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**The Technical Viability of Alternative Blowing Agents
in Polyisocyanurate Roof Insulation: A Cooperative
Industry/Government Project**

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EDITOR'S NOTE

Although Oak Ridge National Laboratory follows the policy of reporting its work in SI metric units, this report uses English units. The justification is that the insulation industry at present operates completely with English units, and reporting otherwise would confuse the meaning for the intended readership. To assist the reader in obtaining the SI equivalents, they are listed below for the units occurring in this report.

Property	Unit used	SI equivalent
Dimension	in.	25.4 mm
Dimension	ft.	0.3048 m
Density	lb/ft ³	16.02 kg/m ³
Power	Btu/h	0.2929 W
Thermal conductivity	Btu·in/h·ft ² ·°F	0.1441 W/m·K
Thermal resistance	h·ft ² ·°F/Btu	0.1762 K·m ² /W
Temperature	°F	°C = (5/9)(°F-32)
Temperature difference	°F	°C = (5/9)°F

ABSTRACT

The cooperative industry/government project to study replacements for the chlorofluorocarbon gas CFC-11 that has been used as a blowing agent for foam insulations has been under way since 1989. Comprehensive reports of results obtained by the Oak Ridge National Laboratory (ORNL) Building Materials Group during FY 1989 and FY 1990 were published in ORNL/TM-11645 (September 1991), and work done during FY 1991 and FY 1992 was published in ORNL/M-2387 (October 1992). This report summarizes results given in those two reports and in 13 open literature publications.

This summary report contains apparent thermal conductivity (k) values from field exposures and laboratory aging of a set of industry-produced, experimental polyisocyanurate (PIR) laminated boardstocks foamed with hydrochlorofluorocarbons (HCFCs) as alternatives to chlorofluorocarbons (CFCs). The PIR boards were blown with five gases: CFC-11, HCFC-123, HCFC-141b, and 50/50 and 65/35 blends of HCFC-123/HCFC-141b.

The k -values were determined from 30 to 120°F using techniques that meet American Society for Testing and Materials (ASTM) C 1114 (Unguarded Thin-Heater Apparatus) and ASTM C 518 (Heat Flow Meter Apparatus). The increase in k observed for field exposure in the ORNL Roof Thermal Research Apparatus (RTRA) was confirmed by independent laboratory tests. The observed laboratory increase in k was about the same, between 22 and 28%, for all three blowing agent foams for a 1000-day field exposure in the RTRA.

Thin specimens were planed from the industry-produced boardstock foams and aged at 75°F and at 150°F for up to 875 days. An exponential dependency of k with the quantity (diffusion coefficient $\times$ time)^{1/2}/thickness, yielded effective diffusion coefficients for air into the foams and blowing agent out of the foams. The foams blown with alternative blowing agents exhibited long-term k -values 7 to 15% above those for CFC-11 foams under similar conditions. The thermal data have been expressed in terms of scaled time (time^{1/2}/thickness) to provide estimates of the R -value or time-averaged R -value for full-thickness boards.

Boards from the same batches of industry-produced boardstock that were laboratory tested were installed in outdoor test [RTRA and the Envelope Systems Research Apparatus (ESRA)] facilities and instrumented to determine if the insulation thermal performance aging characteristics depend on how they are handled and installed in the field. The 3.4 years of field data validate the laboratory-accelerated thermal aging procedure. The laboratory measurements of the apparent thermal conductivity (k) of 0.4 in. thick slices conducted over a period of less than a year, as an example, can be used to predict the k of 1.5–2.0 in. full-thickness PIR laminated board stock for 12–20 years after production. The k -factor prediction over time from the aging procedure is compared with actual field data on the 1.5-in. full-thickness specimens installed in a variety of common roof applications. The permeable facer used on these experimental boards is representative of over 90% of the PIR laminated board stock installed in roofs in 1991. In-situ thermal performance of these well-characterized boards under white and under black ethylene propylene diene monomer (EPDM) membranes is compared with the accelerated aging procedure and with boards from the same batch in several other roofing systems: mechanically attached EPDM, fully adhered EPDM, and built-up roof. The

comparisons show that the accelerated aging procedure should be seriously considered for providing PIR laminated board stock in-service thermal performance information to building owners and roofing contractors.

The relative performance of test specimens of HCFC-141b under a black and under a white membrane is reported, and the data suggest that differences are relatively small. The field data analysis suggests that the percentage increase in k over that of the foam blown with CFC-11 is, after 1000 days of aging, 2.6% for HCFC-123 and 9.5% for HCFC-141b. This leads to the same ordering of foams as derived from the thin-specimen analysis.

This cooperative project provided a means to combine the talents of manufacturers, users, and measurers to focus on the global issue of reducing CFC use in PIR foam insulations. ORNL should recommend this type of project to the producers of other types of foam.

1. INTRODUCTION

This report is a summary of the cooperative industry/government program to establish the viability of alternative blowing agents to chlorofluorocarbons (CFCs). The project was initiated in 1989 following two workshops that focused on needed research on thermal insulation blown with substitutes for CFC-11 and CFC-12.¹

The project is directed by a steering committee of representatives of the sponsors and of Oak Ridge National Laboratory (ORNL). The purpose of the project is to determine if the performance of polyisocyanurate (PIR) roof insulation foam boards blown with alternate agents differs from the performance of boards blown with CFC-1 (ref. 2).

This report describes apparent thermal conductivity (k) results obtained from field and laboratory tests from 1989 to 1992 on a set of experimental PIR laminate boardstock produced to evaluate the viability of alternative hydrochlorofluorocarbons (HCFCs) as blowing agents. All boardstock was manufactured from similar formulations that were not optimized for thermal performance. Commercial boardstock made in the future may differ in performance from this set³. The PIR boards were prepared with CFC-11, HCFC-123, HCFC-141b, and 50/50 and 65/35 blends of HCFC-123/HCFC-141b.

The project publications include two ORNL reports and 13 publications in the open literature.²⁻¹⁴ Copies of these open literature publications are available from R. S. Graves. References to these publications are used to reduce the length of this summary report. Appendix A is a bibliography of publications produced by this project.

2. OBJECTIVES

The cooperative project at ORNL includes two field tasks that are supported by two laboratory tasks. One field task is to monitor thermal performance of roof test panels of the boardstock installed in the ORNL Roof Thermal Research Apparatus (RTRA) and exposed to local seasonal weather cycles. A second field task is to examine the behavior of roof panels for a range of installation conditions in the ORNL Envelope Systems Research Apparatus (ESRA). The objective of the first laboratory task (Task A) is to establish the k of boardstock from mean temperatures of 30 to 120°F (0 to 50°C) before installation and as a function of exposure time to field conditions in both the RTRA and the ESRA. The objective of the second laboratory task (Task B) is to establish k at a mean temperature of 75°F (24°C) as a function of aging time at 75 and 150°F (24 and 65°C) for specimens of three thicknesses sliced from the original boardstock (accelerated aging procedure).

The major objective of field testing these insulation boards is to provide benchmark field performance with which laboratory thermal aging results can be compared. The field data validate the accelerated thermal aging test procedure. The 2-3 year field exposure tests were designed to determine whether roof installation practices and roof system type impact the thermal aging characteristics.

The dedicated outdoor test facilities used for these field exposures are located at ORNL in Oak Ridge, Tennessee. Continuously collected average hourly temperatures and heat flux data are used in data analysis procedures and reported as weekly k -factors for the full test period. HCFC-141b, HCFC-123, and CFC-11 blown PIR laminated boardstock were installed loosely stacked under an ethylene propylene diene monomer (EPDM) membrane from September 1989, and under fully adhered EPDM and built-up roof (BUR) membrane from June 1990 to October 1992. The two blends of HCFC-123 and HCFC-141b blown PIR were installed loosely stacked under an EPDM membrane from February 1990 to October 1992. The HCFC-141b boards were installed loosely stacked under both a black and a white membrane to determine if keeping the installed insulation at a lower temperature might reduce the PIR foam board aging rate.

Since the aging of PIR insulation can be affected by temperature and the permeance of the facers, the system in which it is installed can impact its aging rate. Shipp et al.¹⁵ have demonstrated that the color of the roof impacts the temperature of the roof surface and therefore the temperature of the roof system components. The attachment of a fully adhered membrane directly to the insulation can reduce the permeance of that surface and therefore retard the aging rate. It has been hypothesized that a reduction in aging occurs in BUR systems where the asphalt encapsulates the boards. If these system effects are significant, then any acceptable accelerated aging procedure would have to be sensitive to how insulation boards are installed.

The field data are compared with the laboratory k -factor measurements on test specimens taken before and at six-month intervals during field exposures. The field data are compared with the accelerated aging procedure based only on the laboratory k -factor measurements of a stack of four 0.4-in. thick slices. The thin slices came from planing full 1.5-in. specimens of the PIR stock that was used as the field-exposed boards.

3. EQUIPMENT AND ANALYSIS

The following paragraphs briefly describe the equipment used in the project. The field testing was undertaken on the RTRA and the ESRA at ORNL (refs. 3-17). These facilities are shown in Figs. 1 and 2.

3.1 ORNL ROOF THERMAL RESEARCH APPARATUS

The RTRA is a 10 × 30 ft. continuously conditioned building that can accommodate eight 4 × 4 ft. test roofs. Six of these test roof slots were used for this project. Figure 3 shows a top view of how two of these test roofs were installed in the RTRA. The central 2 × 2 ft. section of each foam test specimen is physically separated from the remaining foam so that it can be removed periodically to measure its k-factor and check calibration of the heat flux transducer. The 1-ft. perimeter pieces are used as a passive thermal guard. Figure 4 shows a cross section of the two layers of 1.5-in. thick PIR foam insulation and a 0.045-in. EPDM membrane resting on a metal deck. A 2 × 2 in. 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 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 conditions, as well as solar and infrared radiation.

3.2 ORNL ENVELOPE SYSTEMS RESEARCH APPARATUS

The ESRA is a 32 × 72 ft. one-story conditioned, temperature- and humidity-controlled building that projects less than 5 ft. above grade for easy access to the roof surface. This permanent facility was designed and built explicitly to accommodate the needs of this research project. Complete details for this facility have been reported by Smith et al.⁴ The ESRA was constructed in a manner that allows the roof area to receive the same environmental exposure as the RTRA. The roof deck is 22-gauge galvanized steel, 1.5 in. deep with a wide rib, and can be sloped .25 in./ft by varying the heights of the bearing walls.

The overall design of the ESRA roof complies with the minimum requirements of the Steel Deck Institute Design Manual (1989 edition) and the FM Approval Guide and obtains maximum permitted deflection. This design results in a "bouncy" deck that exposes the insulation to typical severe loading conditions during application. The design loads of 10 lb/ft² for the west half and 19 lb/ft² for the east half can accommodate heavier roofs than installed for this exposure test, and a single-ply system ballasted with normal weight concrete pavers and aggregate surfaced BUR, respectively.

The ESRA roof plan is depicted in Fig. 5. The roof deck is divided in half by a 1-ft-high curb wall. On one side of the roof, two 1.5-in. thick foam boards with five different blowing agents (CFC-11, HCFC-141b, HCFC-123, 50/50, and 65/35 blends of HCFC-123 and HCFC-141b) are installed in two different types of BUR systems with and without perforated facers. The other half of the ESRA roof has the same five board types

Fig. 1. Photograph of the Roof Thermal Research Apparatus at Oak Ridge National Laboratory.

Fig. 2. Photograph of the Envelope Systems Research Apparatus at Oak Ridge National Laboratory

Top View of CFC-11 vs. HCFC 123 Panel

SIDE B : BLACK EPDM MEMBRANE

SIDE A : BLACK EPDM MEMBRANE

- EPDM MEMBRANE IS MECHANICALLY ATTACHED TO ALUMINUM FLASHING
- HCFC 123 and CFC-11 are NOMINALLY 1.5" THICK BY 2 LAYERS TOTAL 3.0"
- ALL TEST PIECES REST ON METAL DECK

Fig. 3. Top view of a Roof Thermal Research Apparatus test panel.

Fig. 4. Cross section of instrumentation in field assembly.

Fig. 5. Envelope Systems Roof Apparatus roof plan showing the location of the test specimens discussed in this report.

with perforated and unperforated facers under a fully adhered and mechanically fastened EPDM membrane.

