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A Comparison of Accelerated Aging Test Protocols for Cellular Foam Insulation

Reference: Stovall, T. K., Fabian, B. A., Nelson, G. E., and Beatty, D. R., **"A Comparison of Accelerated Aging Test Protocols for Cellular Foam Insulation**,**"** *Insulation Materials Testing and Applications, 4th Volume, STP 1426*, A. O. Desjarlais and R. R. Zarr, Eds., American Society for Testing and Materials, West Conshohocken, PA, 2002.

Abstract: Both the ASTM Standard Test Method for Estimating the Long-Term Change in the Thermal Resistance of Unfaced Rigid Closed-Cell Plastic Foams by Slicing and Scaling Under Controlled Laboratory Conditions (C 1303) and the Standard for Determination of Long-Term Thermal Resistance of Closed-Cell Thermal Insulating Foams (CAN/ULC-S 770) are based on accelerating the foam aging process by slicing the foam into thin specimens. This accelerates the diffusion process so that thermal conductivity for foam insulation of varying thickness can be determined in a short period of time, typically less than one year. The C 1303 process calls for a series of measurements to define a relationship between thermal conductivity and a scaled aging time which is then analyzed to calculate the time-average thermal conductivity over any given service life. The S 770 process also uses scaled aging time, but uses the projected thermal conductivity at precisely five years of age to represent the insulation's useful service value. There is also a difference in how the thermal results are reported. The S 770 protocol calls for very careful determination of the initial thermal resistivity of a full thickness board, to which an aging factor is applied to determine the five-year value. The C 1303 protocol calls for reporting both the average thermal resistance for the selected thickness and service life and the aging curve data from the thin specimens. During a round-robin exercise performed in support of the S 770 standard, parallel measurements were made on the same specimens to permit application of the C 1303 procedure. This paper presents the results of that comparison for several types of foam. This paper also gives more explicit instructions on the proper application of the C 1303 methodology than is found in that document.

Keywords: Insulation, Closed-Cell Foam, Accelerated Aging, Diffusion, Thermal Conductivity, Thermal Resistance

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Introduction

There are several different types of foam insulation products. Some contain only atmospheric gases and others are made with an open cellular structure. These types of insulation may show a change in thermal properties during a very short time period after fabrication, but are then stable over their service life. Other foam products consist of a closed cellular structure, which may be filled with a gas specially selected for its low thermal conductivity. However, over a long period of time, these low-conductivity gases diffuse through the thickness of the foam, and atmospheric gases diffuse into these same closed cellular volumes. Because of this gas movement, the overall thermal conductivity of the insulation product changes over time. This phenomenon is typically called "aging".

Both the American Society for Testing and Materials (ASTM) and the Underwriters' Laboratories of Canada (ULC) have recognized the foam-aging phenomenon and on-going efforts within these standards-setting organizations are seeking to improve the quality of information available about these products. The ASTM method is described in the ASTM Standard Test Method for Estimating the Long-Term Change in the Thermal Resistance of Unfaced Rigid Closed-Cell Plastic Foams by Slicing and Scaling Under Controlled Laboratory Conditions (C 1303). The ULC procedure is described in the Standard for Determination of Long-Term Thermal Resistance of Closed-Cell Thermal Insulating Foams (CAN/ULC-S 770).

Accurately identifying the thermal properties of the insulation products is important for several reasons. First, designers need accurate material specifications to determine the heating and cooling loads for buildings and appliances. If the insulation's thermal properties are not properly determined, the heating and cooling equipment could be undersized for the loads. Second, these insulation products are compared to other insulation products on both price and performance. It is important that the performance be accurately described and understood by the consumer.

Initial efforts to provide useful information resulted in the use of a 180-day aging period for foam insulation products subject to aging. However, as will be described here, that process is flawed in its ability to properly represent the thermal performance of many products.

Diffusion 101

In order to enhance its insulating qualities, foam products are often produced with low-conductivity gases. It is obviously desirable to maintain these gases within the foam's cells for as long a time as possible. However, diffusion processes continuously release these low-conductivity gases, and also allow the incursion of atmospheric gases.

