THERMAL PROPERTIES OF POLYISOCYANURATE FOAM BOARD ROOF INSULATION BLOWN WITH CFC-11 SUBSTITUTES

D.L. McELROY, G.E. COURVILLE, J.E. CHRISTIAN, R.S. GRAVES and R.L. LINKOUS
Oak Ridge National Laboratory
Oak Ridge, Tenn.

Participants at government and industry-sponsored workshops decided to fully evaluate several hydrochlorofluorocarbons for their suitability as blowing agents in polyisocyanurate laminate boardstock. Laminated boardstock was chosen because of its superior insulating qualities, commercial significance, high technical dependence on alternate blowing agents and diverse requirements. The project is under the guidance of a cooperative industry/government steering committee with representation by the Society of the Plastics Industry (SPI), Polyisocyanurate Insulation Manufacturers Association (PIMA), National Roofing Contractors Association (NRCA), U.S. Environmental Protection Agency (EPA) and U.S. Department of Energy (DOE).

A specific formulation with an organic/inorganic facer was selected as generally representing current polyisocyanurate roof insulation technology. With this as a base, foams blown with HCFC-123, HCFC-141b, and two blends of HCFC-123 and HCFC-141b are being compared to foam blown with CFC-11, the current industry standard product.

This study deals with the key question: To what extent are the thermal properties of foams with alternate blowing agents differ from foam with CFC-11? Results are reported that compare foam thermal performance under laboratory conditions, as well as the thermal performance in long-term in situ testing of roof sections. The former involves both full thickness and thin slicing techniques, and utilizes a heat flow meter apparatus with expanded temperature range capabilities (ASTM C 518) and an Unguarded Thin Heater Apparatus (ASTM C 1114). The long-term, in situ testing is carried out on small-scale, conventionally installed roof systems on the Roof Thermal Research Apparatus (RTRA). All tests are being conducted at the Oak Ridge National Laboratory (ORNL) with technical guidance from the steering committee.

KEYWORDS

CFC, diffusion coefficients, HCFC, insulation, polyisocyanurate, thermal aging, thermal conductivity, thermal drift, thermal resistance.

INTRODUCTION

This paper describes progress on laboratory and field thermal properties tests on a set of prototypical, experimental, polyisocyanurate (PIR) foam laminate boardstock. These boards were produced to evaluate the viability of hydrochlorofluorocarbons (HCFCs) as alternatives to CFC-11 as a blowing agent for PIR boards used in roof systems. All boards for the test, those with HCFCs and those with CFC-11, were produced from formulations which were not optimized for performance. Boards made in the future may differ in performance from this set. PIR boards tested were prepared with CFC-11, HCFC-123, HCFC-141b, and two blends of HCFC-123 and HCFC-141b. The primary purpose of the project is to determine if the performance of PIR boards blown with alternate agents differs from boards blown with conventional CFC-11. In addition, the project will provide data for the development of test procedures that accurately characterize PIR thermal aging (thermal drift).

The project is in response to the global ozone depletion problem which is largely a consequence of large releases of ozone-destroying CFC gases. These chemicals face an immediate reduction in use and a total phase-out by the year 2000. The CFC problem has significant implications to the buildings industry. About 50 percent of current rigid roofing insulations used in the United States are affected by these restrictions.* Reduction in the availability of CFCs for insulations may lead to the use of less thermally efficient substitutes and to a potential annual increase in U.S. energy consumption of about one quad (1 x 10^{15} Btu) or approximately 1.3 percent of national consumption. This cooperative industry/government project follows two widely attended workshops; the first to develop a prioritized list of research needs, and the second to focus on details of the highest rated project (i.e., the long-term performance of roofing board foams with non-CFC blowing agents)[1].

The project is sponsored by the Society of the Plastics Industry—Polyurethane Division (SPI/PD), Polyisocyanurate Insulation Manufacturers Association (PIMA), National Roofing Contractors Association (NRCA), U.S. Department of Energy (DOE) and U.S. Environmental Protection Agency (EPA). The project is under the direction of a steering committee with representatives from each of the sponsors and from Oak Ridge National Laboratory (ORNL) where the testing is taking place.

PROJECT METHODOLOGY

SPI/PD members provided the blowing agents and the polyols for the insulation, and PIMA members made available a production line to make the PIR foam boards. Finished boards were sent to ORNL for long-term laboratory and field thermal properties testing, to Massachusetts Institute of

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Technology (MIT) and SPI/PD laboratories for measurement of cell properties, and to all PIMA members for mechanical tests of these prototypical boards. Only the thermal testing at ORNL will be discussed in this report.

PIR boards being tested have been blown with CFC-11 (the control material), HCFC-123, HCFC-141b, and a 50/50 blend and a 65/35 blend of HCFC-123 and HCFC-141b, respectively. All boards provided for this project are 4 feet by 8 feet and are nominally 1.5 inches thick. The three board types with the single blowing agent were produced in June 1989 and delivered to ORNL for testing in July. The boards with the blends were produced in December 1989 and delivered in January 1990. Consequently, the data base for the first three types is more extensive than for the latter two. The preliminary results in this paper will focus on the characteristics of foams with the single blowing agent for this reason.