Six instrumented panels (with unperforated facers) were installed in the southern half of the roof deck, as shown in Fig. 5. Two 3 × 5 ft. sections of each foam type were cut from the center of two full-size boards. In June 1990, the stacked sandwich assemblies in the ESRA were instrumented in the same manner as the central test sections on the RTRA. The data collection process began at the same time cooling and heating equipment were made operational in September 1990, about 2 months after application of the roof.

The CFC-11, HCFC-123, and HCFC-141b PIR foam from the same batch (June 1989) was used in the RTRA and ESRA. These boards had been stored at ORNL under enclosed unconditioned space for about a year before installation on the ESRA. Three of the two-layered insulation stacks (CFC-11, HCFC-123, and HCFC-141b) mounted in the ESRA were installed under a BUR. In this application, the first layer of insulation was mechanically attached to the deck with metal fasteners—screws and plates. The second layer was attached with Type IV hot asphalt at 330 to 440°F and covered with three fiberglass sheets fully adhered directly to the insulation with hot asphalt and surfaced with a glaze coating. During the attachment of the fiberglass sheets, the asphalt temperature was maintained in the range of 449 to 468°F.

The other three stacks (CFC-11, HCFC-123, and HCFC-141b) were installed under a black 45-mil-thick EPDM complying with American Society for Testing and Materials (ASTM) D 4673, Type I, Grade 2, Class U. Both layers of insulation were mechanically attached with screws and plates. A neoprene-based adhesive with acetone solvent was applied to the insulation facer and EPDM with a roller. After the solvent flashed off (~60 min), the EPDM was mated with the insulation.

Both the EPDM and the BUR systems were installed by a roofing subcontractor in accordance with commonly accepted good industry practice and manufacturer recommendations. An exception was made with the BUR system, whereby the BUR was directly applied to the insulation rather than to a thin cover board as recommended in National Roofing Contractors Association Bulletin 9 (September 1988). Since this application is sometimes performed, the more severe temperatures encountered by the insulation in this application were deemed to represent a reasonable test.

The variations in the field-tested roof systems permit the following comparisons.

1. The two HCFC-141b PIR systems installed on the RTRA can be compared to determine whether the color or reflectance of the membrane will affect the aging rate of the PIR foam roof insulation.
2. The systems in the RTRA can be compared with the systems installed in the ESRA to ascertain application effects. The boards in the RTRA were set in place carefully and were never walked on, even during installation.
3. Comparisons between the RTRA two-layered dry stacked specimens with a black membrane and the BUR, and the fully adhered EPDM systems on the ESRA may supply evidence of the effect of various encapsulations such as EPDM fully

adhered to one side of the foam board and asphalt applied to three sides of the two-layered foam board stack.

3.3 FIELD DATA COLLECTION AND ANALYSES

Temperature and heat flux data from the sensors installed in the test panels are automatically recorded at 1-min intervals and averaged into hourly values. A computer program PROPOR (Properties—Oak Ridge) is used to compute the thermal conductivity of the insulation.¹⁹⁻²¹ PROPOR is an application of one-dimensional inverse heat transfer analysis. Using a time 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 final output from PROPOR, as configured for this project, is two weekly estimates of thermal conductivity for the insulation at two temperatures for the two-board combination. This output is used to determine k at the mean insulation temperature experienced for the week for the two-board combination.

The k -factor for PIR insulation varies with mean temperature. The actual field thermal performance is better (lower k -factor) in the winter than in the summer (higher k -factor). Usually, k -factors are tested in the laboratory on insulation with an average temperature of 75°F. To see the thermal drift of the weekly field data clearly and to compare the field data with the laboratory accelerated aging procedure, two different data analysis procedures were developed. The first procedure is a normalization routine that permits the use of all the weekly data and adjusts the field thermal conductivities to a single average insulation temperature of 75°F. This is accomplished by using laboratory k -factors measured at discrete points in time as a function of average specimen temperature. Figures 6–8 show the k measured in the laboratory versus temperature for the CFC-11, HCFC-141b, and HCFC-123 stacks measured after exposure in the RTRA for three different lengths of time. Notice that in most cases, the k at lower temperatures decreases from 30 to 40°F, and these decreases are reduced over time.

The normalization procedure uses the data shown in Figs. 9–11 to adjust the field-measured k -factors. The correction was obtained by subtracting the k at 75°F from the data shown in Figs. 6–8. Thus the correction at 75°F for all cases is zero. A correction in each week's k -factor is based on the actual average temperature experienced. The k -factors at mean insulation temperatures were adjusted to 75°F using the May 17, 1990, laboratory data to adjust the field data from October 1, 1989, to September 30, 1990; the May 13, 1991, laboratory data to adjust the field data from October 1, 1990, to September 30, 1991; and the September 11, 1992, laboratory data to adjust the field data from October 1, 1991, to October 2, 1992. For example, for the week of May 1, 1990, the boards are normalized using the May 17, 1990, laboratory data for CFC-11, shown in Fig. 9. If the average temperature was 50°F, then the field k -factor at 50°F is reduced by $-0.0097 \text{ Btu} \cdot \text{in}/\text{h} \cdot \text{ft}^2 \cdot ^\circ\text{F}$ to report the apparent thermal conductivity at 75°F.

Using the normalization procedure described above, Fig. 12 shows all the weekly k -factors for 3 years at the actual average insulation temperature for the combined HCFC-141b boards and the normalized k -factors at 75°F. Figure 12 shows how this

CFC-11 k vs Temperature

Laboratory Measurements

Fig. 6. Laboratory thermal conductivity of CFC-11 boards as a function of specimen temperature.

HCFC-141b Black & White k vs Temp.

Laboratory Measurements

Fig. 7. Laboratory thermal conductivity of HCFC-141b boards as a function of specimen temperature.

HCFC-123 k vs Temperature

Laboratory Measurements

Fig. 8. Laboratory thermal conductivity of HCFC-123 as a function of specimen temperature.

CFC-11 k Correction

from Laboratory Measurements

Fig. 9. Correction curve used to normalize the PROPOR k-factor at the weekly experienced average specimen temperature to 75°F for the CFC-11 boards.

HCFC-141b k Correction

from Laboratory Measurements

Fig. 10. Correction curve used to normalize to 75°F for the HCFC-141b.

HCFC-123 k Correction

from Laboratory Measurements

Fig. 11. Correction curve used to normalize to 75°F for the HCFC-123.

HCFC-141b

k-factor - Mean and Normalized to 75°F

Fig. 12. Comparison of the k-factor weekly data at the mean weekly specimen temperature with the same data normalized to 75°F.

normalization procedure tends to flatten the seasonal fluctuations actually experienced with higher relative weekly k-factors in the winter and lower ones in the summer.

The second procedure for reporting the field data, to delineate the thermal aging clearly and to compare with periodic laboratory data taken at 75°F, is to use only those weeks with recorded mean insulation temperatures between 74 and 77°F (ref. 10).

3.4 ORNL UNGUARDED THIN-HEATER APPARATUS

The k of the RTRA panels and the calibrations of the embedded HFTs (Task A) were determined from 75 to 120°F in the ORNL UTHA.²²⁻²⁴ Initial tests were performed in a one-sided heat flow mode on specimens with GAF black facers (0.025 in. thick) in place, as recommended in ASTM C 1013 (refs. 25 and 26). The UTHA tests were performed in a two-sided heat flow mode operation for the ESRA panels.

The UTHA meets the requirements of ASTM C 1114-92 (ref. 22). The UTHA is an absolute, longitudinal heat flow technique with less than 2% uncertainty for steady-state thermal resistance tests at mean temperatures from 70 to 120°F. This technique has been described in the literature, and tests have been conducted on two standard reference materials (SRMs) from the National Institute of Standards and Technology (NIST). The agreement with the NIST values was 0.3% for SRM 1451 and 1.1% for SRM 1450b (ref. 24). Since this value is within the most probable uncertainty of 1.2%, the UTHA k-values documented in this report provide an accurate description of the temperature dependency of k of several materials.

3.5 ORNL HEAT FLOW METER APPARATUS

The thermal conductivities of the RTRA panels (Task A) were determined from 30 to 120°F in the ORNL HFMA.²⁷ This apparatus was also used to determine k at 75°F of the sliced, aging specimens (Task B). This comparative heat flow metering technique is designed to meet ASTM C 518, Configuration B: transducers installed on both faces.²⁸ The ORNL HFMA is described in references 12-29.

As specified by ASTM C 518-91, the HFT is calibrated with SRM 1450b and SRM 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 $\pm 5\%$ by tests on identical specimens in the UTHA and in other C 518 apparatuses. The two-standard-deviation value (2σ) from a comparison with other C 518 apparatuses was 2.2% for planed PIR boards.^{30, 31}

4. SPECIMENS

Thermal performance tests were conducted on two types of test specimens produced from the laminate boardstock manufactured by industry:³² (1) panels for the RTRA and ESRA and (2) thin specimens for aging at 75 and 150°F. The boardstock blown with CFC-11, HCFC-123, or HCFC-141b was produced in June 1989, and the boardstock blown with 50/50 and 65/35 blends of HCFC-123/HCFC-141b was produced in December 1989.

The Task A test specimens were nominally 2 × 2 ft. × 1.5 in. with GAF black facers (0.025 in.) on each face for each type of blowing agent. Two of these specimens formed the central area of each 4 × 4 ft. panel for the RTRA tests. A 2 × 2 × 0.125-in. slot was routed into the lower board to position the embedded HFT at the interface of the two boards, as shown in Fig. 4.

Thermal performance tests and HFT calibrations were performed in a one-sided mode of operation in the UTHA on panels at mean temperatures of 80, 100, and 120°F. Thermal performance tests were performed in the HFMA on the panels (consisting of two boards), the top board, and the bottom board at mean temperatures of 30, 60, 75, 90, and 120°F. Table 1 summarizes the characteristics of panels produced from the boards to be tested before RTRA exposure. The calibration constant, *A*, is reported for each embedded HFT, and this factor is the term by which to multiply the millivolt signal from the RTRA test to obtain the heat flux through the specimen. The calibration constant was obtained from three levels of heat flow through the specimen that spanned the range 0.25 to 2.4 Btu/h · ft².

Table 1. Characteristics of Roof Thermal Research Apparatus (RTRA) panels tested in the Unguarded Thin Heating Apparatus and the Heat Flow Metering Apparatus prior to installation in the RTRA.

Blowing gas	Panel numbers	Density (lb/ft ³)		Age (days)	Calibration constant <i>A</i> (Btu · h · ft ² · MV)
		Panel	Core ^a		
CFC-11	T3B9-1,2	2.78	2.02	65	0.3826
HCFC-123	T2B7-1,4	2.78	2.02	72	0.3859
HCFC-141b (black)	T1B8-5,6	2.72	2.00	76	0.3749
HCFC-141b (white)	T1B8-3,7	2.72	1.97	82	0.3786
Blend 50/50, 123/141b	T1B6-3,4	2.89	2.15	14	0.3849
Blend 65/35, 123/141b	T2B5-1,2	2.78	2.10	19	0.3682

^a Core density corrected for GAF facer weight 0.05625 lb/ft² and air buoyancy effect (0.0740 lb/ft³).

Task B required 2×2 ft. specimens of three thicknesses for each type of blowing agent. Three thicknesses, nominally 1.3, 0.75, and 0.39 in. were produced by planing the facer and foam from boardstock to produce one, two, and four specimens, respectively, for tests in the HFMA. Table 7 of ref. 12 contains the average specimen thickness produced.

Table 2 contains structural results obtained on the three boardstock foams produced in June 1989. The cells are elongated parallel to the direction of boardstock production; cell wall thicknesses are between 0.3 and 0.5 μm ; and the fraction solid in the cell wall is greater for the HCFC gases. Previous studies at Massachusetts Institute of Technology on foams blown with HCFC-123 and HCFC-141b show a similar increase in the fraction solid in the cell wall.³³

Table 2. Structural features of boardstock blown with CFC-11, HCFC-123, or HCFC-141b

Feature	CFC-11	HCFC-123	HCFC-141b
Average distance between cell walls (mm):			
Parallel to facer	0.24	0.20	0.27
Perpendicular to facer	0.16	0.15	0.16
Cell wall thickness (μm)	0.30	0.40	0.53
Percentage solid in cell wall	.17	30	38

5. RESULTS AND INTERPRETATION

5.1 RTRA PANELS AND ESRA PANELS (TASK A)

Apparent thermal conductivity, k , results obtained as a function of temperature in the UTHA for six panels before installation in the RTRA are given in Table 9 of ref. 12. All the k -values increase with temperature, and linear equations describe the results with an average percentage deviation of $< \pm 0.23\%$. Reference 12 in Appendix A contains the k results obtained on the RTRA panels as a function of temperature from 30 to 120°F in the HFMA.

