IN-PLACE THERMAL AGING OF POLYURETHANE FOAM ROOF INSULATIONS

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INTRODUCTION

For many years since the first polyurethane foam was used in a commercial roof insulation application, there has been a controversy regarding the proper specification for the foam thermal conductivity (k) which changes with time and the subsequent thermal resistance (R) of the composite.

The use of polyurethane foam in roofing insulation applications has resulted in the evolution of many types of composites to meet numerous specification needs. There are products faced with both organic and inorganic materials such as organic felt, asbestos, glass fiber mats, and aluminum foil. Some of the composites may have perlite or glass fiber boards as the bottom surface, depending on various aspects such as fire performance or dimensional stability requirements.

The actual physical configuration of the foam composite roof insulation is among many factors which can affect the thermal aging characteristics of the product. Others may include the type of foam (formulation or processing), foam open cell content, cell orientation, cell dimension, foam thickness, roof configuration, type of deck, type of BUR, installation conditions, and many more.

Freon is usually the blowing agent in the manufacturing process for polyurethane foam. This encapsulated Freon in the final product acts to increase the foam's thermal resistance, or stated differently, to lower the foam thermal conductivity. With time, air enters the foam cells and Freon exits, thereby causing an increase in foam thermal conductivity or degradation of the product's thermal resistance. Theoretically, polyurethane foams in the two (2) pounds per cubic foot range can have an initial thermal conductivity (k) of 0.10 to 0.12 BTU-in/hr-ft^2-°F. The thermal conductivity can degrade to as high as 0.22 to 0.24 BTU-in/hr-ft^2-°F if all of the Freon in the cells is replaced with air.

For some time, the manufacturers of polyurethane foam composites have specified various foam thermal conductivities (k) for their products based on various test procedures. Recently, specific laboratory conditioning and testing procedures have been established by the Roof Insulation Committee/Thermal Insulation Manufacturers Association (RIC/TIMA) so that all manufacturers can specify their product thermal value, thermal conductance (C) or thermal resistance (R), based on this common test (i.e., condition the foam specimens at 73°F, 50 percent relative humidity for six months and measure the resulting aged value).

However, up to this point, very little aged thermal conductivity data has been presented from actual roof installations to determine the in-place thermal conductivity as a function of time for polyurethane composite roof insulations. This paper presents the results of recent work conducted to establish these properties.

EXPERIMENTAL PROCEDURE

In order to establish the in-place thermal aging characteristics of various polyurethane roof insulations, test sections were installed several years ago at various locations in the country. The test sections were parts of actual commercial roofs installed by experienced contractors in a conventional manner, i.e., roof insulation applied in hot asphalt to the deck, followed by a three- or four-ply hot applied BUR. All of these roofs were installed under typical roofing conditions and pertinent data, such as roof construction details, weather conditions, asphalt application temperatures, etc., were recorded.

The thermal conductivity (k) of the polyurethane foam in the composite was measured and recorded at the time of installation. After construction, test samples (cuts) were subsequently taken from these roofs at various times after installation. These test cuts consisted of 22 inch by 22 inch samples removed completely down to the roof deck from the center of an insulation board including the attached membrane (see Figure 1). These samples were then immediately transported to the laboratory where the BUR membrane and bottom facing boards, or surfaces, were removed. The thermal conductivity of the foam only (16 inch by 16 inch sample) was then determined according the ASTM test method C518 (rapid thermal conductivity test).

IN-PLACE THERMAL AGING OF TWO IDENTICAL POLYURETHANE COMPOSITE ROOF INSULATIONS WITH DIFFERENT FOAM FORMULATIONS

The first set of in-place thermal aging data presented is that from a test roof installed in 1979. In order to establish the effect of the polyurethane foam formulation on thermal aging performance, sufficient quantities of two types of foam composite roof insulation boards (glass fiber baseboard/foam/glass fiber mat top facer) were manufactured on the same day and installed within two weeks on a test roof. The two sample types consisted, however, of markedly different foam formulations. The first formulation used, referred to as Sample 1—Manufacturer A, was known to have excellent thermal conductivity retention as measured under laboratory conditions. The second, Sample 2—Manufacturer A, was expected to have poor laboratory aging characteristics based on the open cell content of the foam. The foam open cell content is a measure of the volume in the foam which can be expected to lose Freon gas more rapidly.

