System Effects on the Thermal Aging of Experimental Polyisocyanurate Roof Insulation Foamed with an Alternative Blowing Agent

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ABSTRACT

Experimental polyisocyanurate foam roof insulation with 0.6-mm-thick permeable black facers blown with HCFC-141b installed on test roofs at a national laboratory for almost three years shows various degrees of aging. Four roof systems are being monitored to determine the effect of system type on board aging. The four systems are composed of a dry stack of insulation boards covered, respectively, by a loosely laid single-ply white membrane, a loosely laid single-ply black membrane, a built-up roof (BUR), and a fully adhered ethylene propylene diene monomer (EPDM) membrane. A comparison with periodic laboratory testing of the insulation boards is also included.

A data analysis program, PROPOR, has been used to estimate the thermal properties of the polyisocyanurate foam insulation, to gain insight into the data and the pure conduction model used by PROPOR through sequential value and residual analyses, and to estimate the precision of the results with confidence intervals. These confidence intervals are then used to determine if the differences noted due to aging of the insulation boards contained within these systems are statistically significant.

These experiments are part of a joint industry/government project established to evaluate the technical viability of alternative HCFC blowing agents for rigid, closed-cell polyisocyanurate foam roof insulations. Members of the project are the U.S. Department of Energy, the U.S. Environmental Protection Agency, the Society of the Plastics Industry, the Polyisocyanurate Insulation Manufacturers Association, and the National Roofing Contractors Association.

INTRODUCTION

A joint industry/government project was initiated in 1989 to determine the thermal performance of polyisocyanurate foam roof insulation blown with alternative blowing agents and to compare its performance with boards produced with CFC-11. The project involved several laboratory and field experiments. One objective of the field experiments was to determine whether installation practices or the type of roofing system that was employed affected the aging characteristics of the foam insulations. This aspect of the project is the subject of this paper. Other aspects of the project have been reported by Baumann (1990), Blanpied and Knis (1990), McElroy et al. (1990), Christian et al. (1990), Courville et al. (1992), and Smith, et al. (1991).

Aging is defined as a change with time in the thermophysical properties of rigid, closed-cell plastic foam due to changes in the composition of the gas contained within the cells. Since the aging of polyisocyanurate foams can be affected by several factors, among them the temperature and the permeance of the facers, it is possible that the system in which the foam is installed has an impact on its aging rate. Shipp and Griggs (1989) demonstrated that the color of the roof can affect the temperature of the roof surface (and therefore the temperature of the roof system components). Attachment of a membrane to insulation can potentially reduce the permeance of that surface and therefore retard the aging rate. However, these system effects have not as yet been addressed in the literature.

OUTDOOR TEST FACILITIES AND ROOF SYSTEMS

The experiments reported in this paper were undertaken on the roof thermal research apparatus (RTRA) and the envelope systems research apparatus (ESRA) at a national laboratory (Figures 1 and 2, respectively).

The RTRA is a 3-m-by-8.5-m conditioned building that can accommodate four 1.2-m-by-2.4-m roof test panels. One of these panels was used for this project and is depicted in Figure 3. The test panel was divided into two 1.2-m-square specimens. Two 38-mm layers of HCFC-141b blown foam were stacked and laid over a continuous metal deck. One specimen was covered with a loosely laid white EPDM membrane; the second specimen was similarly covered with a black EPDM membrane. The membranes were attached along the perimeter of each specimen to guarantee a weathertight seal. The central 0.6-m-square section of each foam test specimen was physically separated from the remaining foam so that it could be periodically removed to measure its thermal performance and calibrate the installed instrumentation.

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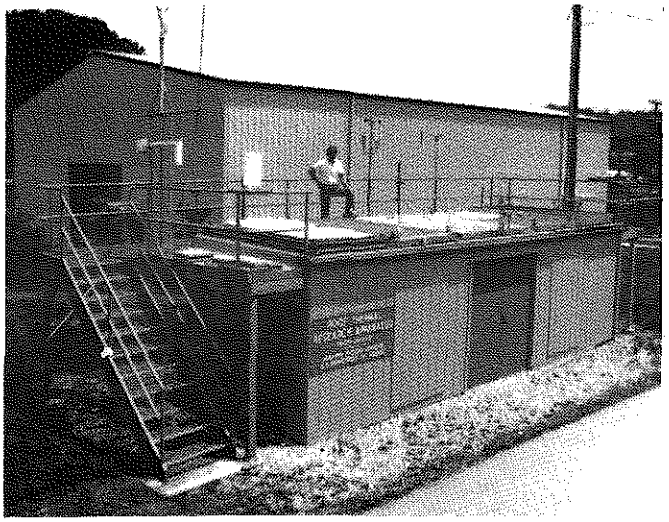