The diffusion of multiple gases through foam products is well understood and described fully in reference [*1*], which in turn includes 50 references on the subject. First, the rate of gas movement through the foam is different for different gases. Two gas characteristics, molecular size and the relative solubility of the gas in the polymer matrix, affect the rate at which gases diffuse in and out of the foam. Smaller molecules, such as air molecules, migrate through the foam's cellular spaces at a much faster rate than larger molecules. Larger molecules, including some of the low-conductivity gases originally placed in the cells, move through the foam at a much slower rate, sometimes requiring many years to fully diffuse out of the foam. Second, the rate of gas movement through the foam is proportional to the thickness of the material squared. For example, if one foam product is ½ as thick as another product manufactured from the same materials, it will reach its fully aged status in 1/4 the time required for the thicker specimen.

Because of this relationship between the foam's composition and thickness and the progress of the gas diffusion phenomena, the 180-day aging period produces vastly different results for different foam products. For example, a ½-in. thick foam insulation product may be very close to equilibrium properties at the end of 180 days. But a 2-in. thick foam insulation product would still be in the fast-changing portion of its aging process (when air is entering the cells), and would still show a much higher thermal resistance that it would ultimately provide to the customer. Similarly, depending on the polymer and gas composition, some foams will age much faster than others, so that some will have reached their equilibrium value in 180 days and others will not.

Defining Thermal Performance

The apparent thermal conductivity of the foam is affected by the gas composition within the foam. Because the gas composition is changing with time, the apparent thermal conductivity is also changing. This instantaneous apparent thermal conductivity will be referred to throughout this paper as λ. If you want to determine the amount of heat that passes through a layer of insulation over an extended period of time, you need a time-averaged apparent thermal conductivity, referred to in this paper as λ_{avg} and defined in Eq. 1, where SL is the service life and τ is time.

$$\lambda_{avg} = \frac{\int_0^{SL} \lambda d\tau}{SL} \qquad (1)$$

The service life of a foam insulation product can vary depending on its application, from 15 to 20 years for a refrigerator to 30 years for a basement wall. However, it is not necessary to monitor the thermal conductivity over such a long period of time in order to determine λ_{avg}. The squared relationship between foam thickness and gas diffusion time makes it possible to accelerate the aging of a foam product by slicing the foam into thin pieces. Both C 1303 and S 770 take advantage of this acceleration method to provide a better characterization of the foam's thermal performance than is currently available with the 180-day aging period. An abbreviated summary of each procedure is shown in Table 1. A portion of the C 1303 procedure is not included in this summary. Specifically, the tests for homogeneity and the calculation of the thickness of the destroyed surface layer have been omitted. These omissions would not be acceptable if the foam was a new product of unknown characteristics. However, all the products tested here have been tested previously and these data show that the thickness of the destroyed surface layer has a negligible effect on the results for specimens thicker than about 0.8 cm.

Despite the fundamental similarity of their accelerated aging methods, there are some differences between the two approaches. The S 770 method selects a 15-year service life and three product thicknesses as typical and uses λ at an age of five years to represent λ_{avg} for a 15-year service life. This relationship was derived using a logarithmic model for the aging phenomenon[*2*]. The C 1303 method defines λ_{avg} as a function of the product's service life and thickness, but doesn't specify a particular service life or thickness. Both methods are applicable to homogenous foam insulation products, and both define homogeneity by comparing the aging of surface slices to core slices. However, C 1303 bases its reported results on a stack of core slices or a mixed stack of core and surface slices, while S 770 bases its reported results on whichever type of specimen, core or surface, shows the least aging.

Another point of difference lies in the way the thin-slice thermal conductivity data are applied to determine λ at a given point in time. S 770 uses a ratio of the five-year thin-slice λ to the initial thin-slice λ, and applies that ratio to λ of a freshly-manufactured full thickness specimen. C 1303 discusses the application of an aged ratio to the freshly-manufactured full thickness value as a way to account for the effect of the destroyed