Field and laboratory tests are being carried out at ORNL. PIR boards have been installed in a field apparatus, the Roof Thermal Research Apparatus (RTRA)[2,3]. The measurement sections are 2 feet by 2 feet with a 1 foot perimeter guard of the same material. Each 4 feet by 4 feet test specimen on the RTRA has two layers of insulation over a metal deck and under a black EPDM membrane. The active measurement area is defined by a 2-inch square, 1/8-inch thick heat flux transducer positioned in the center of the measurement section and between the two insulation boards. The heat flux transducers and thermocouples for temperature measurements are connected to a data acquisition system and a computer which stores hourly averages of measured parameters. Foam boards containing the five blowing agents are represented in the test. A sixth specimen contains the HCFC-141b foam under a white membrane in order to compare performance over two slightly different temperature ranges. The objective of the RTRA tests is to continuously monitor the apparent thermal conductivity (k) of all six specimens and observe thermal performance differences between specimens.

The laboratory test series has three purposes. The first is to calibrate the heat flux transducers used in the field testing, while the second is to provide periodic, steady-state laboratory measurement of the apparent thermal conductivity of the field test samples as validation for the field measurements. The third is to conduct a series of laboratory thermal aging tests on these prototype PIR foams that produce data for a subsequent industry standard on aging. The lab testing utilizes the ORNL Unguarded Thin-Heater Apparatus (UTHA) (ASTM C 1114)[4] and the Heat Flow Meter Apparatus (HFMA) (ASTM C 518)[5]. The former is an absolute, longitudinal-heat-flow method consisting of an unguarded, electrically heated, flat, 3 feet by 5 feet nichrome screen wire heat source sandwiched between two horizontal layers of insulation with flat isothermal bounding surfaces. The UTHA can be operated either in a two-sided mode with specimens of insulation on either side of the screen or in a one-sided mode with the specimens of insulation only on one side. The UTHA operates within a mean insulation temperature in the range of 75°F to 120°F. A determinate error analysis of the two-sided heat flow mode of operation predicts a maximum uncertainty of 1.7 percent if ΔT is 9°F and 0.7 percent if ΔT is 54°F.[6,7] Results with Standard Reference Materials 1450b and 1451 are within 1.2 percent of values certified at the National Institute of Standards and Technology (NIST).

The HFMA[8] is a comparative heat flow meter. It also is a horizontal device with top and bottom 24-inch square isothermal plates with calibrated 10-inch square heat flux transducers in the center of each. The temperature of each plate can be separately controlled to provide a range of ΔTs, and either heat flow up and heat flow down. The range of mean temperatures available with the device is from 20°F to 120°F. The apparatus accommodates specimens with thicknesses between 0.5 inch and 7 inches. Based on calibrations with NIST Standard Reference Materials, the uncertainty of measurements over the temperature and thickness ranges indicated is less than ± 5 percent.

The final series of tests are being carried out on a recently built Roof Mechanical Properties Research Apparatus (RMPRA). This apparatus is an unoccupied, 32 feet by 72 feet, one-story structure predominately below grade with a roof platform about 5 feet above grade. The roof deck is divided in half by a wooden control curb. Half of the roof is a built-up roof system, and the other half has EPDM systems, fully adhered and mechanically attached. Each type of roof system incorporated all five insulation products. All test systems have two layers of the 1.5-inch thick insulation. In some cases the organic/inorganic facers on the insulation are perforated. The RMPRA Research Program is discussed in another paper in these proceedings. Six instrumented panels are included in this installation to provide quantitative performance results on boards foamed with CFC-11, HCFC-123 and HCFC-141b.

A comprehensive series of installation tests has been designed to determine whether roof systems with the new foams perform comparably to foam with CFC-11 under typical installation procedures. Since these tests were only recently initiated, they are not discussed in this report.

LABORATORY RESULTS

Task A—Steady-State Thermal Measurements

Figure 1 shows the temperature dependency of k as measured in the UTHA and the Advanced R-Matic Apparatus for the Task A specimen blown with CFC-11. The panels for the other blowing agents showed a similar temperature dependency for k, i.e., a level value of k below 60°F, a nearly linear temperature dependence above 80°F, but a displacement in k that depended on blowing agent and age at the time of testing. The k-values determined with the UTHA are lower than the k-values determined with the Advanced R-Matic Apparatus in the temperature range of overlap, but are within the experimental uncertainties expected for the two apparatuses. Because the UTHA is more accurate, our data analysis is weighted toward the UTHA k values. A least squares fit was produced for both data sets. Each curve for the Advanced R-Matic data showed a minimum and was displaced to lower k-values to produce agreement with the UTHA data from 80°F to 120°F. The resulting curve is shown in Figure 1. Table 1 contains the equation k values (including the facers) as function of temperature. Table 1 also shows the specimen density and the time since manufacture when the tests were conducted.

