each field specimen throughout the five-year life of this project. Each six months or so, a set of laboratory ASTM C 518 tests was run. These laboratory data were then used to adjust the field data to report it at a constant specimen temperature of 75°F (24°C). The net effect was quiet small when one compares the measured field data using actual mean temperature that occurred in these test roofs over the last five years of Oak Ridge, Tenn. weather. The measured temperature in all cases was 4° to 10°F (2° to 5.5°C) lower than 75°F (24°C). If one uses this field data, the measured thermal resistivity was found to be only 1 to 2.5 percent higher than when reporting at 75°F (24°C).

CONCLUSIONS

The PIMA Method was applied to the most extensive data base of aged and field exposed PIR available worldwide in 1995. In-service thermal conductivity data for more than five years of field exposure and complimentary laboratory ASTM C 518 measurements on the same roof insulation specimens were compared with 0.39-inch (10 mm) thick sliced specimens which generated a scaler ratio of 14 for the full-thickness, 1.5-inch (38 mm) permeably-faced PIR product. This paper provides validation that the method works reliably in the prediction of the full scale thermal performance in a roof system. After five years the method predicts within 1.5 percent the actual integrated resistivity of full 1.5-inch (38 mm) thick PIR blown with HCFC- 141b. The differences in results between the accelerated laboratory method and the in-situ method are within the precision of these procedures.

ACKNOWLEDGMENTS

The authors would like to thank the members of the PIMA/SPI/NRCA/DOE CRADA steering committee for their guidance and support: Fran Lichtenberg, The Society of the Plastics Industry; Jared Blum, PIMA; Bill Cullen, NRCA; M. Peter Scofield, DOE; Robert Blanpied, Atlas Roofing Corporation; John Clinton, NRG Barriers; Joe Hagan, Center for Applied Engineering, Inc.; Frank Dwyer, Allied Engineered Materials; and Robert Riley, BASF Corporation. This project was partially supported by the Office of Buildings Technology, U. S. Department of Energy, as part of the National Program Plan for Building Thermal Envelope Systems and Materials, managed by Lockheed Martin Energy Systems, Inc. under contract number DE-AC05- 84-OR21400.

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Age (yr.)	CFC-11 (R/in)@ 75°F measured [RSI]	CFC-11 (R/in)@ 75°F predicted [RSI]	HCFC-141b Black (R/in)@ 75°F measured [RSI]	HCFC-141b White (R/in)@ 75°F measured [RSI]	HCFC-141b (R/in)@ 75°F predicted [RSI]	CFC-11 (R/in)@ Mean °F measured [RSI]	HCFC-141b White (R/in)@ Mean °F measured [RSI]	HCFC-141b Black (R/in)@ Mean °F measured [RSI]
1	6.93 [48.1]	7.19 [49.7]	6.24 [43.3]	6.44 [44.7]	6.33 [43.9]	7.19 [49.9]	6.67 [46.3]	6.42 [44.6]
2	6.7 [46.5]	6.93 [48.1]	6.07 [42.1]	6.22 [43.2]	6.13 [42.5]	6.82 [47.3]	6.39 [44.3]	6.16 [42.7]
3	6.53 [45.3]	6.79 [47.1]	5.96 [41.4]	6.08 [42.2]	6.03 [41.8]	6.63 [46.0]	6.25 [43.4]	6.03 [41.8]
4	6.45 [44.8]	6.71 [46.6]	5.88 [40.8]	5.98 [41.5]	5.98 [41.5]	6.54 [45.4]	6.13 [42.5]	5.94 [41.2]
5	6.40 [44.4]	6.65 [46.1]	5.84 [40.5]	5.92 [41.1]	5.93 [41.2]	6.49 [45.0]	6.07 [42.1]	5.9 [40.9]

Table 4. *Integrated thermal resistivity for 1.5-inch (38 mm) boards field measured compared to slicing predictions (h•ft^2• °F/Btu•in.).*

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APPENDIX

Example of Data Utilization and Calculated Properties Form Using the HCFC-141b PIR