Table 1 – *An Abbreviated Comparison of C 1303 and S 770*

C 1303	S770
	Measure the as-manufactured λ of the full thickness product.
Cut the foam into pieces 30 x 30 cm (12 x 12 in). If using a rotary slicer, prepare one to two slices from the core of each piece. If using a band saw, prepare up to four slices from a five cm-thick specimen.	Slice the material with very smooth surfaces, meeting prescribed tolerances on the distribution of the specimen thicknesses. Produce both surface and core slices and test them separately.
Measure λ of a stack of several thin slices immediately after slicing and several times during the first few weeks. Take a minimum of ten measurements over the course of a year, with the latter few measurements spanning larger time steps.	Measure the initial λ of the surface and core specimen stacks within two hours of their production. Use the average specimen thickness for each stack to precisely determine the test time that corresponds to a full-thickness age of five years for three specified product thicknesses. Measure λ for both the core and surface stacks on the dates calculated.
Using the average slice thickness, the times of each test, and the measured λ, represent λ as a function of scaled time (time divided by the square of the average specimen thickness). Calculate λ_{avg} for the desired service life and product thickness. Report this value and the overall functional relationship.	Compare the ratios of the five-year λ to the initial (two-hour) λ for the surface and core stacks of specimens. Using the lower of the two ratios, multiply that ratio times the as-manufactured λ of the full thickness product. Report the reciprocal of this value.

surface layer. Based on experience with commonly used products and test specimen thicknesses, however, this practice has been eliminated, and the C 1303 results are based directly on the measured thin-slice values, without any use of an initial full-thickness value.

Results

Comparing C 1303 to Full-Thickness Aging Data

The C 1303 procedure was first published by ASTM in 1995, but was in development for some time before then. During that time there have been several instances where parallel data were taken to compare the predicted aging values from C 1303 to actual full-thickness aged specimens. Some of that data for extruded polystyrene (XPS) and polyisocyanurate (PIR) is presented in Table 2. The XPS specimens were aged under laboratory conditions, the PIR specimens were aged in a field installation. Although many of the full thickness specimens were measured after only one year, 53 specimens have been aged for five years, and show that C 1303 provides estimates of the five-year aged λ accurate to within 2%.

Comparing S 770 to C 1303

During a round robin exercise performed in support of the S 770 standard, parallel

Table 2 – *Comparison of Aged Full-Thickness Thermal Resistance to That Predicted by C 1303*

Data source	Foam type and thickness	Age (yr)	Number of specimens	Standard deviation (% of $1/\lambda_{\text{full thickness}}$)	$\lambda_{\text{full thickness}}/\lambda_{C1303}$ (or $R_{C1303}/R_{\text{full-thickness}}$)
Lab B*	XPS, 2.5 cm	1	11	2.6	1.01
Lab B*	XPS, 2.5 cm	5	12	2.4	1.02
Lab B*	XPS, 3.8 cm	1	11	2.5	1.01
Lab B*	XPS, 3.8 cm	5	12	2.4	1.01
Lab B*	XPS, 5.1 cm	1	26	2.0	1.01
Lab B*	XPS, 5.1 cm	5	29	1.9	1.01
Lab A [*3*]	CFC-11 PIR, 38 mm	1	1		1.00
Lab A [*3*]	HCFC-123 PIR, 38 mm	1	1		1.01
Lab A [*3*]	HCFC-141b PIR, 38 mm	1	1		0.99
Lab A [*3*]	HCFC-141b PIR, 38 mm	1	1		0.99

*Owens Corning data provided by author

Table 3 – *Comparing The S 770 Five-Year Aging Factor To The C 1303 15-Year Service Life Integrated Average. (All Measurements Lab A)*

Thickness (mm)	S 770 λ_0/λ_5 (equivalent to R_5/R_0) / C 1303 λ_0/λ_{avg} for 15 year service life		
	Product 1	Product 2	Product 3
50	**1.01**	**1.00**	**1.01**
75	**1.01**	**1.00**	**1.00**

measurements were made to permit application of the C 1303 procedure. A portion of these data are summarized in Table 3. This initial comparison considers only the thin-slice data, that is, it compares the S 770 "aging factor" to a similar ratio derived from the C 1303 λ_{avg}. For this comparison, the initial thin-slice λ was divided by the C 1303 λ_{avg} corresponding to a 15-year service life and the specified thickness (because the S 770 five-year λ values were selected to represent the λ_{avg} over a 15-year service life). There was insufficient data to calculate the C 1303 15-year service life λ_{avg} for the 25 mm product thickness. For the two thicknesses shown, the C 1303 ratios and S 770 aging factors agree within 1%.