Figure 1   *The roof thermal research apparatus (RTRA) at the national laboratory. The test panel discussed in this paper is second from right.*

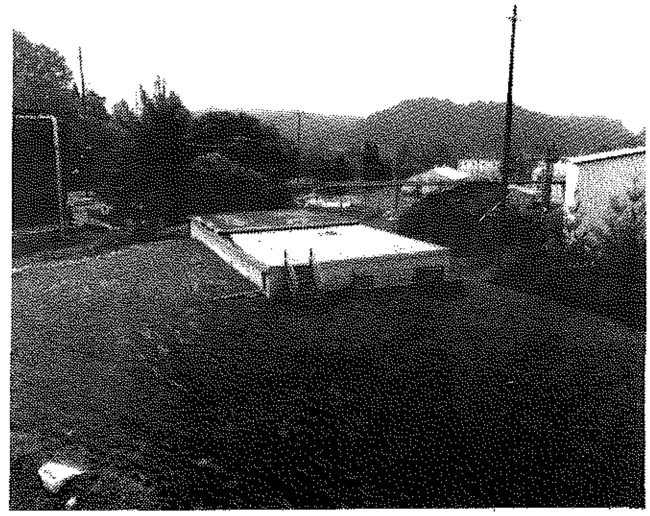

Figure 2   *The envelope systems research apparatus (ESRA) at the national laboratory.*

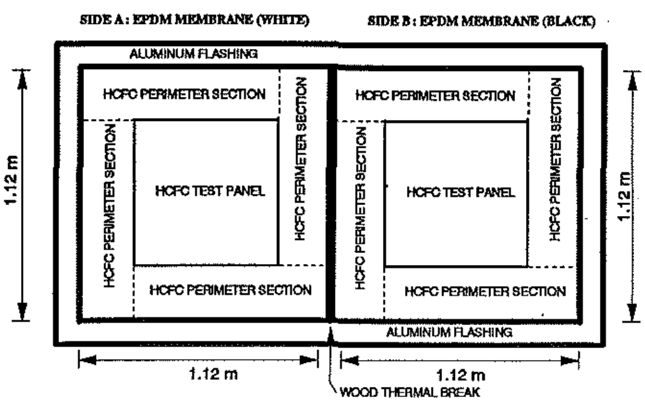

Figure 3   *Top view of the RTRA test panel.*

Each RTRA specimen was instrumented with a 50-mm-square heat flux transducer (HFT) mounted between the insulation layers and a type-T copper-constantan thermocouple at each internal interface (i.e., between the EPDM and the top foam layer, between the foam layers, and between the bottom foam layer and the metal deck). The instrumented boards were installed in the RTRA in October 1989 and data collection was initiated at that time.

The ESRA is a 10-m-by-22-m one-story, temperature- and humidity-controlled building that rises approximately 1.5 m above grade. Complete details for this facility have been reported by Smith et al. (1991). The roof deck is galvanized steel and is sloped 1:48 (1/4-inch per foot) by varying the heights of the bearing walls. The ESRA roof plan is depicted in Figure 4. The roof deck is divided in half by a 0.3-m-high curb wall. Two layers of 38-mm-thick foam board with various blowing agents (including HCFC-141b) were installed under two different membranes, with each membrane having two variations. The EPDM membranes were either mechanically fastened or fully adhered, while the BUR systems included a vented base sheet or were directly applied. Pertinent to this project are the instrumented panels that were placed along the southern edge of the roof deck. Two 0.9-m-by-1.5-m sections of foam were cut from the center of a stack of two full-sized boards, instrumented like the central sections of the RTRA specimens, and installed in the ESRA roof along with uninstrumented boards in June 1990. The data collection process began in September 1990.

The polyisocyanurate foam used in the RTRA and ESRA panels was manufactured in June 1989. The formulation was not optimized for thermal performance or any specific blowing agent. The boards used to insulate the ESRA roof had been stored at the laboratory under enclosed uncontrolled ambient conditions for approximately one year prior to their installation on the ESRA roof while the facility was being constructed.