Figure 13 shows the temperature dependency of k as measured in the UTHA and the HFMA for the Task A specimen blown with CFC-11 before installation in the RTRA. The panels for the other blowing agents showed a similar temperature dependency for k (i.e., a minimum k below 60°F, a nearly linear temperature dependency above 80°F, but a displacement in k that depended on blowing agent and age at the time of testing as shown in Figures 6, 7, and 8).

The results shown in Table 3 describe the thermal performance of the panels blown with CFC-11, HCFC-123, and HCFC-141b. The panels blown with the blends were installed in the RTRA in February 1990. Results on RTRA panels show that for an age of 14 to 19 days, the panels blown with the blends had nearly equal k values (75°F). Results for the other panels at an age of about 75 days show:

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

Table 3 shows that the apparent thermal conductivity increases with the age of the foam and exposure time in the RTRA. After exposure in the RTRA for about 450 days, the order relation remained, but the average k had increased 22% for CFC-11, 21% for HCFC-123, 19% for HCFC-141b under black EPDM, and 17% for HCFC-141b under white EPDM.

Further increases in k occurred with increased exposure time in the RTRA. The panels blown with blends increased about 20% after nearly 290 days of exposure in the RTRA. The panels blown with CFC-11 had a k that increased with age and time in the RTRA.

Figure 14 shows the temperature dependency of k for panels exposed in the RTRA as measured in the UTHA and reported in ref. 13. This figure shows the relation of the k -values of the foam boards at the ages of 924–934 days for blends and 1087–1117 days for individual gases. The order of increasing $k(75)$ is CFC-11, HCFC-123 (3%), 50/50 blend (7%), 65/35 blend (7%) and HCFC-141b (8%), where the values in parentheses correspond to the percent increase in $k(75)$ over that of the foam blown with CFC-11.

In June 1990, tests were conducted on panels to be installed in the ESRA. These panels were produced from boardstock that had been stored at ORNL since June 1989 and that were just over a year old at the time of the tests. Table 4 contains the results of two-sided heat-flow UTHA tests on those panels that contained embedded heat flux

Fig. 13. The temperature dependency of the thermal conductivity of boardstock blown with CFC-11 before installation in the Roof Thermal Research Apparatus.

Table 3. The thermal conductivity^a of Roof Thermal Research Apparatus (RTRA) panels blown with CFC-11, HCFC-123, HCFC-141b, and two blends (50/50 and 65/35) of HCFC-123/HCFC-141b

1. Before RTRA exposure

Temperature	Thermal conductivity (Btu • in/h • ft ² • °F)				
°F	CFC-11	HCFC-123	HCFC-141b	50/50	65/35
Age, days ^b	65	71	76	12	18
30	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

2. After 256 days of RTRA exposure

Age, days ^c	332	336	340	-	-
75 ^c	0.139	0.150	0.156	-	-
Irrese, %	8.6	11.1	9		

3. After 456 days of RTRA exposure

Age, days ^c	532	534	524	309	314
75 ^c	0.156	0.163	0.170	0.163	0.164
Increase, %	21.9	20.7	18.9	20.7	20.6

4. After 639 days of RTRA exposure

Age, days	715	718	730	538	536
75	0.158	0.165	0.169	0.170	0.170
Increase, %	23.2	22.0	21.5	25.6	24.9

5. After 1041 days of RTRA exposure

Age, days	1117	1111	1104	924	934
75	0.164	0.169	0.177	0.173	0.173
Increase, %	27.7	24.8	22.5	27.6	27.1

^a Includes GAF 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.

Fig. 14. The temperature dependency of the thermal conductivity of polyisocyanurate boardstock blown with various gases after 1000 days exposure in the Roof Thermal Research apparatus.

Table 4. The thermal conductivity of Envelope Systems Research Apparatus (ESRA) panels produced from boardstock stored for 1 year as tested in the Unguarded Thin Heating Apparatus (UTHA) and after 814 days exposure in ESRA as tested in the Heat Flux Metering Apparatus (HFMA)

Blowing agent	Mean temperature	k(Btu • in/h • ft ² • °F)	A (Btu/h • ft ² • MV)
CFC-11	83.84	0.1570	(1,2) 0.4138
	120.87	0.1690	(3,4) 0.4085
	129.10	0.1744	

UTHA (stored 1 year): $k = 0.1261 + 3.660 \times 10^{-4} T$, $\pm 0.51\%$
 $k(75) = 0.1535$, increased 20.3%

HFMA (after 814 Days in ESRA): $k(75) = 0.1631$, increased in ESRA 6.2%

HCFC-123	83.86	0.1561	(3,2) 0.3765
	119.75	0.1741	(1,4) 0.4110

UTHA (stored 1 year): $k = 0.1126 + 5.1828 \times 10^{-4} T$
 $k(75) = 0.1515$, increased 12.6%

HFMA (after 814 days in ESRA): $k(75) = 0.1706$, increased in ESRA 12.6%.

HCFC-141b	83.58	0.1707	(1,2) 0.4147
	110.05	0.1934	(3,4) 0.4162

UTHA (stored 1 year): $k = 0.1172 + 6.400 \times 10^{-4} T$
 $k(75) = 0.1652$, increased 15.4%

HFMA (after 814 days in ESRA): $k(75) = 0.1840$, increased 11.4% in ESRA

transducers. The $k(75)$ values given in Table 4 (after 1 year of storage) are greater than those given in Table 3 by 12 to 20%. Tests in the HFMA after 814 days exposure in the ESRA show increases in k in ESRA of from 6 to 13%.

5.2 THIN SPECIMENS AGING AT 75 AND 150°F (TASK B)

The thermal data obtained for laboratory-aged, planed foamboard specimens of three thicknesses are shown in Tables 5 and 6. Table 5 contains $k(75)$ for the five products aged at 75°F. Table 6 contains $k(75)$ for test specimens that were aged at 150°F. In both Tables 5 and 6, a horizontal dashed line separates long-time data¹³ from those previously reported.¹² Reference 13 of Appendix A contains specific values for the quantity t/h^2 in d/mm^2 and $t^{1/2}/h$ in $d^{1/2}/mm$ for the test results given in Tables 5 and 6 and lists the average specimen thicknesses.

Table 5. k(75) values for planed specimens aged at 75°F. [k(75) values above the dashed line were reported in ref. 12]

Thermal conductivity (Btu • in/h • ft ² • °F)						
Age (days)	Boards	CFC-11	HCFC-123	HCFC-141b	50/50	65/35
2	1	-	-	-	0.1370	0.1381
	2	-	-	-	0.1360	0.1352
	4	-	-	-	0.1468	0.1452
3	1	0.1268	0.1371	0.1423	-	-
	2	0.1206	0.1342	0.1406	-	-
	4	0.1322	0.1411	0.1509	-	-
17	1	0.1239	0.1374	0.1452	-	-
	2	0.1286	0.1437	0.1534	-	-
	4	0.1390	0.1515	0.1580	-	-
42.5	1	-	-	-	0.1454	0.1486
	2	-	-	-	0.1596	0.1579
	4	-	-	-	0.1758	0.1755
51.5	1	0.1315	0.1423	0.1512	-	-
	2	0.1396	0.1536	0.1641	-	-
	4	0.1502	0.1622	0.1695	-	-
74.5	1	-	-	-	0.1522	0.1578
	2	-	-	-	0.1712	0.1708
	4	-	-	-	0.1812	0.1804
106.5	1	0.1322	0.1464	0.1540	-	-
	2	0.1476	0.1644	0.1697	-	-
	4	0.1560	0.1681	0.1734	-	-
127	1	-	-	-	0.1571	0.1569
	2	-	-	-	0.1750	0.1707
	4	-	-	-	0.1848	0.1811
190	1	0.1418	0.1522	0.1606	-	-
	2	0.1540	0.1721	0.1769	-	-
	4	0.1592	0.1709	0.1767	-	-

Table 5 (continued)

Thermal conductivity (Btu • in/h • ft ² • °F)						
Age (days)	Boards	CFC-11	HCFC-123	HCFC-141b	50/50	65/35
289.5	1	0.1440	0.1556	0.1625	-	-
	2	0.1602	0.1713	0.1788	-	-
	4	0.1628	0.1762	0.1816	-	-
305	1	-	-	-	0.1637	0.1644
	2	-	-	-	0.1773	0.1766
	4	-	-	-	0.1797	0.1822
463.5	1	0.1488	0.1600	0.1656	-	-
	2	0.1634	0.1730	0.1791	-	-
	4	0.1652	0.1788	0.1837	-	-
710	1	-	-	-	0.1763	0.1764
	2	-	-	-	0.1848	0.1854
	4	-	-	-	0.1904	0.1897
873.5	1	0.1579	0.1711	0.1775	-	-
	2	0.1691	0.1798	0.1868	-	-
	4	0.1728	0.1835	0.1900	-	-

Table 6. k(75) values for planed specimens aged at 150°F. [k(75) values above the dashed line were reported in ref. 12]

Thermal conductivity (Btu • in/h • ft ² • °F)						
Age (days)	Boards	CFC-11	HCFC-123	HCFC-141b	50/50	65/35
1.5	1	0.1335	0.1442	0.1527	0.1360	0.1417
	2	0.1305	0.1398	0.1532	0.1397	0.1388
	4	0.1473	0.1556	0.1630	0.1458	0.1499
13.5	1	0.1409	0.1520	0.1586	-	-
	2	0.1574	0.1630	0.1793	-	-
	4	0.1616	0.1707	0.1743	-	-
29.5	1	-	-	-	0.1533	0.1577
	2	-	-	-	0.1723	0.1717
	4	-	-	-	0.1870	0.1862
43	1	0.1511	0.1598	0.1682	-	-
	2	0.1631	0.1701	0.1836	-	-
	4	0.1644	0.1737	0.1789	-	-
62.5	1	-	-	-	0.1632	0.1690
	2	-	-	-	0.1850	0.1833
	4	-	-	-	0.1952	0.1986
114.5	1	0.1579	0.1665	0.1769	-	-
	2	0.1680	0.1737	0.1913	-	-
	4	0.1698	0.1813	0.1850	-	-
118.5	1	-	-	-	0.1591	0.1590
	2	-	-	-	0.1732	0.1721
	4	-	-	-	0.1904	0.1893
185	1	0.1527	0.1576	0.1665	-	-
	2	0.1655	0.1719	0.1815	-	-
	4	0.1746	0.1820	0.1917	-	-
298.5	1	-	-	-	0.1629	0.1626
	2	-	-	-	0.1764	0.1803
	4	-	-	-	0.1981	0.1936

Table 6 (continued)

Thermal conductivity (Btu • in/h • ft ² • °F)						
Age (days)	Boards	CFC-11	HCFC-123	HCFC-141b	50/50	65/35
391	1	0.1528	0.1599	0.1667	-	-
	2	0.1655	0.1711	0.1875	-	-
	4	0.1784	0.1832	0.1997	-	-
709.5	1	-	-	-	0.1717	0.1703
	2	-	-	-	0.1929	0.1895
	4	-	-	-	0.2131	0.2076
801	1	0.1609	0.1665	0.1762	-	-
	2	0.1741	0.1832	0.2024	-	-
	4	0.1916	0.1963	0.2127	-	-

In nearly every case, the k-values shown in Tables 5 and 6 at a given age and for a given blowing agent increase from single-board specimens to two-board specimens to four-board specimens, that is, from thick to thin boards. For example, the CFC-11 exceptions are limited to specimens aged for short times (3 days or less at 75°F and 1.5 days or less at 150°F). Figure 15 shows the increases in k-values (the accelerated aging) associated with the thinner specimens. The k data are shown graphically in Figs. 16 and 17 as a function of "scaled" time.