The S 770 procedure, however calls for this ratio to be applied to the freshly-manufactured (between seven and 14 days old) full thickness λ. During this study, significant differences were noted between these full-thickness measurements and the initial (within two hours) thin-slice value. The λ of the full thickness specimens ranged between 3 to 7% lower than those for the thin slices at lab B, which used a band saw method and was therefore able to complete all the measurements within one day as specified in the S 770 procedure. Lab A used a slicer to prepare the thin slices, which is more time consuming, so that the thin slices were prepared one day after the full-thickness measurements were made. For Lab A, the full thickness λ values ranged from 0.4 to 2% lower than the initial thin slice measurements for the surface slices. When this portion of the S770 procedure (applying the ratio to the initial full-thickness slice) is included, S 770 can be compared to C 1303 as shown in Table 4. This table compares

Table 4 – *Compare Insulation R-Values Predicted By S 770 And C 1303 Five Years After Production, Values Shown are $\lambda_{C\ 1303}/\lambda_{S\ 770}$ (Equivalent to $R_{S\ 770}/R_{C\ 1303}$).*

	Lab A	**Lab B**	**Lab B**	**Lab B**
Product 1, 25 mm	1.03			
Product 1, 50 mm	1.03			
Product 1, 75 mm	1.03			
Product 2, 25 mm	0.95			
Product 2, 50 mm	1.01	1.03		
Product 2, 75 mm	1.08			
Product 3, 25 mm	1.09	1.06		
Product 3, 50 mm	1.08	1.14	1.04	1.11
Product 3, 75 mm	1.08	1.20		

the five-year λ values from the C 1303 curve to the S 770 five-year λ values.

This comparison of results from the two procedures shows much larger differences. A portion of the difference, on the order of 1-2% for products 1 and 2, and from 2-5% for product 3, comes from comparing the S 770 surface-slice measurement to the C 1303 core or mixed-slice values. But a large part of the difference is due to the application of the aging factor to the initial full-thickness value. The thermal conductivity of freshly manufactured foam changes much more rapidly than that of older foam products[*4*]. Figure 1 shows an aging curve, or λ vs. time, for polyurethane foam from an evaluation of alternative blowing agents (other curves shown on this figure are discussed in the appendix)[*5*]. This prototypical curve shows just how sensitive λ is during the early life of a foam product, and why it may be problematical to define the initial thermal conductivity with a single measurement. The S 770 procedure acknowledges this sensitivity by requiring a thin-slice λ measurement within two-h of slicing, and the full-thickness within a carefully defined seven-day period. The C 1303 integrated average approach is much less sensitive to this initial value, because λ_{avg} weights each λ measurement by the elapsed time at that value, and the foam is in this fast-changing state for a relatively short period of time.

Conclusions

There are advantages and disadvantages to each approach. The S 770 approach is more useful for product rating purposes, because it produces a single value for each