One of the insulation stacks mounted in the ESRA was installed under a BUR. In this application, the first layer of insulation was mechanically attached to the deck with metal fasteners and plates. The second layer of insulation was attached with Type IV hot asphalt at approximately 210°C and covered with three fiberglass sheets fully adhered directly to the insulation with hot asphalt and surfaced with a glaze coat. During the attachment of the fiberglass sheets, the asphalt temperature was maintained in the range of 195°C to 205°C.

The second stack was installed under a 1.1-mm-thick black EPDM complying with ASTM D 4673, Type I, Grade 2, Class U. Both layers of insulation were mechanically attached with fasteners and plates. A neoprene-based adhesive with solvent was applied to the insulation and EPDM with a roller. After the solvent flashed off (approximately 60 minutes), the EPDM was mated with the insulation.

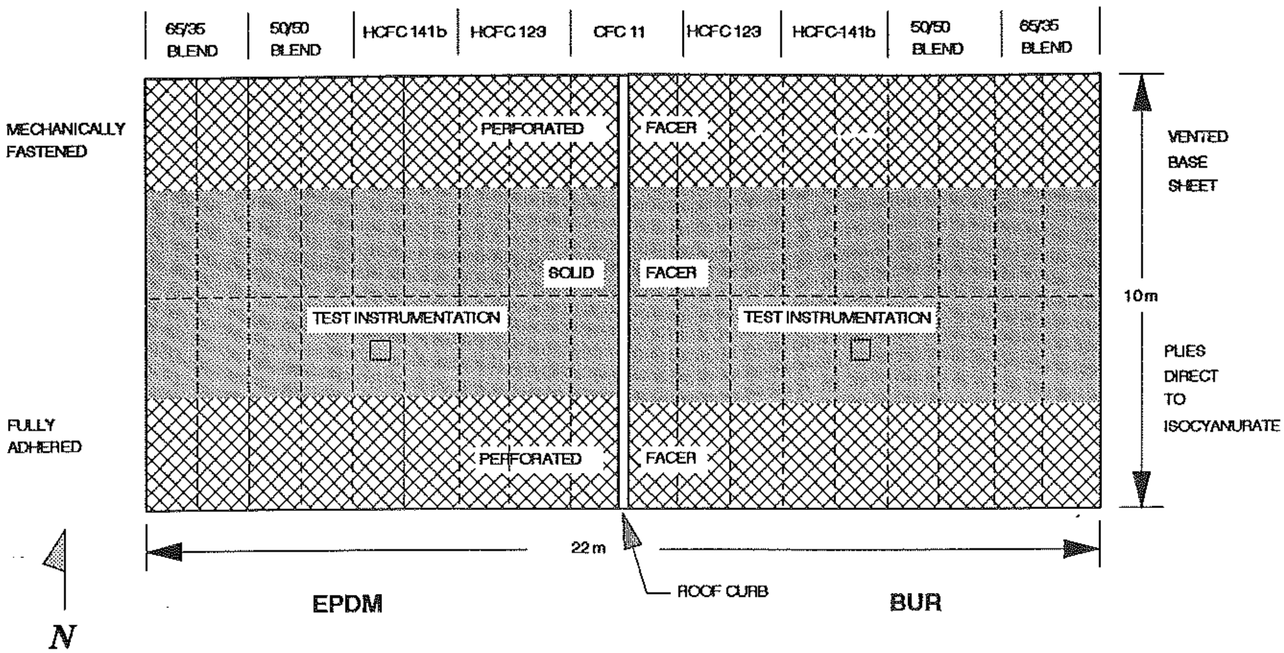

Figure 4 *ESRA roof plan details the layout of the insulation boards and the location of the test specimens.*

Both the EPDM and the BUR systems were installed by roofing professionals in accordance with good, commonly accepted industry practice and manufacturers' recommendations. An exception was made with the BUR system, where the BUR was applied directly to the insulation rather than to a thin cover board as recommended in NRCA Bulletin 9 (NRCA 1988). Since this application is sometimes still performed by industry, the more severe temperatures encountered by the insulation in this application were deemed acceptable.