These figures show k values for the alternative blowing agents (HCFC-123, HCFC-141b) compared with k values for foamboards produced with CFC-11. The alternative blowing agent foamboards have lower thermal resistances than the foamboards produced with CFC-11 for the time period studied. The blowing agent blends appear to have poorer thermal performance than the single-component alternatives. The reasons for the differences are not obvious but could be related to differences in the initial gas pressures.

The k-values for three materials plotted in Fig. 17 show a nonlinear dependence on t/h^2 for values up to 8.5 d/mm^2 at 75°F. The k-values for the two blends show the same trends noted for the other material, but the aged k is greater than that for the specimens blown with HCFC-141b. The k-values for the two blends are very similar in magnitude.

The scaling factor t/h^2 does not give results in $k(t)$ that exactly coincide for specimens of different thickness. The curves for a given blowing agent, relatively small t, and different specimen thicknesses agree, but the curves diverge as time (or t/h^2) increases. This divergence is shown for CFC-11 in Fig. 16 for t/h^2 values up to 1.0 day/mm^2 . This divergence could be due to differences in the time required to complete the inward diffusion of nitrogen and oxygen.

5.3 DISCUSSION OF RESULTS ON AGED THIN SPECIMENS

Discussions in ref. 12 noted that the nonlinear behavior of the increase in k with $\text{time}/(\text{thickness})^2$ can be described by two linear regions if one plots $\ln k$ versus $(\text{time})^{1/2}/\text{thickness}$. If one empirically assumes that k can be described by an exponential dependence on diffusion coefficient (D), time (t), and thickness (h):

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

where

k_0 is the initial thermal conductivity,

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

$$Y = A + B X, \quad (3)$$

where

$$A = \ln k_0,$$

$$Y = \ln k,$$

$$X = t^{1/2}/h,$$

$$B = D^{1/2}.$$

Fig. 15. The thermal conductivity of thin specimens of foam board insulation blown with CFC-11 as a function of time.

Fig. 16. The thermal conductivity at 75°F for thin specimens aged at 75°F as a function of time/(thickness)² in d/mm².

fig. 17

Fig. 17. The thermal conductivity at 75°F for thin specimens aged at 75°F as a function of time/(thickness)² in d/mm².

Thus if one measures the k of a foam product of thickness (h) as a function of aging time (t), then a plot of Y versus X should yield a straight line with slope B . A least square fitting of the data to the straight line represented by Eq. 3 yields an intercept of $\ln k_0$ and a slope of $D^{1/2}$. Figure 18 shows the increase of $k(75)$ (plotted as $\ln 100 k$ 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. Figures 19 and 20 are the same type of plot as Fig. 18, but for the other blowing agents.

Similar plots for the blends aging at 75°F and for all five products aging at 150°F are given in ref. 13. The test data for the specimens of three thicknesses describe two distinct linear regions of behavior with an intermediate transition zone. The thin specimens have reached larger values of $t^{1/2}/h$ than the thick specimens. We 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 for eight tests up to 873 days after planing are similar for each thickness. At 75°F, the linear region extrapolations intersect near a value of $t^{1/2}/h$ of near 0.75 d^{1/2}/mm, but ref. 12 shows at 150°F this interaction is near 0.55 d^{1/2}/mm. This result shows that, as expected, the diffusion of air components into the foam is faster at 150°F than at 75°F.

We treated the model predictions for 75°F aging and the available test data for the foams blown with five gases aging at 75°F and at 150°F, as suggested by Eqs. 2 and 3. The specific equations used were

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

$$\ln k \text{ (Region 2, blowing agent)} = \ln k_2 + (D_2 t)^{1/2}/h, \quad (5)$$

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,

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

The k -value results given in Tables 5 and 6 were fit by a least-squares method. Table 7 is a summary of the data fits obtained. The average percentage deviation is less than 1% for all of the results, except the deviation for the blends in Region 2 aging at 150°F, which is 1.5%. These results are within 2% of those given in ref. 12 for the individual blowing agents and within 5% of those given for the blends. Figure 21 is a plot of the equations given in Table 7, for aging at 75°F, where the units for k (ip) are Btu · in/h · ft² · °F and for $t^{1/2}/h$ are sec^{1/2}/cm. Figure 21 shows the relative positions for the five blowing agents as a function of age at 75°F.

The square roots of the B coefficients for the data fits provide the effective diffusion coefficients for Region 1 and Region 2. The resulting values for D_1 , D_2 , and the ratio D_1/D_2 , are given in Table 8. The effective diffusion coefficients derived from the aging tests are of the expected order of magnitude and appear to be reasonable values. The results for aging at 75°F show D_1 values near 1.2×10^{-8} cm²/sec for the foams blown with individual gases and near 1.9×10^{-8} cm²/sec for the foams blown with the blends.

Fig. 18. Increase in k (75) for thin specimens of rigid board foamed with CFC-11 aging at 75°F 38.

Fig. 19. Increase in k (75) for thin specimens of rigid board foamed with HCFC-123 aging at 75°F.

Fig. 20. Increase in k (75) for thin specimens of rigid board foamed with HCFC-141b aging at 75°F.

Fig. 21. Comparison of equation values for k (75) for thin specimens aging at 75°F for five blowing agents.

Table 7. Summary of data fits by a least-squares method

Blowing agent	Region	A	$B \times 10^4$	Number of data points	Average percentage deviation (%)	Intercept k (Btu.in/h · ft ² · °F)
Specimens aging at 75°F						
CFC-11	1	2.4944	1.1595	13	0.65	0.1211
	2	2.7088	0.1725	11	0.62	0.1501
HCFC-123	1	2.5877	1.1120	13	0.42	0.1330
	2	2.7939	0.1449	11	0.49	0.1634
HCFC-141b	1	2.6475	1.0067	13	0.60	0.1412
	2	2.8332	0.1328	11	0.49	0.1700
50/50 blend	1	2.5987	1.3992	09	0.74	0.1345
	2	2.8497	0.1172	09	0.45	0.1728
65/35 blend	1	2.6069	1.3636	09	0.65	0.1356
	2	2.8411	0.1326	09	0.49	0.1713
Specimens aging at 150°F						
CFC-11	1	2.5332	3.2858	06	0.64	0.1259
	2	2.7438	0.2230	15	0.70	0.1554
HCFC-123	1	2.6204	2.6107	06	0.57	0.1374
	2	2.7933	0.1973	15	0.86	0.1633
HCFC-141b	1	2.6792	2.7500	06	0.50	0.1457
	2	2.8397	0.2451	15	0.93	0.1711
50/50 blend	1	2.5785	2.9303	06	0.08	0.1318
	2	2.8058	0.3550	12	1.55	0.1654
65/35 blend	1	2.6067	2.7928	06	0.65	0.1355
	2	2.8135	0.3117	12	1.52	0.1667

Table 8. Effective diffusion coefficients derived from aging tests, cm^2/sec : D_1 (air components), D_2 (blowing gas)

MIT ^a model (CFC-11)	$D_1 \times 10^8$	$D_2 \times 10^{10}$	D_1/D_2	$D_1 (150)/D_1 (75)$	$D_2 (150)/D_2 (75)$
75°F	18.78	9.23	203.5		
CFC-11	1.34	2.97	45.1	8.1	1.8
HCFC-123	1.24	2.10	59.0	5.5	1.8
HCFC-141b	1.01	1.76	57.4	7.5	3.4
50/50	1.96	1.37	143.1	4.4	9.2
65/35	1.86	1.75	106.3	4.2	5.5
150°F					
CFC-11	10.80	5.29	204		
HCFC-123	6.81	3.89	175		
HCFC-141b	7.56	6.01	125		
50/50	8.59	12.60	68.2		
65/35	7.80	9.71	80.3		

^a MIT = Massachusetts Institute of Technology

The D_1 values for aging at 150°F are 4 to 8 times larger than the D_1 (75°F aging) as would be expected for temperature-dependent diffusion processes. The results for aging at 75°F show D_2 values significantly lower than the D_1 values.

At 75°F the D_2 values range from 1.8×10^{-10} cm²/sec for the individual gases and are below 1.8×10^{-10} cm²/sec for the blends. The D_2 values for aging at 150°F are 2 to 9 times larger than the D_2 values for aging at 75°F. Some evidence exists that the D_2 values for the foams aging at 75°F are lower for the more complex alternative blowing agents, that is, D_2 (HCFC-123 and HCFC-141b) < D_2 (CFC-11). The ratio of the D_1 to D_2 values ranges from 45 to 140 at 75°F and from 68 to 205 at 150°F. The D_1 and D_2 values are similar to the values reported in ref. 12. The D values are a clear reflection of the foam structural properties and the diffusing species and may be a guide to optimizing boardstock. The D_1 values at 75°F do decrease with increasing cell wall thickness for the individual gases.

The D_1 and D_2 values obtained at 75 and 150°F can be used to obtain the activation energy ΔH for chemical processes such as gaseous diffusion, using

$$D = D_0 \exp (-\Delta H/RT), \quad (6)$$

where

D_0 is a jump frequency,
cm²/sec, R , is the gas constant,
1.987 cal/mol K, ΔH , is the activation energy, cal/mol,
and T is the absolute temperature, K.

Table 9 gives the activation energy values and D_0 values for Region 1 and Region 2 processes. The average ΔH value for Region 1 is near 8 kcal/mol and for Region 2 is near 6 kcal/mol. The jump frequency for Region 1 is greater than for Region 2.

Table 9. Activation energies and jump frequencies for Region 1 and Region 2 derived from effective diffusion coefficients

Gas	Activation energy cal/mol	Jump frequency jumps/sec $\times 10^4$
Region 1		
CFC-11	9,985	3366.0000
HCFC-123	8,149	123
HCFC-141b	9,631	1235
50/50 blend	7,070	31
65/35 blend	6,608	13
Region 2		
CFC-11	2,762	0.0003
HCFC-123	2,950	0.0003
HCFC-141b	5,876	0.0371
50/50 blend	10,617	89
65/35 blend	8,199	1.9

The constants, A, given in Table 7 can be used to obtain the intercept values k_1 and k_2 for Regions 1 and 2. These values are given in Table 7. The values of k_1 , the initial k of the foam, 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 is CFC-11, HCFC-123 (10%), 50/50 (11%), 65/35 (12%), and HCFC-141b (17%), where the value in parentheses is the percentage increase in k over that of the foam blown with CFC-11. The 150°F aging results suggest a slightly different order; that is, the blends are lower in k than the HCFC-123. Both data sets suggest that the blends have very similar k -values.

Discussion in ref. 12 notes that the k of a 2 lb/ft³ fresh (unaged) foam can be calculated by adding the blowing gas k and a constant term, 0.073 Btu · in./h · ft² · °F, to represent the solid and radiation conduction contribution to k . Table 10 shows that this calculation overestimates k_1 , but the percentage difference between k (calculated) and k_1 is less than 10%. An alternative calculation is to subtract $k(\text{gas})$ from k_1 and associate the difference with $k(\text{solid}) + k(\text{radiation})$. Table 10 shows that the result of doing so yields an average value of 0.065 for the prototypical foams being tested in this project. If half of this contribution is assigned to the radiation contribution and if this contribution is described by the Rosseland approximation

$$k(\text{Rad}) = \frac{16}{3} \times \frac{\sigma n^2 T^3}{E} \quad (7)$$

where

σ is the Stefan-Boltzmann constant,
 n is the index of refraction and a value of 1 was used,
 E is the extinction coefficient, ft⁻¹,

then the E -values in Table 10 can be computed from Eq. 7. The average E -value is 534 ft⁻¹. Theory predicts a value of about 900 ft⁻¹ for a foam density of 1.95 lb/ft³ and a cell size of 0.2 mm. This E -value would be obtained if 30%, instead of 50%, of $k(\text{radiation}) + k(\text{solid})$ had been associated with $k(\text{radiation})$.