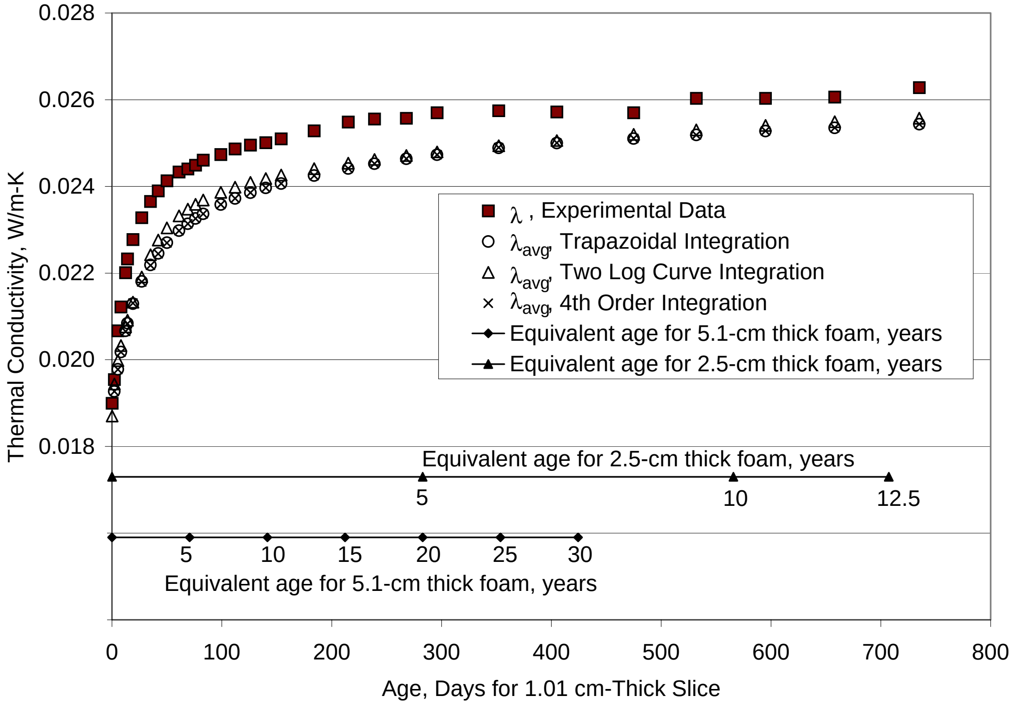

Figure 1. *Aging Data for Polyurethane Foam Blown with HCFC 141b, Aging in a 30 °C Environment [5]*

thickness. However, C 1303 is more useful in providing information necessary for application designs, because its curves give the fully aged value, as well as the average performance for *any* thickness or service life. The calculation procedures and data processing called for in S 770 are explicit and clear; the same cannot be said for the current version of C 1303. Also, given the C 1303 curve, the S 770 five-year value can usually be identified by interpolation. But the S 770 results cannot be used to calculate the C 1303 aging curve.

Although C 1303 tests usually involve a larger number of thermal conductivity measurements, that standard only calls for a minimum of 10 measurements. The S 770 calls for a total of 11 measurements and its test schedule can be challenging. As mentioned above, Lab A was unable to meet the requirements that the thin slices be prepared and measured during the same day as the full-thickness specimens are prepared and measured. Indeed, using a slicer, Lab A was just barely able to meet the two-h requirement for the initial thin-slice thermal conductivity measurement. There were also difficulties meeting the precise test dates, especially when one of the dates fell on December 31, 1999.

The significant differences reported here between the C 1303 five-year value and that produced by the S 770 procedure raise a number of questions and should be investigated more fully. These differences are partially attributable to the differing uses of core/surface slice values. There are also differences introduced by the use of the initial full-thickness R-value in S 770. It is hoped that a detailed examination of these results can lead to improvements in both methods, and perhaps a consensus approach to the identification of the insulation’s service-life R-value.

Appendix: C 1303 Calculation Guide

One frequent complaint about the C 1303 method has been the lack of detailed data processing instructions within the standard itself. While processing the data for this analysis, a computer program was written to process the test data for the C 1303 calculations. Three different integrated average methods were included and are compared in Figure 1.

The two-log curve has traditionally been used for this procedure. In this method, the data for thermal conductivity are represented logarithmically and then regressed, over two regions, against the normalized time as shown in [2]. In performing these regressions, some judgment is necessary to distinguish between the two regions (the first region corresponds to the early rapid aging due to air diffusion into the cells and the second region to the later slower aging due to the diffusion of blowing agents out of the cells) and to decide which data should not be used because it is in the transition between these two regions. The coefficients identified in these regressions are used to define an exponential expression for λ (as a function of time and thickness) that can be analytically integrated using Eq. 1, for any selected thickness and service life, to produce λ_{avg}.

Two numerical integration methods were also explored. The first is a very simple trapezoidal method, shown in Eq. 2.

$$\lambda_{avg} = \frac{\left(\sum_{n=1}^{N} (\tau_n - \tau_{(n-1)}) \times \frac{(\lambda_n + \lambda_{(n-1)})}{2}\right)}{\tau_N} \qquad (2)$$

where

λ_{avg} = integrated average thermal conductivity over total time τ_N,
τ = time,
N = number of data points corresponding to time τ_N,
λ_n = apparent thermal conductivity measured at nth point, and
τ_n = time corresponding to λ_n.