The results shown in Table 1 describe the thermal performance of the respective panels just prior to their installation in the RTRA (on August 28, 1989 for single blowing agent panels and on January 12, 1990 for the panels with blends). Boards with single blowing agents were initially tested at times from 65 to 78 days after production. Thermal conductivity values are taken from the smooth curve in Figure 1. Results for RTRA panels with foams blown with blends at an age of 14 to 19 days show that these foams had k (75°F) values within ½ percent of each other. Density measurements were made first on whole foam boards with facers, and then on a planed centerpiece, the core. Note that the detailed results for the single blowing agent boards show that:

$$k(\text{CFC-11}) \blacktriangleleft k(\text{HCFC-123}) \blacktriangleleft k(\text{HCFC-141b}). \quad (1)$$

After exposure in the RTRA for 241 days and at an age of 330 to 340 days, the order relation remained, but the average k had increased 8.6 percent for CFC-11, 11.1 percent for HCFC-123, and 9 percent for HCFC-141b.

Task B—Slicing Technique

The specific objective of Task B is to establish k at 75°F as a function of aging times at two different conditioning temperatures, 75°F and 150°F, and for three thicknesses of insulation planed from the original boardstock. These thicknesses were nominally 33mm, 19mm and 10mm. Thermal measurements were carried out in the Advanced R-Matic Apparatus. Table 2 indicates the time, in days, that each specimen was held at the aging temperature between measurements with the Advanced R-Matic Apparatus.

This test procedure provides a means to monitor the diffusion processes that causes foams to slowly lose their insulating quality as a function of time. Air diffuses into the foam cells and the blowing agent diffuses out of the foam cells. This process changes the cell gas composition which changes the cell gas thermal conductivity, and this changes the product thermal resistance.

If one simply assumes that k can be described by an exponential dependence on gas diffusion coefficient (D), time (t) and thickness (h):

$$k = k_0 \exp\{ (Dt)^{1/2}/h\} \quad (2)$$

where k_0 is the initial thermal conductivity. Equation (Eq.) 2 may be rearranged as:

$$\varphi n\ k = \varphi n\ k_0 + (Dt)^{1/2}/h \quad (3)$$

Figure 2 shows the increase of k (75°F) (plotted as φn 100 k for convenience) as a function of time$^{1/2}$/thickness, (days$^{1/2}$/mm) for specimens of three thicknesses of foam blown with CFC-11 and aged at 75°F. The test data for the specimens of three thicknesses show two distinct linear regions of behavior, with an intermediate transition zone. The thin specimen has reached larger values of $t^{1/2}/h$ than the thick specimen. The authors believe the first linear region should be associated with the increase in k due to the influx of air components, and the second lower slope, linear region should be associated with the loss of CFC-11 from the foam. The results of five tests up to 190 days after slicing are similar to independent MIT model predictions[9,10] (also shown in Figure 2) for 50.8mm thick specimens aged for 5,400 days ($t^{1/2}/h$ of 1.45) and 5.08mm thick specimens aged for 15 days ($t^{1/2}/h$ of 0.76) at 75°F. The predictions are higher in k due to the MIT model assumptions, but the behavior of k with $t^{1/2}/h$ is supportive of the test results. Similar results have been obtained for specimens aged at 150°F.

In order to obtain preliminary values for the diffusion coefficients and the initial k values from Eqs. 2 and 3, the authors have used

$$\varphi n\ k\ (\text{Region 1, Air}) = \varphi n\ k_1 + (D_1\ t)^{1/2}/h \quad (4)$$

$$\varphi n\ k\ (\text{Region 2, Blowing Agent}) = \varphi n\ k_2 + (D_2 t)^{1/2}/h \quad (5)$$

where k_1 is the projected initial k of the foam (Region 1),

k_2 is the intercept for Region 2,

D_1 is the effective diffusion coefficient for air components into the foam, cm²/s and

D_2 is the effective diffusion coefficient of the blowing agent out of the foam, cm²/s.

The resulting values obtained are given in Tables 3 and 4. D-values were found to be very sensitive to the input test data and this result was interpreted to mean that more data are needed to reduce uncertainty. Table 3 also shows D_1, D_2 and the D_1/D_2 ratios obtained for 75°F and for 150°F aging.

The results for 75°F aging show D_1 values near 1.5 x 10^{-8} cm²/s (10 or more data points), D_2 values from 1 to 3 x 10^{-10} cm²/s (4 data points) and D_1/D_2 ratios of 50 to 150. These test data are less than those derived from the fits to the MIT model predictions for aging at 75°F, since different foams are involved in the comparison. The MIT model calculates the foam k using values of diffusion coefficients for oxygen, nitrogen and blowing agent.

The results for 150°F aging show D_1 values up to 11 x 10^{-8} cm²/s, D_2 values of 3 to 8 x 10^{-10} cm²/s, and D_1/D_2 ratios of 40 to 350. The values for 150°F aging are larger than those for 75°F aging, which shows that the diffusion rate increases with temperature, as expected. It is premature to speculate on these D-values. The D-values depend on the foam structural characteristics (cell wall thicknesses) and may provide a valuable guide to optimizing this prototypical, experimental boardstock. It should be clear that if one assumed another model to describe the change of k with D, t, and h, then one would obtain other values for D. The D-values are expected to be different for each gas and to depend on temperature. Clearly, additional data are needed to help define the D-values.