Table 10. Calculated $k(75)$ for unaged foams for various gases, (Btu · in/h · ft² · °F)

Gas	Gas k	k calculated	% difference ^a	$k_1 - k(g)$	E ft ⁻¹
CFC-11	0.057	0.130	-7.3	0.064	539
HCFC-123	0.072	0.145	-9.0	0.061	566
HCFC-141b	0.070	0.143	-1.3	0.071	486
50/50	0.071	0.144	-7.1	0.063	547
65/35	0.0713	0.144	-6.2	<u>0.064</u>	<u>532</u>
Average				0.065	534

$$^a 100 \times [k_1 - k(\text{calculated})]/k_1$$

The accelerated aging test results from this study can be used to predict the thermal resistivity (r , where $r = 1/k$) at 75°F as a function of aging time at 75 or 150°F for 1.5-in.-thick unfaced prototypical foam boards. Table 11 shows initial and predicted r -values for 1, 2, and 5 years, which correspond to values of $t^{1/2}/h$, (days)^{1/2}/mm, of 0.50, 0.71, and 1.12, respectively, for a 1.5-in. (38.1 mm) thickness. Table 12 contains the initial and predicted thermal resistivity and time-averaged thermal resistivity at 75°F for 5 and 10 years. The predicted r -values decrease with time at 75°F, but exceed 5.7 h · ft² · °F/Btu · in for the individual gas blowing agents tested. The time-averaged values ($\bar{r}$) are about 3 to 5% greater than the predicted r values. This value exceeds the minimum stabilized r -value of 5.6 for unfaced polyurethane or PIR foams stated by the Society of the Plastics Industry assessment.³⁴ The 1.5-in. boards foamed with blends reach an r -value of 5.5 at 5 years. The predicted 75°F r -values decrease with time at 150°F and reach lower r -values than when aged at 75°F. All of the values reported in Table 11 are within the existing accelerated aging data set; that is, these are interpolated values. As Table 5 shows, the longest exposure time is 873 days for the initially produced boardstock. Table 13 shows the predicted r -values at 10 years that are based on thicknesses of 1.0, 1.50 and 2.50 in. The r -values increase 3 to 8% depending on the board type and the thickness selected for the calculation.

The equations for Regions 1 and 2 are given in Table 7 and can be used to calculate the intersection values, $\text{time}^{1/2}/\text{mm}$, and the time until intersection for various thicknesses. Table 14 contains the results of these calculations and shows the intersection value is greater for aging at 75°F than for aging at 150°F. Consequently the expected time to reach the intersection is greater at 75°F (about 770 days or 2.1 years for 1.5-in.-thick material) than for aging at 150°F (about 80 days or 0.2 years for 1.5-in.-thick material). As expected, decreasing the thickness from 1.5 in. to 0.5 in. reduces the aging time to the intersection at 75°F from about 770 days to about 86 days. Since about 3/4 of the change in k with time occurs during Region 1, this calculation suggests aging 0.5-in.-thick boards for 90 days at 75°F would be a useful supplement to the 180-day aging test recommended by ASTM.

Table 11. Predicted thermal resistivity at 75°F for unfaced 1.5-inch-thick prototypical foam boards aged at 75°F and at 150°F

Blowing agent at 75°F	Initial		Aging time, years		
	k _i	r ^a	1	2	5
			r(1) ^b	r(2)	r(5)
Aged at 75°F					
CFC-11	0.121	8.29	6.90	6.51	6.35
HCFC-123	0.132	7.58	6.31	5.98	5.87
HCFC-141b	0.140	7.14	6.02	5.76	5.67
50/50	0.133	7.52	5.93	5.67	5.43
65/35	0.134	7.46	5.87	5.71	5.47
Aged at 150°F					
CFC-11	0.126	7.94	6.18	6.07	5.85
HCFC-123	0.137	7.30	5.91	5.80	5.59
HCFC-141b	0.146	6.85	5.89	5.50	5.33
50/50	0.132	7.58	5.63	5.40	4.95
65/35	0.136	7.35	5.64	5.42	4.98

^a $h \cdot ft^2 \cdot ^\circ F/Btu \cdot in.$

^b Number in parentheses indicates years.

Table 12. Predicted thermal resistivity at 75°F for unfaced experimental foam boards aged at 75°F ($h \cdot ft^2 \cdot ^\circ F/Btu \cdot in$)

Resistivity	CFC-11	HCFC-123	HCFC-1416	50/50 blend	65/35 blend
r initial	8.29	7.51	7.14	7.52	7.46
r (5 years)	6.35	5.87	5.67	5.58	5.58
r (10 years)	6.17	5.73	5.55	5.52	5.45
$\bar{r}$ (5 years) ^a	6.63	6.12	5.88	5.81	5.82
$\bar{r}$ (10 years) ^a	6.43	5.94	5.74	5.67	5.67

^a Time-averaged thermal resistivity

Table 13. Predicted thermal resistivity for 10 years at 75°F for unfaced experimental foam boards aged at 75°F based on three thicknesses ($h \cdot \text{ft}^2 \cdot ^\circ\text{F}/\text{Btu} \cdot \text{in}$)

	CFC-11	HCFC-123	HCFC-1416	50/50 blend	65/35 blend
r (1.0 in.)	5.93	5.52	5.39	5.42	5.24
r (1.50 in.)	6.17	5.73	5.55	5.52	5.45
r (2.50 in.)	6.38	5.90	5.70	5.60	5.63

Table 14. Calculated intersection values for Region 1 and 2 for aging at 75 and 150°F

1. Calculation for aging at 75°F

Blowing agent	Intersection value	Days to intersection	Days to intersection
	$d^{1/2}/\text{mm}$	1.5 in. (38.1mm)	0.5 in. (12.7 mm)
CFC-11	0.739	792.8	38.1
HCFC-123	0.725	763.8	84.8
HCFC-141b	0.723	758.6	81.3
50/50 blend	0.666	644.0	71.5
65/35 blend	0.647	608.1	67.5

2. Calculation for aging at 150°F

Blowing agent	Intersection value	Days to intersection
	$\text{days}^{1/2}/\text{mm}$	1.5 in. (38.1 mm)
CFC-11	0.234	79.4
HCFC-123	0.244	84.8
HCFC-141b	0.224	73.0
50/50 blend	0.300	130.9
65/35 blend	0.284	116.7

The results given in Tables 11, 12, 13, and 14 show that thin specimen aging is a promising accelerated aging procedure and provides a positive response to the key question of this program: The blowing agents tested in these prototypical experimental boards exhibit a long-term thermal performance at 75°F that is within 7 to 15% (average 11.6%) of that obtained by CFC-11 under similar conditions.

5.4 LABORATORY DATA ON PANELS EXPOSED IN THE FIELD (RTRA AND ESRA)

Table 15 shows that the apparent thermal conductivity increases with the age of the foam and exposure time in the RTRA. Both laboratory and field measurements are shown in the table. The results shown in Table 15 describe the thermal performance of the respective panels just before their installation in the RTRA on August 28, 1989. The RTRA panels blown with blends had nearly equal $k(75)$ -values at an age of 12 to 18 days. The other panels at an age of about 65 to 81 days show:

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

After exposure in the RTRA for about 450 days (530 days after manufacture), the order relation remained, but the average k had increased 15 to 22% for CFC-11, 11 to 21% for HCFC-123, 12 to 19% for HCFC-141b under black EPDM, and 13 to 17% for HCFC-141b under white EPDM.

Further increases in k occurred with increased exposure time in the RTRA. The k of panels blown with blends increased about 20% for a 285-day exposure in the RTRA. The panels blown with CFC-11 have a k that increases with age and time in the RTRA. The increases of the other panels with respect to the CFC-11 are given in Table 15 and range from 3 to 8%, according to laboratory measurements at up to 1100 days of age, and from 3 to 10% based on field measurements at up to 600 days of RTRA exposure.

The testing procedure of instrumented panels exposed in the RTRA provided the opportunity to check the HFT calibration constants as a function of time in the RTRA. Table 16 contains the calibration constants determined for each panel as a function of exposure time. The individual HFT calibration constants show a range of about 6%, but the values have changed less than 1.4% during these tests that include over 1000 days of exposure in the RTRA.

To compare the $k(75)$ values for thin specimens aged in the laboratory with laboratory $k(75)$ value for foam board panels exposed in the RTRA, it was necessary to relate the laboratory data to time. Table 17 contains the results for $k(75)$, full thickness, obtained from the Region 2 equations given in Table 7 using an h of 1.5 inches. The average value for the ratio of the latter is 0.997, indicating agreement to about 0.3%. The difference observed for the HCFC-141b black and white EPDM panels is not significant.

Table 15. The apparent thermal conductivity of panels blown with alternative gases as a function of age and Roof Thermal Research Apparatus (RTRA) exposure time

Foam age	RTRA time	Lab data	Percentage increase		Field data	Percentage increase	
days	days	k(Btu.in/h •ft ² •°F)	vs time	vs CFC-11	k(Btu.in/ h.ft ² •°F)	vs time	vs CFC-11
CFC-11							
65	0	0.1283	-	-	0.1359	-	-
332	256	0.1387	8.1	-	0.1491	9.7	-
532	456	0.1560	21.6	-	0.1560	14.8	-
680	604	-	-	-	0.1602	17.9	-
715	639	0.1581	23.2	-	-	-	-
1117	1041	0.1639	27.7	-	-	-	-
HCFC-123							
71	0	0.1352	-	5.4	0.1449	-	6.6
336	258	0.1498	10.8	8.0	0.1553	7.2	4.2
534	456	0.1629	20.5	4.4	0.1608	11.0	3.1
680	602	-	-	-	0.1643	13.4	2.6
718	640	0.1650	22.0	4.4	-	-	-
1111	1033	0.1687	24.8	2.9	-	-	-
HCFC-141 b (white)							
81	0	0.1442	-	12.4	0.1477	-	8.7
342	257	0.1581	9.6	14.0	0.1601	8.4	7.4
523	438	0.1692	17.3	8.5	0.1664	12.7	6.7
680	595	-	17.3	-	0.1706	15.5	6.5
728	643	0.1748	21.5	7.0	-	-	-
1087	1002	0.1767	22.5	7.8	-	-	-
HCFC-141 b (black)							
76	0	0.1428	-	11.3	0.1525	-	12.2
340	255	0.1560	9.2	12.5	0.1643	7.7	10.2
524	439	0.1699	19.0	8.9	0.1706	11.8	9.3
680	595	-	-	-	0.1747	14.5	9.1
730	645	0.1719	20.4	8.7	-	-	-
1104	1019	0.1765	23.6	7.7	-	-	-
50/50 blend							
12	0	0.1352	-	5.4	0.1470	-	-
312	285	0.1629	20.5	17.4	0.1629	10.8	9.3
500	473	-	-	-	0.1712	16.5	9.8
538	511	0.1698	25.6	8.8	-	-	-
924	897	0.1725	27.6	7.0	-	-	-
65/35 blend							
18	0	0.1359	-	5.9	0.1428	-	-
314	287	0.1636	20.4	18.0	0.1567	9.7	5.1
500	473	-	-	-	0.1650	15.5	5.8
536	509	0.1698	24.9	8.8	-	-	-
934	907	0.1727	27.1	7.1	-	-	-

**Table 16. Heat flux transducer calibration constants for various exposures
in the Roof Thermal Research Apparatus (RTRA)**

Panel	RTRA time, days	Heat flux transducer constant Btu/h · ft ² · MV
CFC-11	0	0.3826
	256	0.3800
	456	0.3842
	639	0.3823
	1041	0.3829
HCFC-123	0	0.3859
	258	0.3840
	456	0.3892
	640	0.3885
	1033	0.3877
HCFC-141b(white)	0	0.3769
	257	0.3772
	438	0.3764
	643	0.3767
	1002	0.3769
HCFC-141b(black)	0	0.3749
	255	0.3721
	439	0.3756
	645	0.3747
	1019	0.3758
50/50 blend	0	0.3849
	285	0.3873
	511	0.3860
	897	0.3883
65/35 blend	0	0.3682
	287	0.3702
	509	0.3704
	907	0.3692

Table 17. Comparison of $k(75)$ value from full-thickness tests/predictions with $k(75)$ values measured on panels exposed in the Roof Thermal Research Apparatus (RTRA)

Blowing agent	Age (days)	$k(75)$ full thickness ^a	$k(75)$ panel	Panel/full thickness
CFC-11	1117	0.1569	0.1639	1.045
HCFC-123	1111	0.1697	0.1687	0.994
HCFC-141b (black)	1104	0.1759	0.1765	0.997
HCFC-141b (white)	1087	0.1759	0.1763	0.997
50/50 blend	924	0.1776	0.1725	0.971
65/35 blend	934	0.1768	0.1727	0.977
Average				0.977

^a Calculated from Region 2 equations of Table 7.