Extreme care was taken to install the two polyurethane composite roof insulation boards under similar conditions on the roof. The boards were "sprinkle mopped" in hot asphalt to a vapor barrier over fluted metal decking. The membrane of four glass fiber felts was hot mopped to the insulation boards and left with a smooth surface of asphalt. As stated in the experimental procedures, the thermal conductivities of the foams were measured at installation. Roof insulation cuts were removed and measured for foam thermal conductivity periodically during the next three years. The results of the testing appears as Table 1. Included in the table for reference is the common logarithm of the time, in days, on the roof prior to measurement (exposure time). An additional measurement of the foam sample percent open cell content for each cut is also listed in the table (ASTM Method D2856, Procedure A).

The in-place thermal conductivity data are plotted in Figure 2 which clearly shows the increase in foam thermal conductivity with time. For both foam formulations, final values for thermal conductivity are approached in approximately 1000 days or three years. The markedly improved aged thermal conductivity of Sample 1 over Sample 2 is paralleled also by the significantly better average percent open cell content 4 versus 15, respectively (see Table 1).

The rapid increase in foam thermal conductivity initially (zero to 20 days) suggests a dependence on the logarithm of time. Indeed, a similar technique has been previously applied to laboratory results for thermal aging studies with success[1].

Figure 3 is a semi-logarithmic plot of measured foam aged thermal conductivity (k) versus the logarithm of roof exposure time ($\log_{10}t$). A computer-aided regression analysis (polynomial of order one) was then performed on the two data sets. The resulting regression equations are plotted for the two samples in Figure 3. Excellent linear correlation was obtained for the foam aged thermal conductivity (k) to the common logarithm of exposure time in days. The coefficient of determination values (r-squared) for each of the fitted straight lines were 0.96 and 0.95 for Samples 1 and 2, respectively. The regression coefficients can then be used to define equations that describe the experimentally determined foam aged thermal conductivity as a function of the common logarithm of roof exposure time. The equations are as follows and typically predicted values are listed in Table 2:

$$k = 0.0207 \log_{10}t + 0.1019 \qquad \text{(Equation 1)}$$

(Sample 1—Manufacturer A)

and

$$k = 0.0412 \log_{10}t + 0.0885 \qquad \text{(Equation 2)}$$

(Sample 2—Manufacturer A)

where:

k = foam in-place aged thermal conductivity, BTU-in/hr-ft^2-°F

t = long-term roof exposure time, days

Such good correlation was found for in-place aged thermal conductivity to the logarithm of roof exposure time that this technique has been applied to all roof data obtained and presented in the remainder of this paper.

THERMAL AGING DATA FOR VARIOUS POLYURETHANE COMPOSITE ROOF INSULATIONS

Numerous roofs were installed in several different geographical locations during the same time period as the test roof described in the previous section. These experimental roofs were constructed using various polyurethane foam composite roof insulations produced by several manufacturers. In particular, a polyurethane foam with organic felt facers and perlite baseboards from three manufacturers and a polyurethane foam with a glass mat facer and glass fiber baseboard from one manufacturer were used. Additionally, several test roof sections were also installed using Class I all foam isocyanurate boards with both organic and asbestos felt facers from two different manufacturers. These samples were included to compare isocyanurate foam aged thermal conductivity performance to that of polyurethane foam. For the remainder of this paper, all of these products will simply be referred to as foam-glass fiber composites, foam-perlite composites, and all foam isocyanurate roof insulations.

Figure 4 is a summary plot of all in-place aged thermal conductivity data for the foam-perlite composites from eight different test roof sections. The samples used were produced by two different manufacturers, identified here as B and C. Of primary interest from the graph is the "grouping" of the aged thermal conductivity data and fitted lines by manufacturer; that is, the aged thermal conductivity performance was significantly lower in all cases for the polyurethane composite produced by Manufacturer B than by Manufacturer C. Since the composite structural components are essentially the same and sample selection for the installed roofs was random as far as production dates and location, this suggests a possible dependence of aged thermal conductivity performance on the polyurethane foam structure itself, or foam formulation.

All of the aged thermal conductivity data for the foam-perlite products are compiled in Figure 5 in order to obtain a representative regression line for each manufacturer. A similar analysis was performed on all foam isocyanurate roof insulation (Manufacturer D); the data are summarized and compared to the foam-perlite (Manufacturer B) data in Figure 6.