Table 4 contains the initial values of k, k_1 and k_2. The average percent deviation for the data fits (Eqs. 4 and 5) is less than ±0.7 percent and less than ±0.05 percent for the MIT model. These deviations are low and support the use of Eqs. 4 and 5 to describe the accelerated aging of the foams. The values of k_1, the initial k of the foam, right after slicing, can be used to compare the impact of the blowing agents before.any aging occurred. The 75°F aging results show that the order of k_1 values from low to high are: CFC-11, HCFC-123 (9 percent), 50/50 (11 percent), 65/35 (11 percent) and HCFC-141b (15 percent), where the values in parentheses is the percent increase in k over that of the foam blown with CFC-11. This ranking agrees with that of the gas k values.

FIELD RESULTS

Weekly thermal conductivities, calculated from heat fluxes and temperature differences, collected for a 40-week period from September 1989 until May 1990 are shown in Figure 3 for the combined two-board test systems containing CFC-11, HCFC-123 and HCFC-141b boards under the black EPDM. These values represent the actual k-value for each week reported at the combined arithmetic board mid-plane insulation temperature experienced during that week. The bottom set of data represent the CFC-11 boards, the middle HCFC-123 and the upper HCFC-141b. The relative performance of all three boards remains the same for the entire measurement period. These data show increasing k-value over time. A slight decrease in k-value occurred between the age of 150 and 250 days. This period represents the winter season with low mean insulation temperatures and, typically the thermal conductivity decreases with decreasing mean temperatures as shown in Figure 1.

The temperature effect can be eliminated by adjusting k to a 75°F value using the k-T relationship obtained from Table 1. The k at 75°F, resulting from the non-linear equation used to fit the steady-state laboratory measurements at five different temperatures of each of the five different boards, is subtracted. This leaves an equation that describes the delta k between any mean insulation temperature and that at 75°F. Then, this Δk is subtracted from the field data points. The k-values shown in Figure 4 are normalized to an insulation temperature of 75°F. This procedure assumes that the slope of the k-value versus mean insulation temperature remains the same for the entire testing period reported in this paper.

The aging caused by oxygen and nitrogen diffusion into the polyisocyanurate foam and by blowing agent diffusion from the foam is more clearly depicted in the presentation of k-values at a fixed temperature. The planing study in the previous section supports that there are two diffusion phenomena and the dominant aging effect appears to be air diffusion into the cells in boards with 1.5 inch thickness for at least the first 365 days. Since field data has only been collected for about 280 days, it is anticipated that a plot similar to Figure 2 will only show evidence of first-stage (air) diffusion.

Figures 5, 6 and 7 show the increase of field measured k (75°F) plotted in the same form as the laboratory slicing data (shown in Figure 2). Data on these curves are for foams with CFC-11, HCFC-123, HCFC-141b under a black EPDM, and one for HCFC-141b under a white EPDM.

The resulting effective air component diffusion coefficients and the initial k values obtained from the field data are shown in Tables 5 and 6 and compared with the values derived from the slicing analysis, aged at 75°F and 150°F (see Tables 3 and 4).

The effective air diffusion coefficients appear to be higher in the faced field specimens than laboratory measurements on the unfaced sliced specimens conditioned at 75°F by 20 to 71 percent for those specimens under the black membrane. The same HCFC-141b boards under a white membrane lead to a surprisingly higher value than that under the black membrane. The air diffusion appears to be lower in the field specimens under the black membrane than in laboratory specimens conditioned at 150°F by 20 to 80 percent. However, the diffusion coefficient derived from the HCFC- 141b boards under the white membrane is actually 21 percent higher than even the diffusion coefficient derived at 150°F conditioned samples.

The field-derived air component effective diffusion coefficients obtained for the HCFC-141b specimens under the white EPDM are suspect since the diffusion rate ordinarily increases with increased temperature. The mean specimen temperature under the black membrane was 77°F, and under the white membrane 70°F. This observation, however, does raise the possibility that average mean temperature is not the only variable driving the initial foam board aging.

Table 6 displays the values of k_i derived from the faced insulation board field data compared to the k_i derived from the laboratory slicing analyses on unfaced specimens. The percent differences between the CFC-11, HCFC-123 and HCFC-141b field specimens under the black EPDM yield k_i values which agree quite well with the planing analyses when compared to the sliced samples aged at 75°F. The k_i predictions are within ±3 percent between the field and laboratory slicing analyses derived values. The mean temperature of the field-installed test specimens from December 1989 until May 1990 was approximately 77°F. The values of k_i can be used to compare the initial impact of the alternate blowing agents before any aging occurs. The field data suggest that the percent increase in k over that of the other non-blended blown boards with CFC-11 is 6.4 percent for HCFC-123 and 9.6 percent for HCFC-141b. This is the same ordering (9 percent and 11 percent) as estimated by the planing tests.

The long-term (5 + years) prediction of the thermal resistivity of the specimens cannot be made confidently with less than one year's worth of continuous field data from the 1.5-inch thick faced boards. After approximately one year, the diffusion of the blowing agents should begin to dominate the aging effect. Data collected after one year should provide some insight into the effective blowing agent diffusion in these full-thickness boards.