The systems described above offer the possibility for performing the following comparisons:

1. The two systems installed on the RTRA can be compared to determine if the color or reflectance of the membrane will have an impact on the aging rate of the polyisocyanurate foam roof insulation.
2. The systems in the RTRA can be compared to the systems installed in the ESRA to ascertain the effects of installation.
3. Comparisons between the RTRA specimen with a black membrane and the BUR and fully adhered black EPDM systems on the ESRA may supply evidence of the effect of various encapsulations, such as EPDM adhered to one side of the foam board and asphalt applied to one and both sides of the foam board.

DATA COLLECTION AND ANALYSES

Temperature and heat flux data from the sensors installed in the test panels are automatically recorded at one-minute intervals and averaged into hourly values. The computer program PROPOR is used to analyze these data. PROPOR is an application of one-dimensional inverse heat transfer analysis and has been explained by Beck et al. (1990) and Beck and Arnold (1978). Using two appropriate time series of measurements as boundary conditions, the program predicts the temperatures and heat fluxes at sensor locations utilizing the conductive heat transfer equation for a homogeneous medium with initial estimates (best guesses) of thermal properties as parameters. The program then iterates the measured parameters to predict a better set of thermal properties and continues this process until a predetermined error limit is reached (statistically, a best fit to the data). As configured for this project, the final output is a linear (two-point) estimate of thermal conductivity vs. temperature for a fixed product of density times specific heat. The program is applied to weekly (168-hour) sets of data and can be used to estimate either the thermal conductivity of the two-board combination or either individual board. 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 utilize only one heat flux. Two temperatures are used as boundary conditions for all runs.

The program 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 in determining whether the quantity of data (number of time steps) being analyzed is sufficient to yield a converged result.

A second feature is an ability to calculate and review residuals, i.e., 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.

The program will also compute 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.

EXPERIMENTAL RESULTS

Apparent thermal conductivity data at a mean temperature of 24°C for the combined top and bottom boards from the RTRA and ESRA specimens are presented as a function of age in Figure 5. The age of the boards is based on their date of manufacture (i.e., their manufacturing date is defined as Day 0). Each data point represents the output of a PROPOR analysis on a 168-hour data set. Employing the linear estimate provided by PROPOR, the apparent thermal conductivity is computed for the data set's mean temperature. This result is then normalized to a mean temperature of 24°C using an apparent thermal conductivity vs. temperature relationship derived by laboratory testing on the laboratory's heat flowmeter apparatus (HFMA), which is designed and operated in accordance with ASTM C 518 (ASTM 1989a). Figures 6 and 7 present similar data for the bottom and top boards from each specimen, respectively.

Prior to the installation of the RTRA and ESRA specimens, their apparent thermal conductivity was measured in the laboratory using the unguarded thin heater apparatus (UTHA), which conforms to the requirements of ASTM C 1114 (ASTM 1989b). The RTRA specimens were periodically removed during their exposure and retested to verify the calibration of the HFT and to supply a cross-reference between laboratory and field data collection. In October 1991, a specimen of polyisocyanurate foam was removed from the mechanically fastened EPDM quadrant of the ESRA roof and was evaluated in the HFMA in December 1991. These data are also presented in Figure 5.

The full-thickness field data summarized in Figure 5 show an appreciable difference between the apparent thermal conductivities measured in the RTRA (the two loosely laid EPDM systems) and the two ESRA systems (BUR and adhered EPDM). There also appears to be only minor differences between the BUR and fully adhered EPDM data from the ESRA, with the most outstanding feature of these data sets being the increase in the apparent thermal conductivity during the summer months.

The apparent thermal conductivities of the black and white loosely laid systems agree well during the summer months (400 and 750 days old) but diverge in the winter months (600 and 950 days old). Although the reason for this divergence is unknown, it is suspected that PROPOR underestimates the thermal conductivity of the white loosely