The experimentally determined semi-logarithmic equations for these regression analyses are:

[1]Carlos J. Hilado, ref. "Some Laboratory Studies On The Use Of Polyurethane Rigid Foam As A Thermal Insulation Material In Low Temperature Service," **Journal Of Thermal Insulation,** Volume 1 (July 1977), page 27.

$$k = 0.0158 \log_{10}t + 0.1196$$ Polyurethane foam-perlite (Equation 3) (Manufacturer B)

$$k = 0.0092 \log_{10}t + 0.1650$$ Polyurethane foam-perlite (Equation 4) (Manufacturer C)

$$k = 0.0189 \log_{10}t + 0.1283$$ All foam isocyanurate composite (Equation 5) (Manufacturer D)

where:

k and t are as defined previously

These three lines along with equations (1) and (2) (polyurethane-glass fiber composites) are plotted in Figure 7 for purposes of comparison. They are also graphed as a function of actual time in days as Figure 8.

The graphs indicate excellent thermal conductivity retention for the urethane-glass fiber, (Sample 1— Manufacturer A) when compared with the poor performance of the urethane-perlite sample, (Manufacturer C) or urethane-glass fiber, (Sample 2—Manufacturer A.) The relative in-place aging performance of the other foam roof insulations are clearly shown. It appears that all the samples aged at roughly the same rate to their respective, final values with the exception of Sample 2—Manufacturer A. It could be argued that encapsulating the composite insulation in the roof assembly as soon as possible after production aids in retention of the foam thermal conductivity. However, the data for Sample 2—Manufacturer A appear to refute this contention in that the thermal aging proceeds to its approximate equilibrium value rather rapidly even though it was installed immediately after production.

As stated previously, all of these test roofs were installed using various products of different designs and facing materials, with various production dates, and installed in varying locations. However, each sample type exhibited its own performance trend. A measure of the foam structure, percent open cell content, is shown in parentheses for each of the five sample types next to its respective curve in Figure 7 and Figure 8. Each characteristic value represents an average of 30 to 40 measurements from the roof sample cuts. Again, there appears to be a strong dependence of foam thermal performance on percent open cell content; that is, the lower the open cell content for the foam used in the product, the better the retention of thermal conductivity when the composite is aged in an actual roof system. This is shown more clearly in Figure 9 which plots average foam thermal conductivities (k) after one year roof exposure versus percent open cell contents. The dependence of foam aging performance on the percent open cell measurement is evident.

SUMMARY AND CONCLUSIONS

Actual in-place thermal conductivity data have been presented for various polyurethane foam composite insulation products and isocyanurate all foam roof insulations. The data were obtained from actual field test roofs. The following general conclusions were reached:

1. The data analysis indicates good linear correlation of the increase in foam thermal conductivity to the logarithm of roof exposure time.
2. The aged thermal conductivity data were used to develop experimental performance equations for various products from different manufacturers. Each product exhibited a characteristic aging rate to a characteristic approximate equilibrium value.
3. The thermal conductivity retention ability appears to be strongly related to the percent open cell content of the foam.
4. The foam thermal conductivity of a glass fiber-polyurethane composite was measured to be as low as 0.167 BTU-in/hr-ft^2°F after three years of actual roof exposure.

Research in this area is ongoing with the purpose of eventually correlating field performance to a laboratory procedure for testing and predicting the thermal aging of polyurethane foam composites in roof insulation applications.

ACKNOWLEDGEMENTS

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IN-PLACE THERMAL AGING DATA
TWO IDENTICAL POLYURETHANE FOAM COMPOSITES WITH DIFFERENT FOAM FORMULATIONS

Roof Exposure Time (days)	Log_{10} (time)	Foam Aged k BTU-in/hr-ft²-°F Manufacturer A		Foam Percent Open Cell Content	
		Sample 1	Sample 2	Sample 1	Sample 2
10	1.000	0.123	0.120	6	12
21	1.322	0.131	0.139	4	8
40	1.602	0.138	0.160	5	11
52	1.716	0.138	0.167	8	21
70	1.845	0.137	0.162	6	16
95	1.978	0.141	0.180	4	18
171	2.233	0.150	0.180	4	18
220	2.342	0.147	0.185	4	13
338	2.529	0.151	0.196	2	15
696	2.843	0.161	0.202	1	21
1035	3.015	0.169	0.206	—*	—
			Average	4	15