Using the regression fits of the field data for all four test specimens shown by the line of Figures 5, 6 and 7, the predicted thermal resistivity at 75°F for the faced 1.5-inch thick experimental foam boards can be made at a one-year aging time. Table 7 contains these aged field resistivity predictions and compares them to the unfaced 1.5-inch thick boards aged at 75°F and 150°F derived from the planing analyses. The field data derived predictions are 1 to 5.3 percent less than planing analyses predictions for unfaced boards at 75°F, and 4.4 to 7.5 percent above the resistivity prediction for the planing analysis derived samples at 150°F. The faced field-installed boards appear to be aging after one year somewhere between that which can be predicted by laboratory aging at 75 and 150°F. It is important to recall that the field exposure of these experimental boards has not yet seen a full summer season.

A crosscheck of the RTRA measurement of resistivity and steady-state measurements of the exact same specimens taken on the UTHA thin screen heater are shown in Table 8. The RTRA Two-foot assemblies k-value was measured prior to installation (60-80 days of age) and after 240 days of exposure at age 330-340 days. The steady-state laboratory measurements are compared to in situ data derived from linear regression of each of three test specimens; CFC-11, HCFC-123 and HCFC-141b under black membranes.

The RTRA data yield resistivity values that average 4.1 percent lower than the laboratory measurements taken initially before any exposure. The RTRA data yield resistivity values that average 6.6 percent lower after the first periodic check of field data with laboratory data. The first periodic check with steady-state laboratory measurements was conducted a little less than one year since these boards were produced. The observations suggest about a 5 percent offset, or a .2 to .6 h ft^2°F/Btu in. lower in situ resistivity, than that measured by steady-state means in the laboratory. This agreement is believed to be within the combined uncertainty of the two measurements. It is important to note that the emphasis of this overall project is to determine the relative differences between an experimental laminate board blown with CFC-11 compared to experimental prototypes blown with HCFC alternatives.

DISCUSSION

Three types of thermal measurements are being carried out. Insulation specimens with each of the blowing agents are installed in the RTRA, an outdoor test facility, where they are exposed to local ambient conditions and continuous measurements of the thermal conductivity are available. These same specimens were tested in the laboratory under steady-state conditions before installation, and are being removed for confirmation of tests in the lab every six months. Finally, special samples of three different thicknesses are being aged at 75°F and 150°F to monitor k as a function of temperature, time and thickness.

From the field measurements, the extrapolated fresh-foamed apparent thermal conductivities for insulations with pure blowing agents are:

CFC-11 $k = 0.1231$ (Btu in./h ft^2°F)
HCFC-123 $k = 0.1310$
HCFC-141b $k = 0.1349$

From this, one sees that the thermal conductivity of the non-CFC alternates are greater by 6.4 percent and 9.6 percent for HCFC-123 and HCFC-141b, respectively. The same general results are obtained from the laboratory data. The implication of these results is that, subject to optimization of the foaming process, the performance penalty, compared to CFC-11, for using these blowing agents and equal thicknesses, is less than 10 percent.

Thermal drift is readily observed in both the lab and the field measurements. For all specimens the drift after about three months of room temperature storage and six months of field exposure was from 8 to 11 percent of the initial value.

It has been postulated that the increase in k, the thermal drift effect, varies as a function of time(1/2)/thickness and that PIR boards exhibit two distinct gas diffusion stages. The first is associated with air diffusion into the cells and the second with diffusion of the blowing gas outward from the cells. The former appears to be at least 50 times faster than the latter. Once this first process is complete the much slower diffusion of gas from the cells is more readily apparent. Because it is a slow process, the subsequent changes in thermal conductivity are also slow. The laboratory results are consistent with this postulate, and based on the available data, the transition region from the first to the second diffusion process occurs at about one year for 1.5-inch thick PIR at 75°F. The field specimens have only reached about one year of in-service time and should soon begin to show a transition from the first to the second stage after which the rate of change of thermal conductivity should slow considerably. The important consequence of this analysis is its impact on aging tests for PIR foams. The current ASTM procedure calls for 180 days at 75°F with no mention of thickness.[11] The above results suggest that thickness must also be considered. For example, a 1-inch thick PIR insulation reaches the transition region in about 180 days at 75°F, whereas a 2-inch thick sample requires 635 days. It should be noted that other factors, not studied in this project, also influence the diffusion processes in foam insulations. These include the type of facer on the insulation and, in some instances, a thin surface layer of foam having a different density than the core insulation. A committee of the American Society of Standards and Testing, ASTM C 16.30, is currently preparing a foam aging standard test procedure based on slicing techniques similar to those being used in this project.