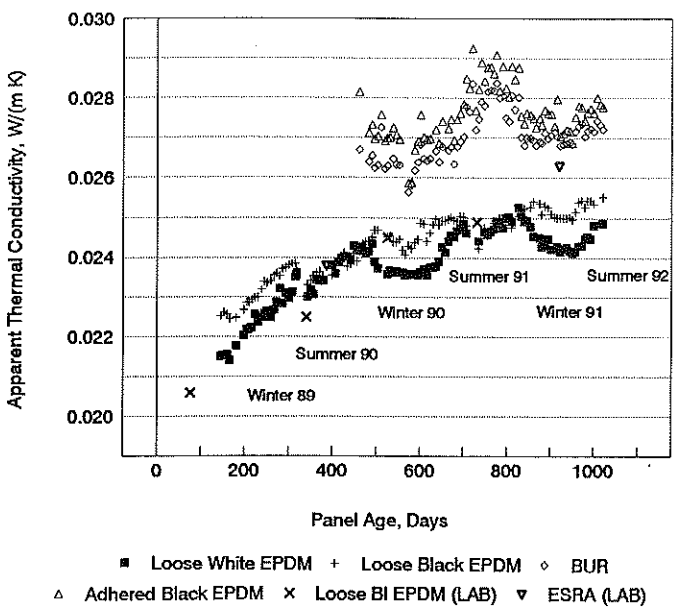

Figure 5 *The apparent thermal conductivity of the four full-thickness test specimens as a function of age. The thermal performance data have been normalized to a mean temperature of 24°C. Laboratory test results are overlaid for comparison.*

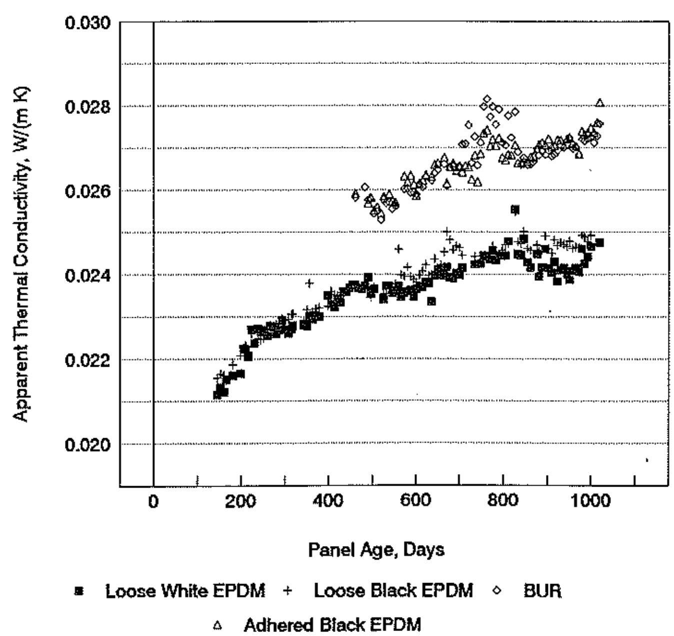

Figure 6 *The apparent thermal conductivity of the four bottom board test specimens as a function of age. The thermal performance data have been normalized to a mean temperature of 24°C.*

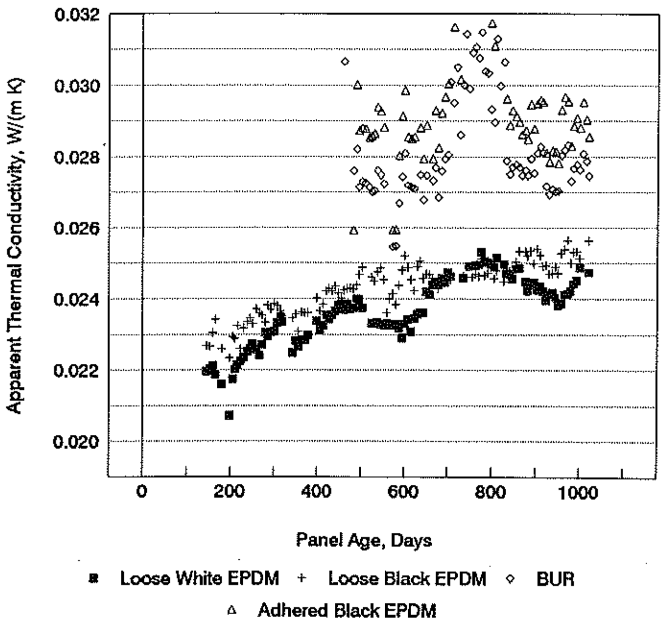

Figure 7 *The apparent thermal conductivity of the four top board test specimens as a function of age. The thermal performance data have been normalized to a mean temperature of 24°C. Substantial scatter in the BUR and adhered EPDM data is due to large confidence intervals.*