Test Date	Test Number	Specimen Age (d)	Specimen Thickness when Tested (in) [min]	Apparent Thermal Conductivity Btu.in./h.ft².°F [w/m.k]	Natural Log of 100 • k Btu.in / h.ft².°F
6/9/89	1	3	1.3 [33]	0.1423 [0.020]	2.6553
6/23/89	2	17	1.3 [33]	0.1452 [0.021]	2.6755
7/27/89	3	51.5	1.3 [33]	0.1512 [0.022]	2.7160
9/20/89	4	106.5	1.3 [33]	0.154 [0.022]	2.7344
12/13/89	5	190	1.3 [33]	0.1606 [0.023]	2.7763
6/9/89	6	3	0.398 [10.1]	0.1509 [0.022]	2.7140
6/23/89	7	17	0.398 [10.1]	0.158 [0.023]	2.7600
7/27/89	8	51.5	0.398 [10.1]	0.1695 [0.024]	2.8303
9/20/89	9	106.5	0.398 [10.1]	0.1734 [0.025]	2.8530
12/13/89	10	190	0.398 [10.1]	0.1767 [0.025]	2.8719

Table A.1. *Summary of test data for the June 1989 experimental HCFC-141b PIR.*

Test Number	t/h^2 in (d/in^2)	$(t/h^2)^{1/2}$ in $(d/in^2)^{1/2}$
1	1.77	1.33
2	10.06	3.17
3	30.47	5.52
4	63.02	7.94
5	112.43	10.6
6	18.94	4.35
7	107.32	10.36
8	325.12	18.03
9	672.33	25.93
10	1199.46	34.63

Table A.2. Calculated aged specimen characteristics.

Region	A	B	Number of Data Points
1	2.6458	0.011794	7
2	2.7862	0.002498	3

Table A.3. Summary of data fit by least-squares method.

Period of Time in Years	Integrated (time averaged) Thermal Resistivity
1	6.41 [44.5]
2	6.18 [42.9]
5	5.95 [41.3]
10	5.8 [40.2]

Table A.4. Calculated properties.

Symbols

B = constant,
D = diffusion coefficient, cm^2/sec,
k = apparent thermal conductivity, BTU•in/(h•ft²•°F) (W/(m•K)),
k_g = thermal conductivity of the cell gas mixture, BTU•in/(h•ft²•°F) (W/(m•K)),
k_r = thermal conductivity due to thermal radiation, BTU•in/(h•ft²•°F) (W/(m•K)),
k_s = thermal conductivity of the solid polymer, BTU•in/(h•ft²•°F) (W/(m•K)),
p = partial pressure, atm,
r = thermal resistivity, (h•ft²•°F)/BTU•in. ((m•K)/W)
R = thermal resistance, (h•ft²•°F)/BTU ((m²•K)/W),
R_a = estimated time-averaged resistance, (h•ft²•°F)/BTU ((m²•K)/W),
R_t = thermal resistance on t^{th} day, (h•ft²•°F)/BTU ((m²•K)/W),
t = time, days, d,
h = specimen test thickness, inches (m).

Thin-Specimen Preparation Guidelines

Specimen preparation equipment that has successfully been used to prepare thin specimens is listed below. This listing is not intended to preclude the development or use of any other demonstrated methods of specimen preparation.

- Surface grinder or planer. This method was used to prepare the specimens discussed in this paper.
- High speed band-saw with a fine tooth blade or razor blade.
- A combination lathe/motor-driven meat slicer.

Surface Damage—Equipment for preparing thin specimens will be selected based on the equipment's ability to reproduce the amount of surface damage (open cells) created in the preparation process. Small variations in surface damage may yield significant variability in the data obtained from the thin specimen. Different specimen preparation equipment may be required to prepare thin specimens from generically different rigid closed cell plastic foams.

Thickness Uniformity—The equipment used to prepare specimens will be capable of producing specimens whose uniformity of thickness imparts an uncertainty no greater than two percent to the thickness measurement.

Precision and Bias (Deviation)

The specimen preparation techniques and the dimension measurement procedures significantly influence the precision of this method as well as the precision of the thermal test method used. Precision data on the combined procedures are not yet available.

Bias (deviation) between the thin-specimen aged R-values and the long-term, full-thickness aged R-values can only be determined after the actual aging of the full- thickness material is completed. The findings in this paper found that the PIMA Standard over predicted the actual five-year integrated resistivity for the CFC-11 and HCFC-141b PIR by 4.8 percent and 1.9 percent, respectively.

An interlaboratory comparison of four laboratories performing experiments at 74°F (24°C) on three test specimens of polyisocyanurate foam ranging in thickness from 1.3 to 2.6 inches (32 to 64 mm) reported an average deviation of 0.8 percent and a two standard deviation (2σ) value of 2.3 percent. See Reference 26 for further details of this comparison. The thicknesses of the specimens in this round robin are near those proposed by this test procedure.

The predicted lifetime R/inch values for the 15 data sets had one standard deviation of 1.4 percent for 10-year lifetimes and 1.7 percent for 20-year lifetimes.[7]