*not measured

TABLE 1
In-Place Thermal Aging Data

PREDICTED FOAM AGED k VALUES (INTERPOLATED AND EXTRAPOLATED) BASED ON EXPERIMENTAL EQUATIONS

Roof Exposure Time (days)	Log_{10} (time)	Predicted Foam Aged k BTU-in/hr-ft²-°F	
		Sample 1	Sample 2
10	1.00	0.123	0.130
100	2.00	0.143	0.171
200	2.30	0.150	0.183
365	2.56	0.155	0.194
2 years	2.86	0.161	0.206
3 years	3.04	0.165	0.214
4 years	3.16	0.167	0.219
5 years	3.26	0.169	0.223
10 years	3.56	0.176	0.235

TABLE 2
Predicted Foam Aged k Values

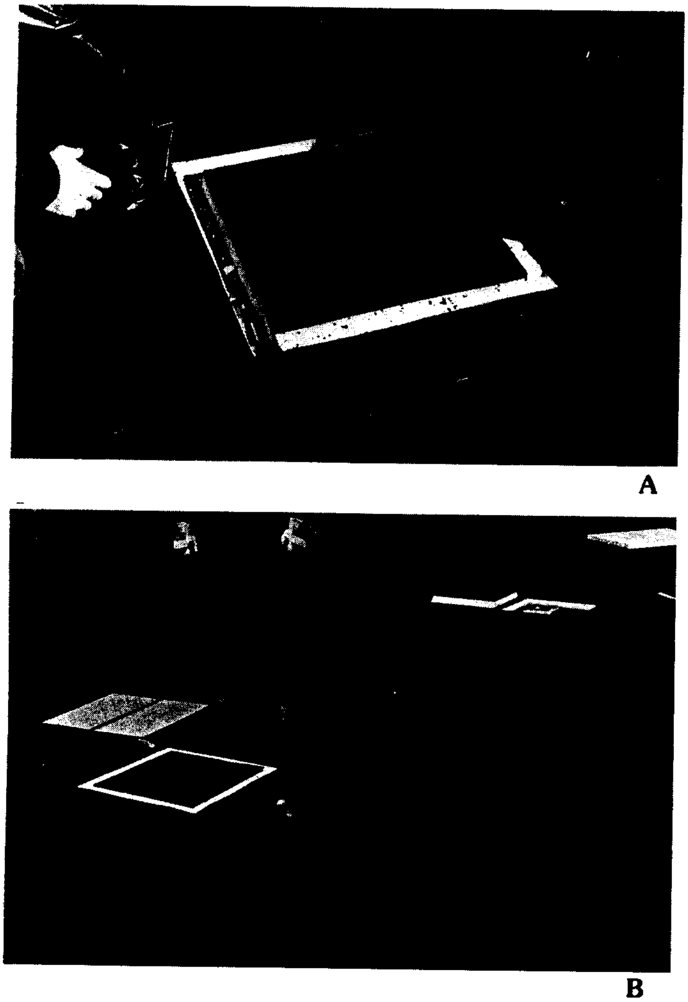

FIGURE 1
Polyurethane Composite Roof Insulation Sample Cuts.

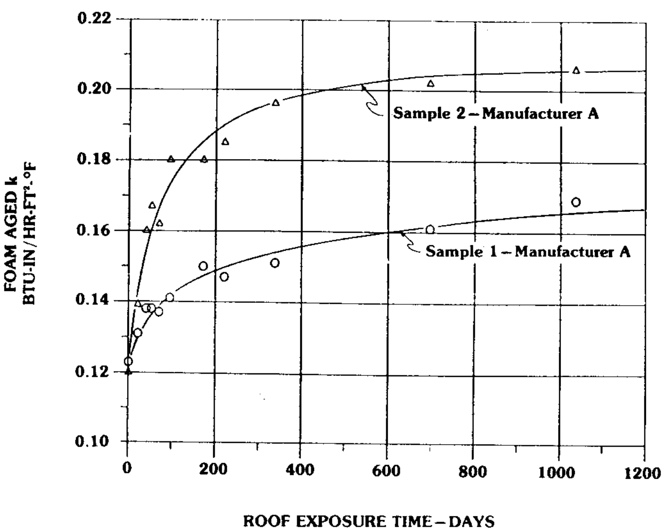

FIGURE 2
In-place aging – two identical polyurethane composite roof insulations with different foam formulations.