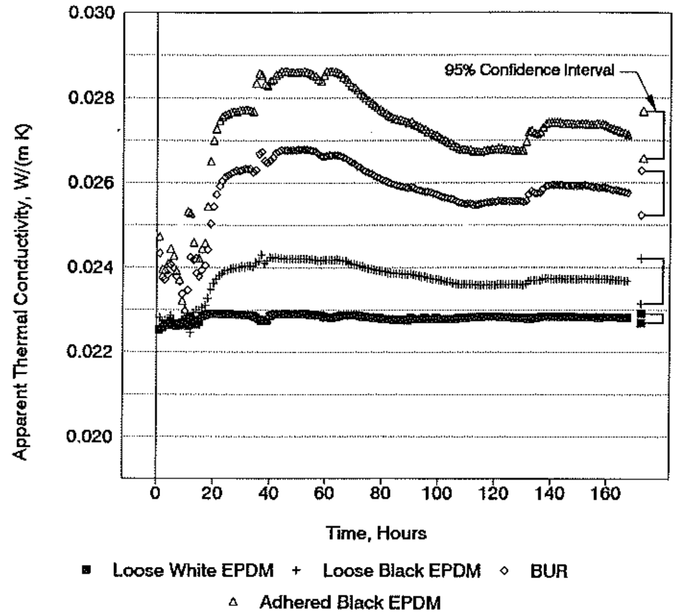

Figure 8 *PROPOR apparent thermal conductivity estimates at 10°C from sequential value analysis. Confidence intervals are overlaid to compare the uncertainty to the convergence. Input data are from the top board for the week of 1/6 to 1/13/92.*

laid EPDM system during the winter months. The apparent thermal conductivity vs. mean temperature relationship for the polyisocyanurate foam is nonlinear at low temperatures due to the condensation of the blowing agent. The effect of the white membrane is to further reduce the mean temperature of the insulation in the roof system and, when PROPOR attempts to linearly fit its thermal conductivity estimates, it creates a negative systematic bias.

Figure 6, the bottom board data, is very similar to the full-thickness test results with the possible exception being that the peak in apparent thermal conductivity during the summer months that is noted on the ESRA specimens is somewhat diminished in magnitude. Figure 7, the top board data, clearly shows a substantial increase in the amount of scatter in the data from the ESRA, while the RTRA data are similar to its full-thickness and bottom-board data.

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. The weeks of 7/1 to 7/8/91 and 1/6 to 1/13/92 were randomly selected for this purpose. These weeks represent approximately 750 and 950 days of aging, respectively. A typical output is depicted in Figure 8: apparent thermal conductivity estimates for the week of 1/6 to 1/13/92 at a mean temperature of 10°C for the top board. The top board was selected for this purpose because its data exhibited the most scatter. PROPOR generates 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 95% confidence intervals (discussed in detail later in this section) for these data sets are also shown in Figure 8. The variation 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 two 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. An example of the residuals for heat flux vs. time for the same week that was used to demonstrate the sequential analyses is shown in Figure 9 for the combined boards. 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 two selected weeks are summarized in Figure 10. On average, the 95% confidence intervals for all cases in the ESRA and RTRA averaged 0.0026 and 0.0009 W/(m·K), respectively. As

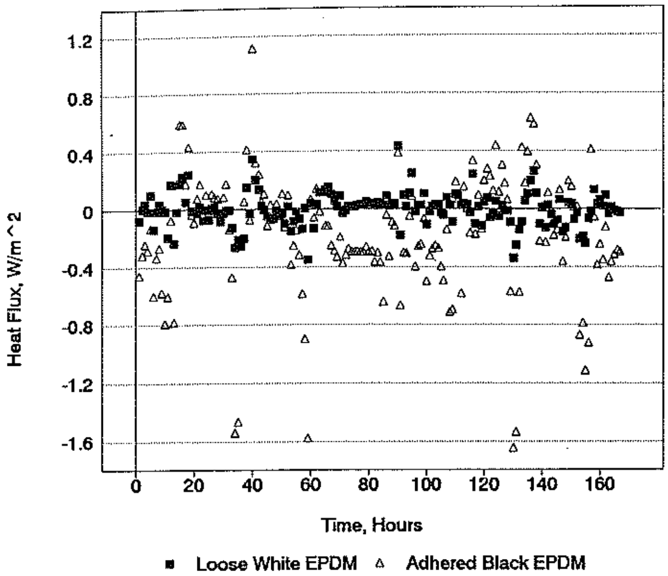

Figure 9 *PROPOR residual analysis identifies a systematic bias in the heat flux residuals for the ESRA specimens. Input data are from the combined boards for the week of 1/6 to 1/13/92.*