5.5 FIELD DATA ON PANELS EXPOSED IN RTRA AND ESRA

Loosely Laid EPDM on the RTRA: Figure 22 shows the reported k-factors at actual mean insulation temperatures from installation in the RTRA under a loosely laid black EPDM membrane of the dry stacked combination boards blown with CFC-11, HCFC-123, and HCFC-141b. The seasonal fluctuations are dramatically reduced by normalizing the k-factors to a base temperature of 75°F as shown in Fig. 23. A second way of displaying this same data is to select the weeks with mean insulation temperatures between 74° and 77°F. This k-factor for weeks with temperatures near 75°F is shown in Fig. 24. The HCFC-141b board in-situ k-factor over the first 3 years was 9.9% higher than that of the CFC-11 over the same period. The HCFC-123 k-factor was 3.7% higher than that of the CFC-11 for the first 3 years.

Black or White: Figure 25 and Table 18 show weekly averaged thermal conductivity with mean insulation temperatures near 75°F spanning more than a 3-year period for the HCFC-141b boards under a black and a white membrane, compared with the CFC-11 board installed under a black membrane. The color of the roof membrane does not affect the aging characteristics of the PIR. For the entire exposure, the full-thickness foam specimens covered with the white and the black membrane experienced average temperatures of 63°F and 68.6°F, respectively, which is only a 5.6°F difference. Figure 25 also shows the periodic laboratory measurements made on these test specimens installed on the RTRA. Except for the two sets of laboratory measurements made in the first year of testing, the laboratory measurements and the in-situ data agree quite well. The relative differences between the HCFC-141b boards and the CFC-11 over the first year after production was about 11.5% over the last year of data. This percentage has leveled off to around 8.5%.

HCFC-141b Compared with 123/141b Blends: Figure 26 shows weekly averaged thermal conductivity for those weeks when the mean insulation temperature was near 75°F for the 50/50 blends and 65/35 blends of HCFC-123 and HCFC-141b, compared with the pure HCFC-141b PIR boards. There is no thermal performance benefit from either of these two blends, even though the pure HCFC-123 showed a significant improvement over the HCFC-141b specimens in Fig. 24. The periodic laboratory measurements taken on the RTRA-exposed specimens are also shown in Fig. 26. They support the conclusion that there is no significant difference between the HCFC-141b and two blends of HCFC-123 and HCFC-141b.

BUR and Fully Adhered Membrane: Apparent thermal conductivity data at a mean temperature of 75°F for the combined top and bottom boards from the RTRA and ESRA specimens of the HCFC-141b, CFC-11, and HCFC-123 boards are presented in Figs. 27-29. The field data show the difference between the k factor measured in the RTRA (the loosely laid EPDM systems) and the ESRA systems (BUR and fully-adhered EPDM). Prior to the installation of the ESRA specimens, their k values were measured in the laboratory (384 days) using the ORNL UTHA. In all three cases, the laboratory data show k's about the same as those exposed on the RTRA for about a year. In October 1991, a specimen of HCFC-141b polyisocyanurate foam was removed from the mechanically fastened EPDM quadrant of the ESRA roof and was evaluated in the HFMA in December 1991 [28]. These data are presented in Figure 27 for the HCFC-141b boards along with the post-laboratory measurements of both the instrumented panels removed from the ESRA in September 1992, at an age of about 1200 days.

CFC-11, HCFC-123 and HCFC-141b

k-factor at mean insulation temperature

Fig. 22. Three years of weekly k-factor data at mean temperatures from the Roof Thermal Research Apparatus for the combination boards blown with CFC-11, HCFC-123, and HCFC-141b.

CFC-11, HCFC-123 and HCFC-141b

Fig. 23. Same data as shown in Figure 22, only corrected to normalized temperature of 75°F.

CFC-11, HCFC-123 and HCFC-141b on RTRA

k-factor for weeks with temp near 75°F

Fig. 24. Roof Thermal Research Apparatus specimens CFC-11, HCFC-141b, and HCFC-123 with actual weekly data with mean insulation temperatures between 74°F and 77°F.

HCFC-141b and CFC-11 on the RTRA

k-factor for weeks with temp near 75°F

Fig. 25. Black and white ethylene propylene diene monomer covered specimens blown with HCFC-141b compared with CFC-11 on the Roof Thermal Research Apparatus for those weeks with mean specimen temperatures between 74°F and 77°F.

**Table 18. Weekly k-factor data with average insulation temperatures of 74 to 77°F
for CFC-11 and HCFC-141b Roof Thermal Research Apparatus specimens
(k in Btu · in/h · ft² · °F)**

Age	Date	CFC-11 k-factor	HCFC-141b white	HCFC-141b black
87	01-Sep-89		0.1524	
104	18-Sep-89	0.1365		
317	19-Apr-90	0.1480		0.1647
356	28-May-90		0.1600	
363	04-Jun-90		0.1622	
370	11-Jun-90		0.1631	
377	18-Jun-90		0.1632	
398	09-Jul-90		0.1660	
426	06-Aug-90		0.1654	
461	10-Sep-90		0.1670	
468	17-Sep-90	0.1550		
475	24-Sep-90	0.1542		0.1695
482	01-Oct-90	0.1539		0.1696
489	08-Oct-90	0.1538		0.1696
678	15-Apr-91	0.1568		0.1727
685	22-Apr-91	0.1578		0.1731
692	29-Apr-91	0.1586		0.1745
706	13-May-91		0.1707	
734	10-Jun-91		0.1691	
741	17-Jun-91		0.1712	
748	24-Jun-91		0.1710	
776	22-Jul-91		0.1735	
797	12-Aug-91		0.1731	
804	19-Aug-91		0.1728	
811	26-Aug-91		0.1732	
825	09-Sep-91	0.1591	0.1751	
832	16-Sep-91	0.1579		0.1751
846	30-Sep-91	0.1614		0.1728
1049	20-Apr-92	0.1623		0.1747
1056	27-Apr-92			0.1756
1070	11-May-92		0.1750	
1112	22-Jun-92		0.1743	
1119	29-Jun-92		0.1775	
1133	13-Jul-92		0.1766	
1140	20-Jul-92		0.1777	
1147	27-Jul-92		0.1767	
1154	03-Aug-92		0.1773	
1161	10-Aug-92		0.1755	
1175	24-Aug-92		0.1754	
1182	31-Aug-92		0.1768	
1189	07-Sep-92		0.1772	
1203	21-Sep-92	0.1622		0.1770

HCFC-141b and 123/141b Blends on RTRA

k-factor for weeks with temp near 75°F

Fig. 26. HCFC-141b and 123/141b blends on the Roof Thermal Research Apparatus show no difference in the long run in thermal k-factor.

HCFC-141b on RTRA and ESRA

k-factor Normalized to 75°F

Fig. 27. Both the HCFC-141b fully-adhered ethylene propylene diene monomer and built-up roof systems suffer significant loss in thermal performance at the time of installation.

CFC-11 on RTRA and ESRA

k-factor normalized to 75°F

■ CFC-11 on RTRA + 11 BUR on ESRA ♦ 11 EPDM on ESRA ▲ Lab ESRA

Fig. 28. The CFC-11 fully adhered ethylene propylene diene monomer suffers significant impact at the time of installation. There is no significant difference in thermal performance of built-up roofing compared with a loosely laid ethylene propylene diene monomer system.

HCFC-123 on RTRA and ESRA

k-factor at 75 °F

Fig. 29. Comparison of the HCFC-123 top and bottom boards illustrates that the major loss in thermal performance occurs in the top boards of both the fully adhered ethylene propylene diene monomer and the built-up roof that have the greatest contact with these roofing adhesives.

The thermal performance differences for HCFC-141b obtained on RTRA and ESRA systems are believed to be partly related to installation practices. Prior to the installation of the HCFC-141b polyisocyanurate foam insulation on the ESRA, the 1.5-in., full thickness specimen k-values were measured in the laboratory using the UTHA. The average apparent thermal conductivity for the subsequent BUR and adhered EPDM specimens was $0.165 \text{ Btu} \cdot \text{in/h} \cdot \text{ft}^2 \cdot ^\circ\text{F}$ at 75°F (see Table 4). This experiment was undertaken when the insulation boards were 384 days old. The full-thickness boards installed on the RTRA had an average apparent thermal conductivity of $0.164 \text{ Btu} \cdot \text{in/h} \cdot \text{ft}^2 \cdot ^\circ\text{F}$ at the same age. These data demonstrate that the boards installed in the ESRA had approximately the same thermal performance as their counterparts in the RTRA at the time of installation.

When the data collection process was initiated in the ESRA, the k had increased to approximately $0.184 \text{ Btu} \cdot \text{in/h} \cdot \text{ft}^2 \cdot ^\circ\text{F}$ for the BUR system and $0.19 \text{ Btu} \cdot \text{in/h} \cdot \text{ft}^2 \cdot ^\circ\text{F}$ for the EPDM. This represented a higher k (8-12%) than was simultaneously being measured in the RTRA in October 1990. In October 1991, a previously uncharacterized specimen of foam was removed from the EPDM side of the ESRA and tested in December 1991 (920 days old). The apparent thermal conductivity of this specimen was $0.183 \text{ Btu} \cdot \text{in/h} \cdot \text{ft}^2 \cdot ^\circ\text{F}$. At 920 days, the average apparent thermal conductivity of the ESRA specimens was $0.186 \text{ Btu} \cdot \text{in/h} \cdot \text{ft}^2 \cdot ^\circ\text{F}$, while the RTRA specimens averaged $0.172 \text{ Btu} \cdot \text{in/h} \cdot \text{ft}^2 \cdot ^\circ\text{F}$. The ESRA specimens were identical in thermal performance to the RTRA at installation and were verified to be ~8-12% higher after installation.

In September of 1992, 1200 days after production, the ESRA instrumented panels were removed and tested in the ORNL HFMA. The ESRA BUR laboratory k-value at 75°F was $0.184 \text{ Btu} \cdot \text{in/h} \cdot \text{ft}^2 \cdot ^\circ\text{F}$ (see Table 4) compared to the last in-situ measurement in the ESRA of $0.192 \text{ Btu} \cdot \text{in/h} \cdot \text{ft}^2 \cdot ^\circ\text{F}$. The HCFC-141b RTRA boards loosely stacked under the EPDM membrane on the RTRA in September 1992 had in-situ measured k-factors of $0.178 \text{ Btu} \cdot \text{in/h} \cdot \text{ft}^2 \cdot ^\circ\text{F}$. The in-situ k-factor for the BUR ESRA panels after 2 years of exposure in the ESRA roof systems was 7.9% above the RTRA panel; the laboratory measurement was 4.5% above the RTRA panel. The 3% difference between the post-exposure laboratory measurement and the in-situ k-factor measurement is not completely understood.

The k-factor of the ESRA CFC-11 and the HCFC-123 specimens in the BUR systems are about the same as that of RTRA specimens. The results are inconsistent with those for the HCFC-141b. It would appear that the initial installation impacted the CFC-11 and HCFC-123 specimens less severely than the HCFC-141b boards. In the installation notes from Smith, it is interesting to note the report that, during hot asphalt mopping of the top layer to the bottom, "the CFC-11 laid down nicely; the HCFC-123 developed blisters below the facer on the mechanically attached bottom board prior to placement of the top board; and then the top board lifted up. The setting of the top board of the HCFC-141b was then put down differently than that of the CFC-11 and HCFC-123. After blister development was observed under the facer, application procedures were slightly modified. Until that point, the top board was set within a few seconds after the first board was mopped. For the HCFC-141b top board, several additional seconds elapsed between mopping and setting of the top board" ⁴ The HCFC-141b top instrumented bottom board did "develop some blisters." It is speculated that this change in application procedure caused the HCFC-141b specimens in the ESRA BUR to be more severely impacted compared with the CFC-11 and HCFC-123 specimens.