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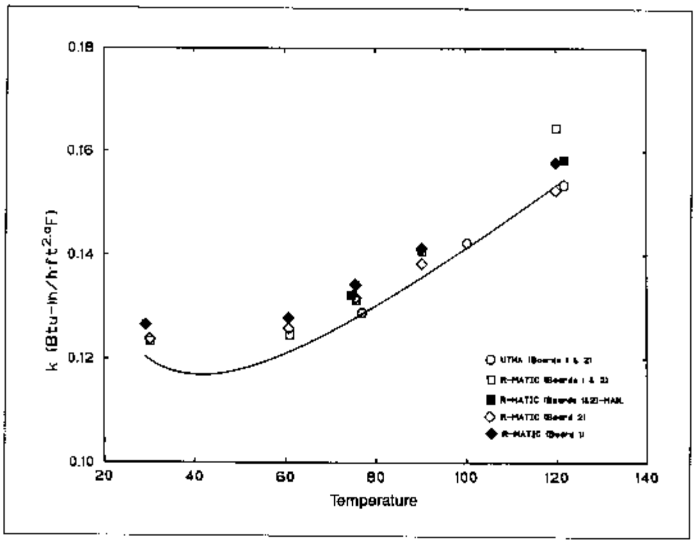

Figure 1 *The temperature dependency of the apparent thermal conductivity of boardstock blown with CFC-11.*

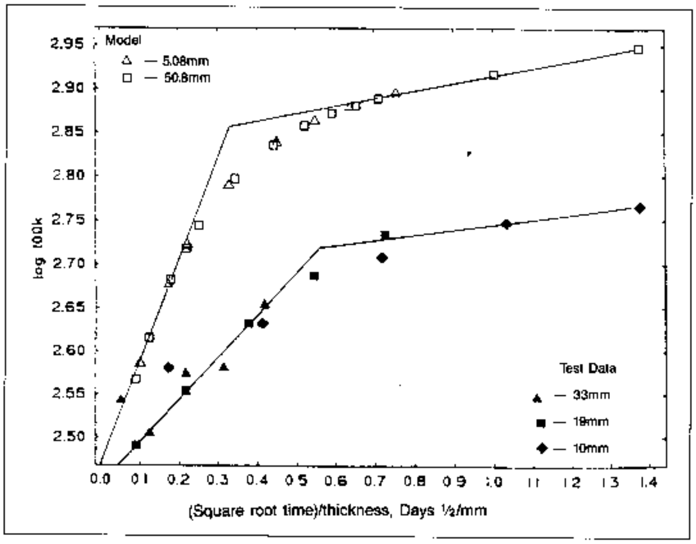

Figure 2 *Increase in k (75°F) for thin specimens of rigid board foamed with CFC-11 aging at 75°F compared to model predictions. The abscissa is the natural log (base 10) of 100* k.*

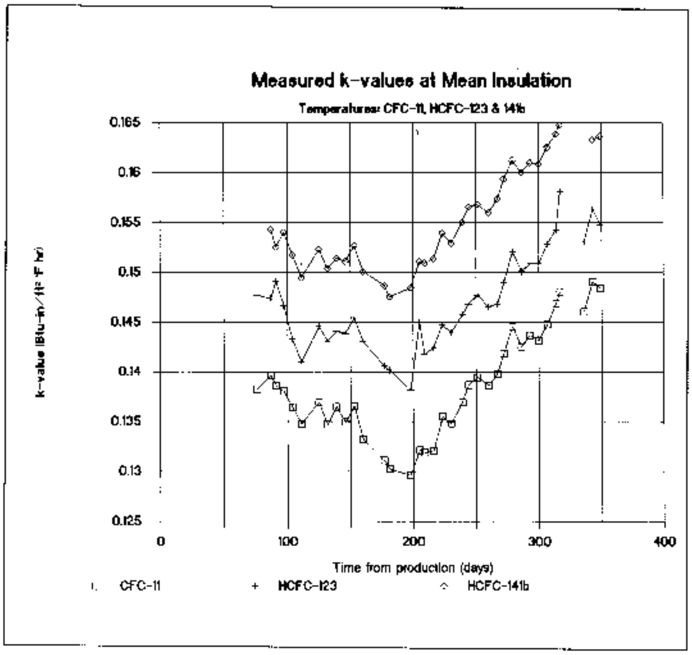

Figure 3 *Measured k conductivity at weekly mean insulation temperatures for CFC-11, HCFC-123 and HCFC-141b boards.*