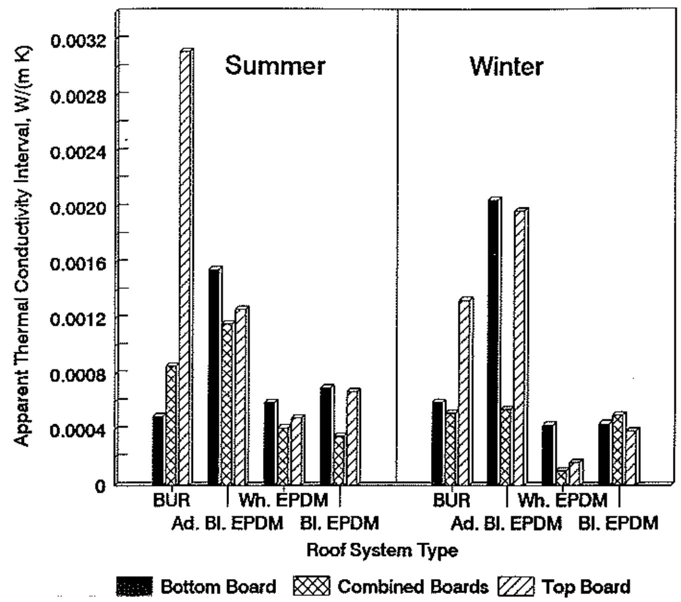

Figure 10 *The 95% confidence intervals for the four systems using input data for the weeks of 7/1 to 7/8/91 and 1/6 to 1/13/92. Confidence intervals for the ESRA average three times that of the RTRA.*

expected, the average confidence interval for the combined boards (0.0012 W/[m·K]) was less than either the bottom (0.0017 W/[m·K]) or top (0.0023 W/[m·K]) board.

Both the residual analysis and the confidence intervals suggest a higher precision in the data sets being compiled on the RTRA than the ESRA. A review of the temperature and HFT sensor data revealed a possible source for this increased variability. Figure 11 shows the interior deck temperature sensor outputs for all four systems for the summer week of 7/1 to 7/8/91. The interior air temperatures of both facilities are controlled and this was confirmed by reviewing the outputs of air temperature sensors installed 75 mm below the metal deck in both facilities. In the RTRA and ESRA, the interior air temperatures averaged 23.7° and 25.3°C, respectively. Figure 11 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 exterior air leakage in the flutes of the metal deck, 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. Checks of temperature and smoke traces seem to rule out air leakage and thermal bridging effects; the air circulation in the RTRA is better than in the ESRA and is the 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 occurs when the interior surface temperature rises and falls with outdoor conditions.

DISCUSSION

The differences in thermal performance between the RTRA and ESRA systems are believed to be related in part to installation. Prior to the installation of the polyisocyanurate foam insulation on the ESRA, the actual full-thickness test specimens were measured in the laboratory using the thin-heater apparatus. The average apparent thermal conductivity for the subsequent BUR and adhered EPDM specimens was 0.0238 W/(m·K) at 24°C. 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 0.0236 W/(m·K) at the same age. These data demonstrate that the boards being 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 apparent thermal conductivity had increased to approximately 0.0267 W/(m·K). In October 1991, a specimen of foam was removed from the EPDM side of the ESRA and was tested in the HFMA in December 1991 when the insulation board was 920 days old. The apparent thermal conductivity of this specimen had increased to 0.0263 W/(m·K). At 920 days, the average apparent thermal conductivity of the ESRA specimens was 0.0269 W/(m·K), while the RTRA specimens averaged 0.0246 W/(mK). The ESRA specimens were similar in thermal performance to the RTRA at installation (0.0236 W/[m·K] vs. 0.0238 W/[m·K]) and were verified to be approximately