The ESRA EPDM HCFC-141b specimens' k-factor measurements, compared with the RTRA boards, follow the same trends as the ESRA BUR. In October 1990, shortly after installation in the ESRA, the in-situ measurement of the k-factor for the HCFC-141b specimens under the fully adhered EPDM was $0.189 \text{ Btu} \cdot \text{in/h} \cdot \text{ft}^2 \cdot ^\circ\text{F}$, compared with the RTRA 141b specimen measurement of $0.17 \text{ Btu} \cdot \text{in/h} \cdot \text{ft}^2 \cdot ^\circ\text{F}$ —an 11% difference. After 2 years of exposure, the ESRA 141b EPDM specimens had in-situ measurements of around $0.196 \text{ Btu} \cdot \text{in/h} \cdot \text{ft}^2 \cdot ^\circ\text{F}$, compared with the corresponding RTRA specimens in October 1992 of $0.177 \text{ Btu} \cdot \text{in/h} \cdot \text{ft}^2 \cdot ^\circ\text{F}$ —an 11% difference. The post-exposure laboratory k-factor was $0.183 \text{ Btu} \cdot \text{in/h} \cdot \text{ft}^2 \cdot ^\circ\text{F}$, only 3% greater than that of the RTRA 141b specimens.

The general trends observed in the ESRA EPDM HCFC-141b specimens repeat themselves for both the CFC-11 and the HCFC-123 boards. The pre-ESRA installation laboratory k-factor for the CFC-11 specimens indicated that they were about the same as the RTRA CFC-11 specimens. After installation in the ESRA, the in-situ measurements, shown in Fig. 28, indicate that in October 1990 the ESRA CFC-11 EPDM specimens had a k-factor of around $0.165 \text{ Btu} \cdot \text{in/h} \cdot \text{ft}^2 \cdot ^\circ\text{F}$, compared with the RTRA CFC-11 specimens at $0.154 \text{ Btu} \cdot \text{in/h} \cdot \text{ft}^2 \cdot ^\circ\text{F}$ —a 7.1% difference. After a 2-year exposure in September 1992, the ESRA CFC-11 EPDM specimen in-situ k-factor averaged around $0.174 \text{ Btu} \cdot \text{in/h} \cdot \text{ft}^2 \cdot ^\circ\text{F}$, compared with the RTRA CFC-11 specimen at $0.162 \text{ Btu} \cdot \text{in/h} \cdot \text{ft}^2 \cdot ^\circ\text{F}$ —a 7.4% difference. Note that the post-k-value laboratory measurement on the ESRA specimens registered $0.167 \text{ Btu} \cdot \text{in/h} \cdot \text{ft}^2 \cdot ^\circ\text{F}$, only 3.1% above the RTRA CFC-11.

The comparisons for the ESRA EPDM HCFC-123 specimens, shown in Fig. 29, are in October 1990; in the ESRA, the k-factor was around $0.176 \text{ Btu} \cdot \text{in/h} \cdot \text{ft}^2 \cdot ^\circ\text{F}$ compared to the RTRA specimens of $0.158 \text{ Btu} \cdot \text{in/h} \cdot \text{ft}^2 \cdot ^\circ\text{F}$, a 11.4% difference. After two years of exposure, the ESRA EPDM HCFC-123 specimen registered a k-factor of around $0.185 \text{ Btu} \cdot \text{in/h} \cdot \text{ft}^2 \cdot ^\circ\text{F}$ compared with the RTRA of $0.164 \text{ Btu} \cdot \text{in/h} \cdot \text{ft}^2 \cdot ^\circ\text{F}$, a 12.8% difference. The laboratory post-exposure k-value at 75°F in October 1992 was $0.171 \text{ Btu} \cdot \text{in/h} \cdot \text{ft}^2 \cdot ^\circ\text{F}$, only 4.3% more than the RTRA EPDM HCFC-123 specimens.

In all cases, both the in-situ measurements and the laboratory pre- and post-exposure measurements on the ESRA panels with the fully adhered EPDM membrane lead to the conclusion that the encapsulation with the adhesive and membrane does not retard the thermal aging. Initially it was believed that the data suggest the net impact of the installation process was a slightly accelerated aging. The installation process, including the handling, foot traffic, and initial direct application of either solvent or hot asphalt, is suspected to be responsible for a portion of this increase in k.

The effect of encapsulating these boards with asphalt during installation (in the case of a BUR system) or partially with an adhesive (in the case of a fully adhered single-ply system) before conducting these field experiments was thought potentially to reduce the thermal aging. Figure 27 for the HCFC-141b, Fig. 28 for the CFC-11, and Fig. 29 for the HCFC-123 boards show no benefit; and for most cases, significant increases in k were observed immediately after installation. The rates of change, dk/dt (k versus age), for the 450- to 1050-day period for the full-thickness HCFC-141b BUR and the adhered black membrane specimens were $8.47 \cdot 10^{-6}$ and $8.54 \cdot 10^{-6} \text{ Btu} \cdot \text{in/h} \cdot \text{ft}^2 \cdot ^\circ\text{F/day}$, respectively. There appears to be no difference in the aging characteristics between these two systems. Recall that the top and bottom boards of the BUR system are coated with asphalt on both

sides and one side, respectively. However, these aging rates are ~30% lower than for the loosely laid black membrane. Because of the potential difference due to the fact that the ESRA specimens may be further along in aging, no definite statement can be made regarding this comparison. These data were reported with confidence intervals that are much larger for the ESRA data than for the RTRA.¹⁴ These differences also make it difficult to determine the effect of encapsulation.

Figure 30 shows data for bottom and top HCFC-141b boards on the RTRA and the ESRA. The first observation is that there is no significant difference between the top and bottom HCFC-141b boards on the RTRA. Second, there does not appear to be any significant difference between the bottom boards of the ESRA BUR HCFC-141b specimen and the ESRA EPDM specimen. The third observation is the enormous spread in weekly in-situ-measured k-factors of both the top board of the ESRA BUR and the ESRA EPDM specimens.

Figure 31 shows only the weekly k-factors for the bottom boards of the HCFC-141b specimens in the RTRA and the ESRA. The k-factor differences between the bottom boards in the ESRA remain about 10% higher than the k-factor of the bottom board in the RTRA. This shows that the rate of thermal aging is identical. The post-ESRA exposure laboratory measurements of only the bottom boards agree extremely well at the end of this field test in October 1992.

Figure 32 shows just the top boards of the HCFC-141b specimens in the RTRA and the ESRA. The very large scatter in the results for the two top ESRA boards, particularly when compared with the post-exposure laboratory data, suggests a problem. The laboratory k-values in October 1992 align quite well with the RTRA top board in-situ measurements. The reason the ESRA top board data are so inconsistent with the data patterns of the RTRA and the bottom boards of the ESRA is not understood. It is believed that the top board in-situ measurements are unreliable. It appears as if PROPOR is not able to predict the top board k-factors in the ESRA test specimens. At first it was speculated that the top boards had actually aged more rapidly than the bottom. However, based on the post-ESRA exposure laboratory k-factors, this argument can no longer be supported.

5.6 PROPOR DATA COLLECTION AND ANALYSES

Estimates of the thermal conductivity of the combined boards are typically used because they are inherently more precise. When combined boards are analyzed, PROPOR has two independent measurements at internal locations (one heat flux and one temperature) with which to estimate parameters; a single board analysis will use only one heat flux. Two temperatures are used as boundary conditions for all runs.

PROPOR has additional features that are useful for data analysis. One of these is called "sequential value analysis." This analysis generates a running tabulation of how the apparent thermal conductivity estimates evolve during the course of a run. It is useful to determine whether the quantity of data (number of time steps) being analyzed is sufficient to yield a converged result.

HCFC-141b Top & Bottom Board Aging

k-factor normalized to 75 °F

Fig. 30. Envelope Systems Research Apparatus HCFC-141b top and bottom board k-factors normalized to 75°F.

HCFC-141b Bottom Board Aging

k-factor normalized to 75 °F

Fig. 31. Envelope Systems Research Apparatus HCFC-141b bottom board k-factors normalized to 75°F compared with laboratory measurements.

HCFC-141b Top Board Aging

k-factor normalized to 75 °F

Fig. 32. Envelope Systems Research Apparatus HCFC-141b top board k-factors normalized to 75°F compared with laboratory measurements.

A second feature of PROPOR is the ability to calculate and review residuals, that is, the difference between the measured and calculated values for each time step. A random distribution of residuals suggests that the model assumptions are correct, whereas a structured distribution implies that the model could be improved to eliminate this nonrandom behavior.

PROPOR also computes the 95% confidence intervals of the estimated parameters as a function of temperature. The confidence intervals are calculated assuming a normal distribution of the residuals. They are used to calculate the precision of the estimated parameters and to determine the statistical significance of any observed changes.

To obtain a better understanding of the test results, sequential value analyses were performed for two typical weeks, one during the summer and the second during the winter.¹⁴ The weeks of 07/01 to 07/08/91 and 01/06 to 01/13/92 were randomly selected for this purpose. These weeks represent ~750 and 950 days of aging. A typical output is depicted in Fig. 33. The top board was selected for this purpose because its data exhibited the most scatter. PROPOR will generate a sequential value analysis for each temperature at which the apparent thermal conductivity is being estimated; for the manner in which PROPOR was configured for this project, two sequential analyses were performed for each run. The variations in the thermal performance estimates of all the specimens are well within the confidence intervals, verifying that an adequate number of time steps have been analyzed for this series of runs. This result was found to be true for all the cases analyzed.

Residual analyses were also performed for the same 2 weeks. PROPOR was used to calculate three types of residuals for the combined boards: heat flux vs time, temperature vs time, and temperature vs temperature. Figure 34 shows an example for the combined boards of the residuals for heat flux versus time for the same week used to demonstrate the sequential analyses. To simplify the figure, data for only a single specimen from the RTRA (loose white EPDM) and the ESRA (adhered black EPDM) are depicted. The residuals from the loose white EPDM show no clear trend and are randomly scattered, indicating that the model and the data have no systematic biases. For the adhered black EPDM, a large majority of the residuals are negative, signifying that the model as configured is, on average, overpredicting the heat flux.

Confidence intervals compiled for the 2 selected weeks are summarized in Fig. 35. On average, the 95% confidence intervals for all cases in the ESRA and RTRA averaged 0.018 and 0.0062 Btu · in/h · ft² · °F, respectively. As expected, the average confidence interval for the combined boards 0.0083 Btu · in/h · ft² · °F was less than either the bottom (0.0118 Btu · in/h · ft² · °F) or top (0.016 Btu · in/h · ft² · °F) board. The confidence interval average for the top ESRA board specimens averaged 67% larger than the bottom ESRA HCFC-141b specimen: 0.0135 Btu · in/h · ft² · °F for the top vs 0.0081 Btu · in/h · ft² · °F for the bottom.

Both the residual analysis and the confidence intervals suggest a higher precision in the data sets being compiled on the RTRA than on the ESRA. A review of the temperature and HFT sensor data revealed a possible source for this increased variability. Figure 36 shows the interior deck temperature sensor outputs for all four systems for the summer week of 07/01 to 07/08/91. The interior air temperatures of both facilities are controlled; this was confirmed by reviewing the outputs of air temperature sensors

k-Factor Estimates @ 50F by PROPOR **Data from 01/06 to 01/13/92**

Fig. 33. PROPOR apparent thermal conductivity estimates at 50°F from sequential value analysis. Confidence intervals are overlaid to compare the uncertainty to the convergence. Input data are from the top board for the week of 1/6 to 1/13/92.

Residual Heat Fluxes from PROPOR Analysis Data from 01/06 to 01/13/92

Fig. 34. PROPOR residual analysis identifies a systematic bias in the heat flux residuals for the Envelope Systems Research Apparatus specimens. Input data are from the combined boards for the week of 1/6 to 1/13/92.

The 95% Confidence Intervals

Fig. 35. The 95% confidence intervals for the four systems using input data for the weeks of 7/1 to 7/8/91 and 1/6 to 1/13/92. Confidence intervals for the Envelope Systems Research Apparatus average three times those of the Roof Thermal Research Apparatus.

Inside Temps of Four Roofing Systems **Data for 07/01 to 07/08/91**

Fig. 36. Envelope Systems Research Apparatus interior surface temperatures were found to vary substantially. The most likely cause is large internal air-film thermal resistances. This phenomenon appears to affect the confidence intervals of the thermal conductivity estimates computed by PROPOR.

installed 3 in. below the metal deck in both facilities. In the RTRA and ESRA, the interior air temperatures averaged 74.7°F and 77.5°F, respectively. Figure 36 shows substantial variations in the interior surface temperature on the ESRA test specimens. For a week in January, the interior surface temperatures fell substantially below the interior temperature. These variations suggest that there may be substantial thermal shorting through the metal fasteners, or a significant interior air-film thermal resistance due to stagnant air near the deck in the ESRA. The air circulation in the RTRA is better than in the ESRA and is another suspected reason for these variations. The impact of this discovery is that the model as configured has more difficulty in estimating thermal properties. The reason for this behavior is not completely understood, although it seems reasonable that confidence diminishes as the temperature difference across the specimens is reduced, as it does when the interior surface temperature rises and falls with outdoor conditions.