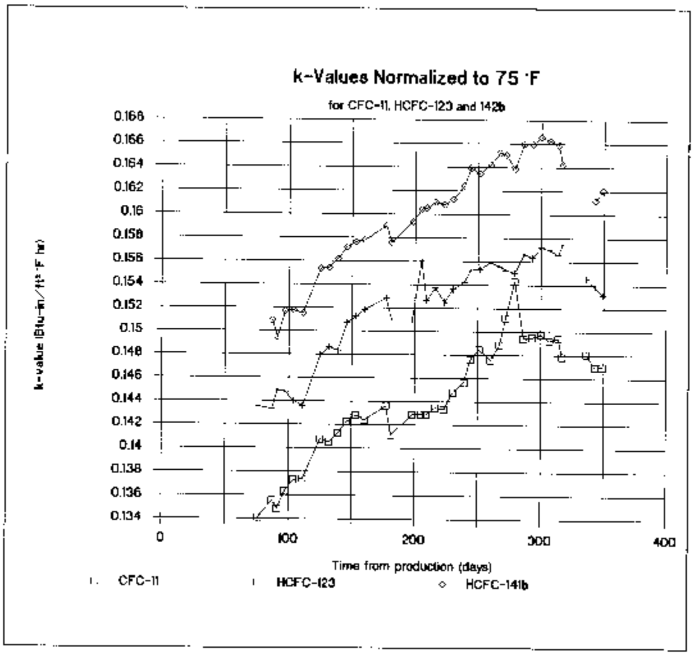

Figure 4 *k-values normalized to 75°F for CFC-11, HCFC-123 and HCFC-141b.*

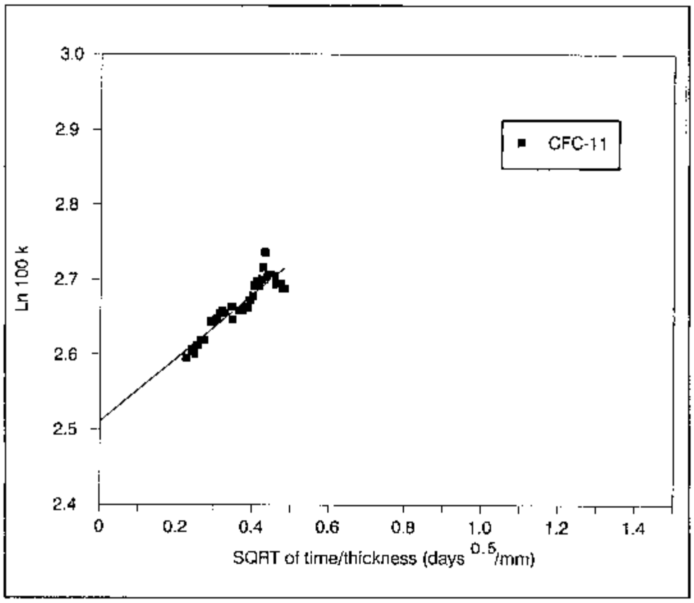

Figure 5 *Increase ink (75°F) for CFC-11 using the weekly field data collected for the first 280 days of exposure.*

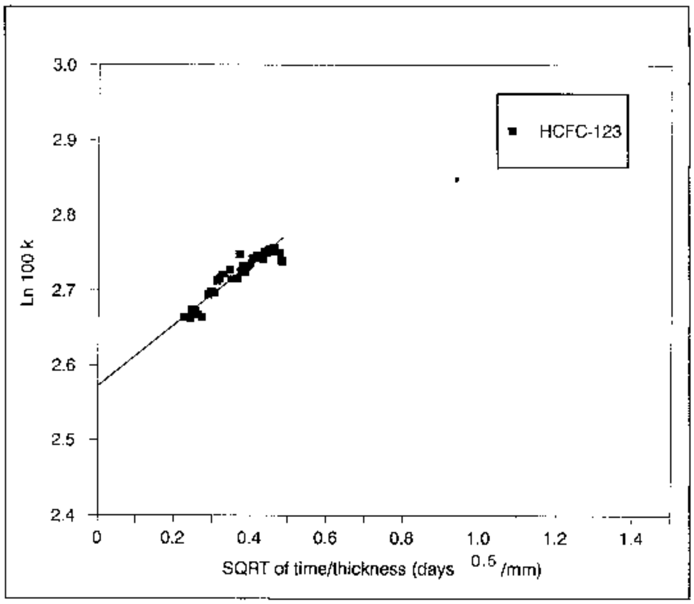

Figure 6 *Increase in k (75°F) for HCFC-123 using the weekly field data collected for the first 280 days of exposure.*

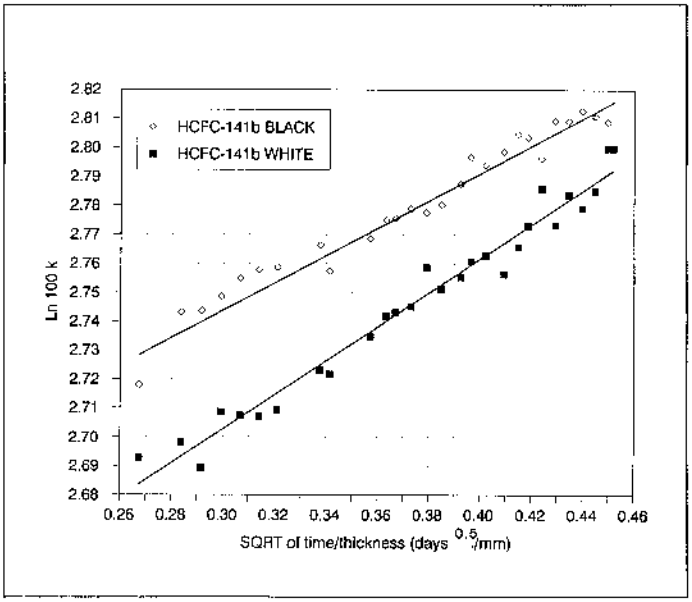

Figure 7 *Increase in k (75°F) for HCFC-141b using the weekly data from both the HCFC-141b under the black and white membranes. (Note: Graph scale is different than that shown for CFC-11 and HCFC-123 in Figures 5 and 6.)*