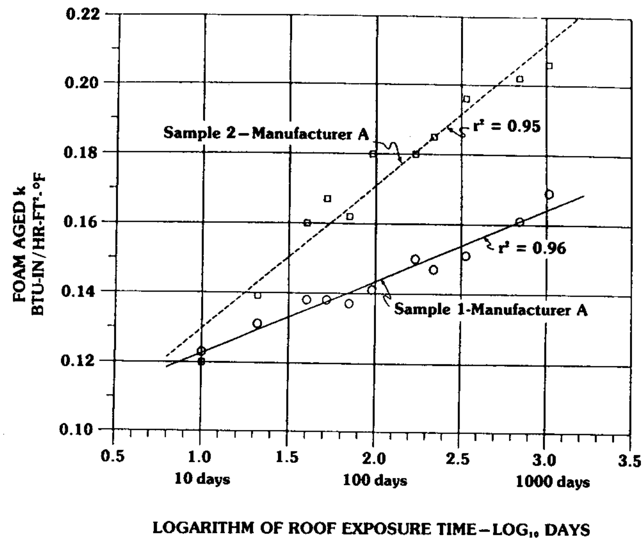

FIGURE 3
In-place aging – two different foam formulations – polyurethane composite with glass fiber baseboard.

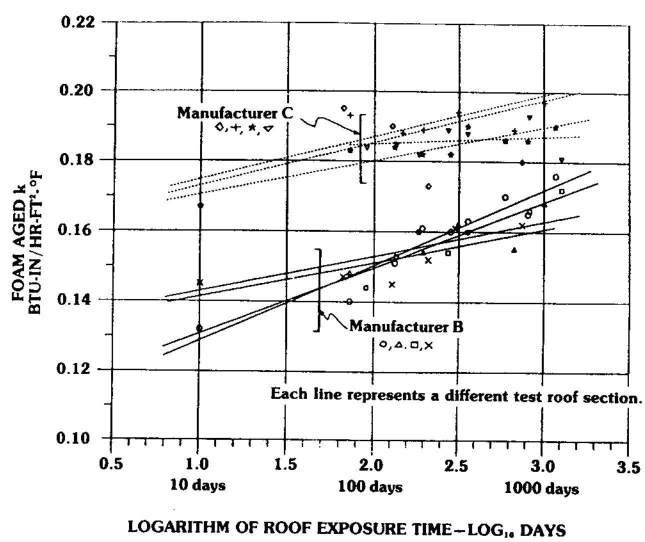

FIGURE 4
Polyurethane foam/perlite composite with organic felt facers from two manufacturers.

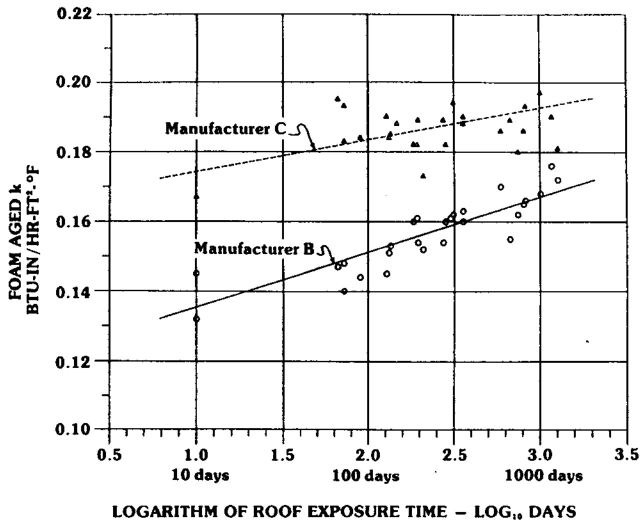

FIGURE 5
In-place aged k data polyurethane foam/perlite composites.