5.7 ACCELERATED AGING PROCEDURE COMPARED WITH FIELD DATA

The slicing technique, described earlier, was used to plane 0.4-in.-thick specimens from the center of full-thickness samples. The four sliced specimens are stacked and the k-factors measured in an apparatus operated in accordance with ASTM C 518 (ref. 28).

Figures 37-39 show plots of the six sets of measurements taken on the 0.4-in. slices versus time/thickness² (labeled "Lab 0.4 in. slice"). This relationship is based on the fact that aging is accelerated by reducing the distance required for oxygen and nitrogen to diffuse into the cells, and for the blowing agents to diffuse out.

Laboratory thermal conductivity measurements of the 0.4-in. slices are used to estimate the k of the 1.5-in. full-thickness boards at age 12 years, using a series of measurements completed in less than 300 days. The six data points plotted with "Δ" in Figs. 37-39 were made at 3, 17, 51, 106, 190, and 290 days. The field data for the HCFC-141b and HCFC-123 boards mounted under the loosely laid black EPDM on the RTRA represent 3 years of weekly k-factors plotted with "■" in Figs. 37 and 38. The accelerated aging procedure for these two materials slightly underpredicts the k-factor. For the CFC-11 boards mounted loosely under the EPDM in the RTRA, the accelerated aging procedure underpredicts the k-factor by 4-5%.

The aging procedure underpredicts the k-factor for all of the fully adhered EPDM systems on the ESRA and for two of the three BUR systems. It would appear that the accelerated aging procedure produces a lower-limit prediction of the in-service thermal conductivity that can be expected from PIR laminated boards with a typical high-permeance facer.

vs 0.4 inch Lab Data at 75°F

HCFC-123 Aging on RTRA and ESRA

vs 0.4 inch Lab Data at 75°F

Fig. 38. HCFC-123 field data compared with the accelerated aging procedure.

CFC-11 Aging on RTRA and ESRA

vs 0.4 inch Lab Data and 75°F

Fig. 39. CFC-11 field data compared with the accelerated aging procedure.

6. CONCLUSIONS

This report presents k-values on a set of industry-produced, prototypical, experimental PIR laminated boardstock foams blown with five gases: CFC-11, HCFC-123, HCFC-141b, and 50/50 and 65/35 blends of HCFC-123/HCFC-141b. The k-values were determined from 30 to 120°F using the ORNL UTHA and the ORNL HFMA. The observed laboratory k(75) values increased with panel exposure time in the RTRA. The increase was between 8 and 11% for a 250-day exposure in the RTRA (CFC-11, 8.6%; HCFC-123, 11.1%; and HCFC-141b, 9.4%) and between 23 and 28% for a 1000-day exposure in the RTRA (CFC-11, 27.7%; HCFC-123, 24.8%; HCFC-141b, 23.1%).

The laboratory tests show that, before the RTRA exposure, the k of the foams blown with the alternate gases was greater than that of the foam blown with CFC-11: 5.5% for HCFC-123 and 11.7% for HCFC-141b. After the 250-day RTRA exposure, these values were 7.9% for the HCFC-123 and 12.9% for the HCFC-141b. After the 430-day RTRA exposure, these values were 4.5% for HCFC-123 and 9% for HCFC-141b. After 1000 days of RTRA exposure, these values were 2.9% for HCFC-123 and 7.7 % for HCFC-141b. The k of foams blown with the blends was about 5.8% greater than that of the CFC-11 blown foam before the RTRA exposure. Foams blown with blends showed an increase in k of about 20% after 300 days and of 27.5% after 900 days of RTRA exposure.

The k-values of a set of thin-specimen foam cores planed from these experimental boardstock insulations increase with time after production. The thin specimens were aged at 75°F and at 150°F for up to 873 days to establish the long-term thermal resistance of each of the gas-filled cellular foams. For each of the foams, the increase in k-values for specimens of three thicknesses can be described as an exponential function of k with $\text{time}^{1/2}/\text{thickness}$. This dependency shows two distinct linear regions of behavior with an intermediate zone when the results are plotted as a function of $\text{time}^{1/2}/\text{thickness}$ ($\text{days}^{1/2}/\text{mm}$). The thinnest specimen reached larger values of $\text{time}^{1/2}/\text{thickness}$ than the thicker specimen for the same amount of aging, (i.e., aging was accelerated).

The first linear region was associated with the increase in k due to the influx of air components (O_2 , N_2); and the second, lower slope, linear region was associated with the loss of blowing agent from the foam. This approach yielded effective diffusion coefficients (D) for air components into the foam and blowing agent out of the foam. The D (air) values for aging at 75°F were between $1 \times 10^{-8} \text{ cm}^2/\text{sec}$ and $2 \times 10^{-8} \text{ cm}^2/\text{sec}$, and D-values for aging at 150°F were three to eight times larger. The D (blowing agent) values for aging at 75°F were between $1.4 \times 10^{-10} \text{ cm}^2/\text{sec}$ and $3 \times 10^{-10} \text{ cm}^2/\text{sec}$, and they increased two to nine times for aging at 150°F. Activation energies of 3000 to 10,000 cal/mol were obtained for these processes. The accelerated aging test results provided an estimate of 5-year thermal resistivity ($1/k$) of these experimental foams at 75°F that is within 12% of that obtained for foams blown with CFC-11 under similar conditions.

The resulting values for the specimens of three thicknesses describe two linear regions of behavior with an exponential dependency on $(\text{diffusion coefficient} \times \text{time})^{1/2}/\text{thickness}$, which were used to predict the 10-year k value of the foams as shown in the following chart with k in $\text{Btu} \cdot \text{in}/\text{h} \cdot \text{ft}^2 \cdot ^\circ\text{F}$.

Blowing agent	CFC-11	HCFC-123	HCFC-141b	50/50	65/35
Initial k	0.1213	0.1331	0.1414	0.1345	0.1359
10-year k	0.1622	0.1747	0.1802	0.1810	0.1837
Percent increase	34	31	27	35	35
Versus CFC-11, %	-	8	11	12	13

Apparent thermal conductivity values at 75°F for 1.5-in.-thick boards—obtained using field data for 680 days for the CFC-11, HCFC-123, and HCFC-141b and 500 days for the blends—agreed to better than 4%. The k values predicted from the thin-specimen aging at 75°C test are shown in the following chart with k in Btu • in/h • ft² • °F.

Blowing gas	CFC-11	HCFC-123	HCFC-141b	HCFC-141b	50/50	65/35
EPDM color	Black	Black	Black	White	Black	Black
Field k	0.1573	0.1615	0.1733	0.1712	0.1691	0.1643
Lab k predicted	0.1532	0.1664	0.1726	0.1726	0.1712	0.1712
Percent difference	-2.6	+3.0	-0.4	+0.8	+1.2	+4.2

Four different roofing systems containing CFC-11, HCFC-141b, and HCFC-123 blown PIR roof insulation have been installed in outdoor test facilities at ORNL for 3 years. In one type of roof system, two blends of HCFC-123 and HCFC-141b have also been field tested. Temperature sensors and HFTs installed in these systems have been employed to monitor their in-situ thermal response to natural weather conditions. A model of these systems has been used in conjunction with PPOPOR to compute an estimate of their k-factors. The following conclusions can be drawn from this project.

1. PIR foamboard insulation specimens with loosely laid membranes are aging at a rate that has been verified by periodic laboratory testing.
2. There is no appreciable difference in the aging characteristics of specimens under black and white membranes for the Oak Ridge, Tennessee, climate. The average annual difference in mean temperature of these specimens for the exposure time of this project was only 5.6°F.
3. The BUR and fully adhered black EPDM systems have very similar aging rates.
4. A 30% difference in the aging rate was measured between the loosely laid membranes and the BUR and fully adhered EPDM systems with HCFC-141b

specimens. Comparisons between the two exposure facilities are difficult because the ESRA roof installation took place a year after the RTRA installation, and because of the difference in thermal performance due to installation practices.

5. The installation process seems to impact the thermal properties of PIR roof insulation. The in-situ field data suggest a much larger impact, 8-13%, compared with 4-8% using the post-exposure laboratory k-factor data.
6. The accelerated aging procedure using 0.4-in. slices produces a lower limit prediction of the in-service thermal conductivity.

It does not matter whether the membrane above the insulation boards is black or white; the aging rate is the same. However, installation of these test specimens in a fully adhered EPDM membrane system appears to cause a 6-8% loss in R-value. The impact of asphalt encapsulation is mixed. One of the three BUR systems tested was found to cause an immediate loss in thermal performance similar to that found in all three fully adhered EPDM systems. The third BUR system showed a 3-4% loss in R-value shortly after installation. The accelerated aging procedure used to predict the long-term thermal performance does a good job of predicting the conductivity of loosely laid boards under the EPDM membrane on the RTRA. Based on the data recorded in the ESRA with these boards installed under BUR and under a fully adhered EPDM, the accelerated aging procedure appears to underestimate the thermal conductivity by 0-10%. For most roof systems, the accelerated aging procedure appears to be able to predict long-term thermal performance of PIR within 5% of field performance.

7. RECOMMENDATIONS

The Cooperative Industry-Government Project provided the opportunity for manufacturers, users, and measurers to bring their combined talents to focus on an initial solution to the global issue of reducing CFC use in PIR foam insulations. ORNL should recommend this type of project to the producers of other types of foams (e.g., polystyrene and phenolic). The cooperative project has raised a number of interesting questions and results that deserve further study. These are given below.

1. The project test results create a valuable data base for the initial set of industry-produced experimental, prototypical PIR laminated boardstock foams. ORNL should recommend close examination of these data by industry to produce and start tests in a cooperative project on the next generation of improved foams blown with alternative agents.
2. A thin-specimen accelerated-aging test procedure was validated by laboratory tests of specimens aging at 75 and 150°F. ORNL should use these results to help draft an ASTM C 16 standard procedure for determining the long-term thermal resistance of gas-filled cellular plastic foams. Draft 7 of this standard was balloted by ASTM C 16.30 and C 16.22 on September 21, 1992.
3. The thin-specimen accelerated-aging test has yielded order-of-magnitude effective diffusion coefficients (D) for O₂, N₂, and blowing agents and process activation energies. Since these are influenced by the foam structural properties (i.e., cell size, wall thickness, and fraction of solid in walls), determination of D could guide product evaluation and development. ORNL should work with industry on a cooperative project to obtain D values by this technique for products with significantly different structural characteristics (i.e., thicker walls, smaller cells, and larger fractions of solid in walls) and using significantly different gases (helium) and gas pressures.
4. The thin-specimen accelerated-aging procedure should be applied to field tests (e.g., RTRA panels composed of thin specimens) to see how the procedure works and how it compares with laboratory aging.
5. The thin-specimen accelerated-aging procedure requires planing thick specimens to a known and uniform thickness of <0.4 in. (10 mm). ORNL should obtain planing equipment to produce uniform-thickness specimens and a means to measure them. For example, NIST has a large flat table with a dial gage to measure specimen thickness over the board area.
6. All means to verify and to confirm the thin-specimen procedure should be explored because it provides a rapid means to predict the long-term thermal performance of foam insulations, and the present ASTM 180-day procedure is inadequate. ORNL should conduct a cooperative test program with industry members and NIST to show that the ORNL procedure for unfaced, rigid, closed-cell PIR foam insulation is a viable procedure.
7. Impermeable facers are often used on foam insulation board to delay their aging and increase in thermal conductivity with time. The thin-specimen accelerated

aging procedure should be applied to such products to develop a means to predict their long-term thermal performance.

8. The ORNL HFMA was used to make many of the thermal conductivity measurements obtained during this project. An interlaboratory comparison with other C518 apparatuses showed their imprecision to be 2.2%. Additional interlaboratory comparisons at fixed thicknesses and with compressible materials as interfacial layers are needed to evaluate interfacial resistance effects and to address test specimens that contain surface undulations (waves).

8. ACKNOWLEDGEMENTS

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