Temperature	Apparent Thermal Conductivity (Btu•in./h•ft²•°F)				
	CFC-11	HCFC-123	HCFC-141b	50/50	65/35
Age, Days[b]	65 days	71 days	78 days	14 days	19 days
30°F	0.120	0.128	0.140	—	—
45	0.117	0.125	0.134	—	—
60	0.121	0.129	0.137	—	—
75	0.128	0.135	0.143	0.135	0.136
90	0.136	0.143	0.151	0.142	0.142
120	0.153	0.161	0.169	0.156	0.156
Days[c]	334	336	340	—	—
75°F	0.139	0.150	0.156	—	—
Density, lb/ft³					
Panel	2.78	2.78	2.72	2.86	2.82
Core	1.95	1.95	1.91	2.02	1.98

a. Includes organic/inorganic facer.
b. Time since production when tested prior to installation in the RTRA.
c. Includes 241 days of exposure in RTRA under black EPDM membranes.

Table 1 *The thermal conductivity[a] of boardstock blown with CFC-11, HCFC-123, HCFC-141b, and two blends 50/50 and 65/35 HCFC-123/HCFC-141b.*

Task B Specimens	75°F	150°F
CFC-11, HCFC-123 and HCFC-141b	3, 17, 51.5, 106.5, 190	1.5, 13.5, 43, 114.5
Blends of 50/50 and 65/35 HCFC-123/141b	2, 42.5, 74.5	1.5, 29.5, 62.5

Table 2 *Time at temperature when k (75°F) tests were conducted on planed specimens (days measured from time of planing).*

	$D_1 \times 10^8$	$D_2 \times 10^{10}$	D_1/D_2
MIT Model (CFC-11)	**18.78**	**9.23**	**203.5**
75°F			
CFC-11	(10)[a] 1.52	(3) 3.07	49.5
HCFC-123	(11) 1.64	(4) 1.55	105.8
HCFC-141b	(11) 1.51	(4) 0.98	154
50/50	(5) 2.61		
65/35	(5) 2.31		
150°F			
CFC-11	(6) 10.78	(5) 3.08	350
HCFC-123	(6) 6.81	(5) 6.80	100
HCFC-141b	(8) 3.33	(3) 8.28	40.2
50/50	(5) 8.64		
65/35	(5) 6.98		

[a] Number of data points used in fits.

Table 3 *Effective diffusion coefficients derived from aging tests, cm²/sec D_1 (air components) and D_2* (blowing gas).

			Average Percent Deviation	
MIT Model	**k_1** **0.1163**	**k_2** **0.1688**	**Air Region 1** **0.05 (5)**	**Blowing Agent Region 2** **0.01 (4)**
75°F				
CFC-11	0.1206	0.1446	0.71 (10)[a]	0.43 (3)
HCFC-123	0.1317	0.1625	0.38 (11)	0.55 (4)
HCFC-141b	0.1393	0.1693	0.47 (11)	0.45 (4)
50/50	0.1341	—	0.47 (5)	—
65/35	0.1339	—	0.49 (5)	—
150°F				
CFC-11	0.1260	0.1596	0.64 (6)	0.28 (5)
HCFC-123	0.1374	0.1652	0.57 (6)	0.08 (5)
HCFC-141b	0.1503	0.1670	0.56 (8)	0.03 (3)
50/50	0.1317	—	0.09 (5)	—
65/35	0.1358	—	0.60 (5)	—

[a] Number of data points used in fits.

Table 4 *Initial k (75°F) derived from aging tests (Btu•in/h•ft^2•°F).*

	CFC-11 Black EPDM	**HCFC-123 Black EPDM**	**HCFC-141b Black EPDM**	**HCFC-141b White EPDM**
RTRA data	2.21	1.96	2.58	4.02
Steady-state lab (75°F)	1.52	1.64	1.51	1.51
% Difference[a]	+45%	+20%	+71%	+166%
Steady-state lab (150°F)	10.78	6.81	3.33	3.33
% Difference[a]	−80%	−71%	−23%	21%

[a] $100 \text{ x } \frac{D_1(\text{RTRA} - D_1(\text{Lab})}{D_1(\text{Lab})}$

Table 5 *Effective diffusion coefficients derived from RTRA data and slicing tests in laboratory, 10^{-8} cm^2/sec for the air components, D_1.*

		k_1		
	CFC-11 Black EPDM	**HCFC-123 Black EPDM**	**HCFC-141b Black EPDM**	**HCFC-141b White EPDM**
Field data	0.1231	0.1310	0.1349	0.125
Steady-state lab (75°F)	0.1206	0.1317	0.1393	0.1393
% Difference[a]	+2%	−0.5%	−3%	−10.2%
Steady-state lab (150°F)	0.1260	0.1374	0.1503	0.1317
% Difference[a]	−23%	−4.7%	−10.2%	−5.1%

[a] $100 \text{ x } \frac{k_1 \textit{ (Field)} - k_1(\text{Lab})}{k_1 \text{ (Lab)}}$

Table 6 *Initial k_1 (75°F) derived from field data (Btu•in./h•ft^2•°F).*