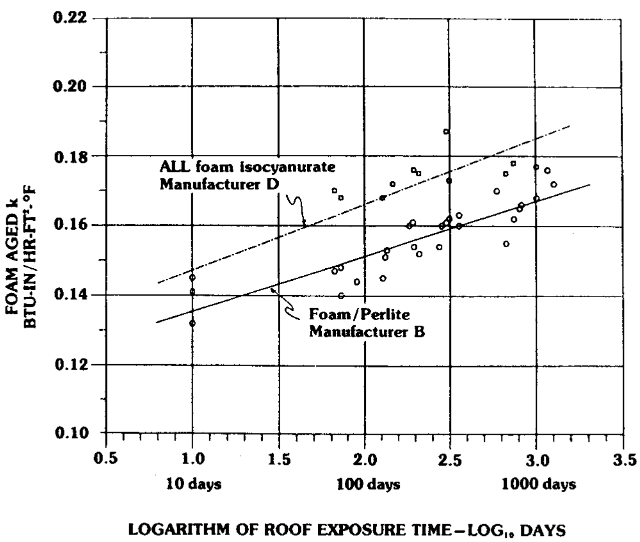

FIGURE 6
In-place aged k data.

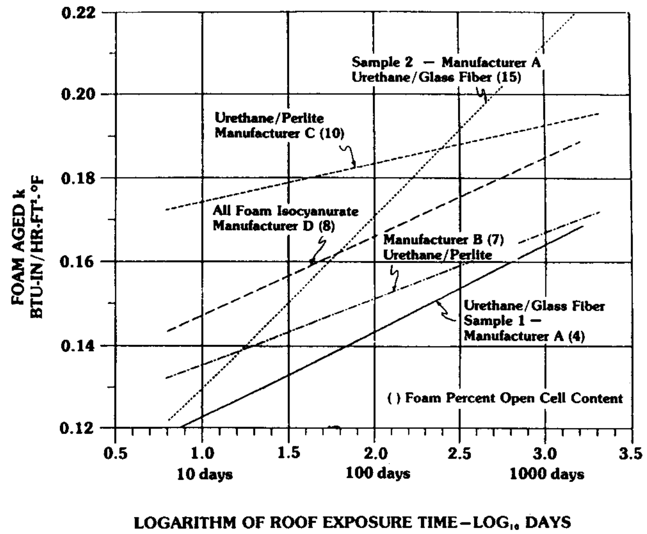

FIGURE 7
Experimental regression analysis in-place thermal aging.

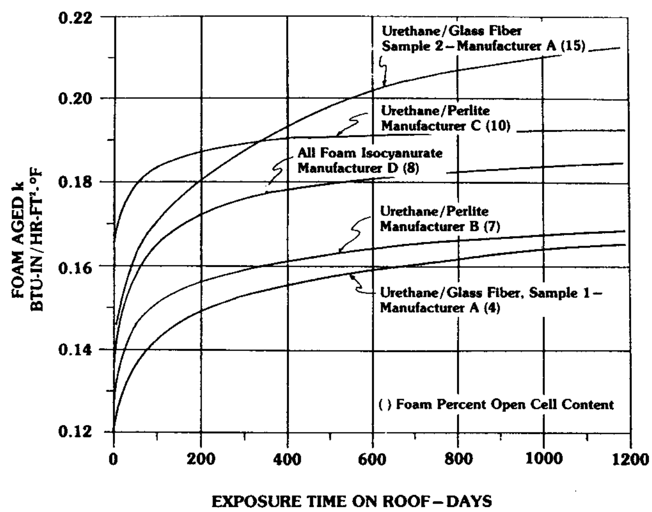

FIGURE 8
Experimental curves for in-place thermal aging.

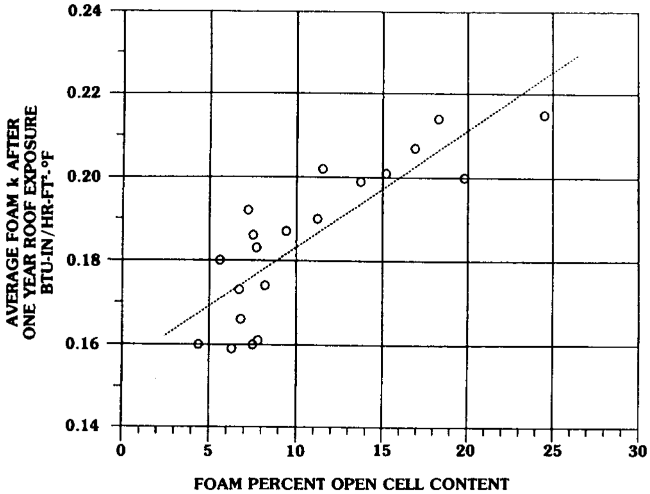

FIGURE 9
Equilibrium thermal conductivity versus foam percent open cell content.