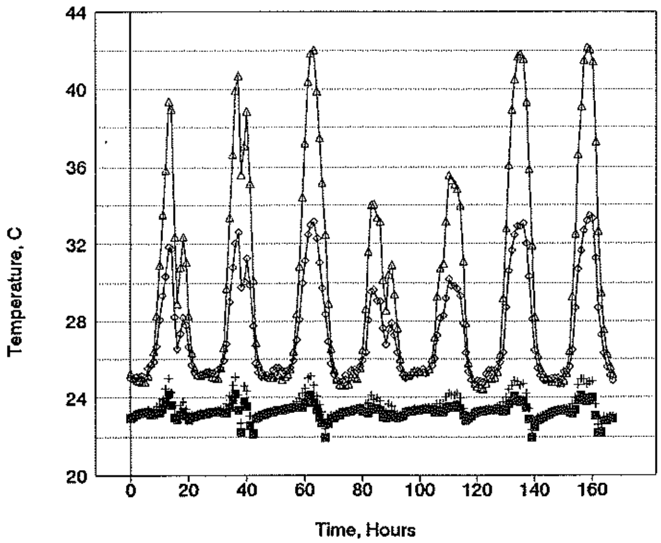

Figure 11 *ESRA interior surface temperatures were found to vary substantially, with the most likely cause being large internal air-film thermal resistances. This phenomenon appears to have an impact on the confidence intervals of the thermal conductivity estimates computed by PROPOR.*

8% higher after installation. The installation process, including the handling, foot traffic, and addition of either solvent or hot asphalt, is suspected to be responsible for a portion of this increase in apparent thermal conductivity.

The color of the roof membrane does not have a substantial impact on the aging characteristics of the polyisocyanurate foam roof insulation. For the entire exposure, the full-thickness foam specimens covered with loosely laid white and black membranes on the RTRA had average exposure temperatures of 17.2° and 20.3°C, respectively, or a difference of just 3.1°C. The slopes of the apparent thermal conductivity vs. age plot for the aging period of 450 days to date for these specimens were $1.59 \cdot 10^{-6}$ and $1.83 \cdot 10^{-6}$ W/([m·K] day), respectively. Although the slopes vary by 15%, the behavior of the apparent thermal conductivity of the white-covered specimen during the winter months is suspect. Because a linear fit is made to the thermal conductivity estimates by PROPOR, data for mean temperatures near the boiling point of the blowing agent will yield a low estimate of apparent thermal conductivity when they are normalized to a mean temperature of 24°C. This bias in the winter data for the white membrane will contribute to a decrease in the slope of the apparent thermal conductivity vs. age relationship.

The slopes of the apparent thermal conductivity vs. age plot for the aging period of 450 days to date for the full-thickness BUR and adhered black membrane specimens on the ESRA were $1.22 \cdot 10^{-6}$ and $1.23 \cdot 10^{-6}$ W/([m·K] 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 approximately 30% lower than the loosely laid black membrane. Because of the differences in the confidence intervals associated with the results of these experiments and the potential difference due to the fact that the installation process of the ESRA specimens may have periodically accelerated the aging, no definite statement can be made regarding this comparison. Since the ESRA specimens are higher in thermal conductivity, it would be expected that their aging rates (or slope of apparent thermal conductivity vs. age) should be lower.

CONCLUSIONS

Four different roofing systems containing polyisocyanurate roof insulation blown with HCFC-141b have been installed in facilities at a national laboratory and exposed to a southern continental climate for almost three years. Temperature sensors and heat flux transducers 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 a computer program to compute an estimate of their thermal properties and qualitatively assess the estimates. The following conclusions and lessons can be drawn from this project.

1. PROPOR provides a unique capability to process in situ data and provide not only estimates of the thermal properties but the statistical basis for assessing the significance of the differences in those estimates.
2. Real-world conditions encountered in the ESRA complicate the processing capability of PROPOR, increasing within-sample variations that preclude the possibility of drawing some definite conclusions.
3. Field and laboratory measurements were in good agreement for the loosely laid membrane systems. Specimens with loosely laid membranes are aging at a rate that has been verified by periodic laboratory testing.
4. There is no appreciable difference in the aging characteristics of specimens under black and white membranes for a climate similar to that in this study. The average difference in the mean temperature of these specimens for this project's exposure period was only 3.1°C.
5. The BUR (with three-fourths of the board surfaces encapsulated in asphalt) and fully adhered black EPDM systems have very similar aging rates.
6. A 30% difference in the aging rate was measured between the loosely laid membranes and the BUR and fully adhered EPDM systems. Comparisons between the two exposure facilities are difficult due to a qualitative difference in the test data and the difference in thermal performance due to installation practices.

Temperature variations on the interior side of the test specimens installed in the ESRA may account for the difference in confidence intervals.

7. The installation process seems to have an impact on the thermal properties of polyisocyanurate roof insulation. Pre- and post-installation thermal performance varied by approximately 8%. The circumstantial evidence used to reach this conclusion will be verified when the project is terminated by performing laboratory tests on the actual test specimens.

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