This approach sums the area under the original data curve, assuming each point is connected to the next with a straight line. A simple interpolation of this integrated value, based on the normalized time corresponding to any selected thickness and service life, can then be used to determine the average thermal conductivity. An example of this calculation is shown in Table 5, again using experimental data from [*5*]. The first and third columns represent the experimental data. The second column represents the time for each data point, normalized by dividing the days since slicing by the average slice thickness squared. The average slice thickness for this experiment was 1.018 cm. The last column is calculated using Eq. 2, and represents the integrated average thermal conductivity up to that point in time. To use this data, first select the desired product thickness and service life. For this example, a 30-year service life and a five-cm product thickness were chosen. The normalized time corresponding to this selection is 438 days/cm^2 (= 30 x 365 / 5 / 5). This value has been inserted in Table 5 between the two bounding experimental data points. A linear interpolation was then used to calculate λ_{avg} from the two bounding experimental data points. This underlined value, 0.02525 W/m-K, represents the average thermal conductivity that this five-cm thick product can be expected to provide over its 30-year service life.

The second numerical integration method also treats the experimental data as a differential equation and uses a fourth-order variable mesh solution to find the area under the curve.[*6*] For this application, the first three data points are evaluated using the trapezoidal method, with all subsequent points evaluated using the variable mesh fourth-order equations. These equations are not shown here because, as will be shown, the added complexity gave results equivalent to those obtained using the simpler trapezoidal method.

Table 5 – *Example of the Application of the Trapezoidal Integration Method to Determine* λ_{avg} *for Any Selected Service Life and Product Thickness, Data from [5].*

Time Since Slicing (days)	Normalized Time (day/cm^2)	λ (W/m-K)	λ_{avg} (W/m-K)
0.05	0.05	.01899	
5.35	5.16	0.02067	0.02050
19	18.33	0.02277	0.02201
69	66.58	0.02440	0.02300
83	80.09	0.02461	0.02363
140	135.1	0.02501	0.02420
296	285.6	0.02570	0.02469
405	390.8	0.02572	0.02521
	438 = 30x365/5/5		*0.02525*
735	709.24	0.02628	0.02547

Table 6 – *A Comparison of* λ_{avg} (W/m-K) for a *15-Year Service Live for Varying Amounts of Test Data, for Polyurethane Foam Blown with HCFC 141b, Aging in a 32 °C Environment, Original Data from[5].*

Foam Thickness (mm)	32 Data Points	17 Data Points	9 Data Points
37.5	0.0250	0.0250	0.0250
50	0.0245	0.0245	0.0244
75	0.0236	0.0236	0.0235

Figure 1 shows λ_{avg} for all three of these methods, along with the experimental λ values used in the calculations. At most points, the λ_{avg} values from all three integration methods are so close as to be indistinguishable. The only region where there is a small difference is in the transition region, between the early rapid aging due to air diffusion into the cells and the later slower aging due to the diffusion of blowing agents out of the cells. The two-log curve method doesn't use the data collected during this transition period and would be expected to be less accurate in this region. The trapezoidal method is clearly the simplest of the three, is most adaptable to a spreadsheet environment, and doesn't require the intermediate regression step. An Excel spreadsheet with Visual Basic macros has been written to calculate these values and is available at the ASTM web site (www.astm.org). One criticism of the C 1303 procedure has been the perceived need for large numbers of tests. A further examination of the same data set from [5] was made to explore this issue. Figure 2 and Table 6 summarize the results of using one-half the data (or every other data point) and one-fourth of the data (or every fourth point). These results indicate that the minimum number of data points specified by C 1303 should be sufficient, so long as they are appropriately spaced. Obviously, the time intervals between data points need to be shorter during the initial period when the foam is changing more rapidly.

Any C 1303 data set can also be used to generate S 770-style rating values, as shown in Table 7 (using the same data from [5]). For example, S 770 calls for five-year λ values for three product thickness, 25, 50, and 75 mm. Table 7 shows how the data can be used to generate these values, again using an interpolation based on the normalized time. Remembering that the five-year λ values were selected to represent the 15-year λ_{avg} values, Table 7B shows a similar interpolation for λ_{avg} on a 15-year service life. A comparison of the example values generated in Tables 7A and 7B is shown in Table 7C. Considering the greater amount of data reflected by the λ_{avg} values, and the reduced sensitivity of these values to the earliest data measurements, the λ_{avg} results should be used when possible. However, as this example shows, data is required for a much longer period, especially for thinner products. In these cases, $\lambda_{5\text{-year}}$ should produce values within 1-2% of the 15-year λ_{avg} results.

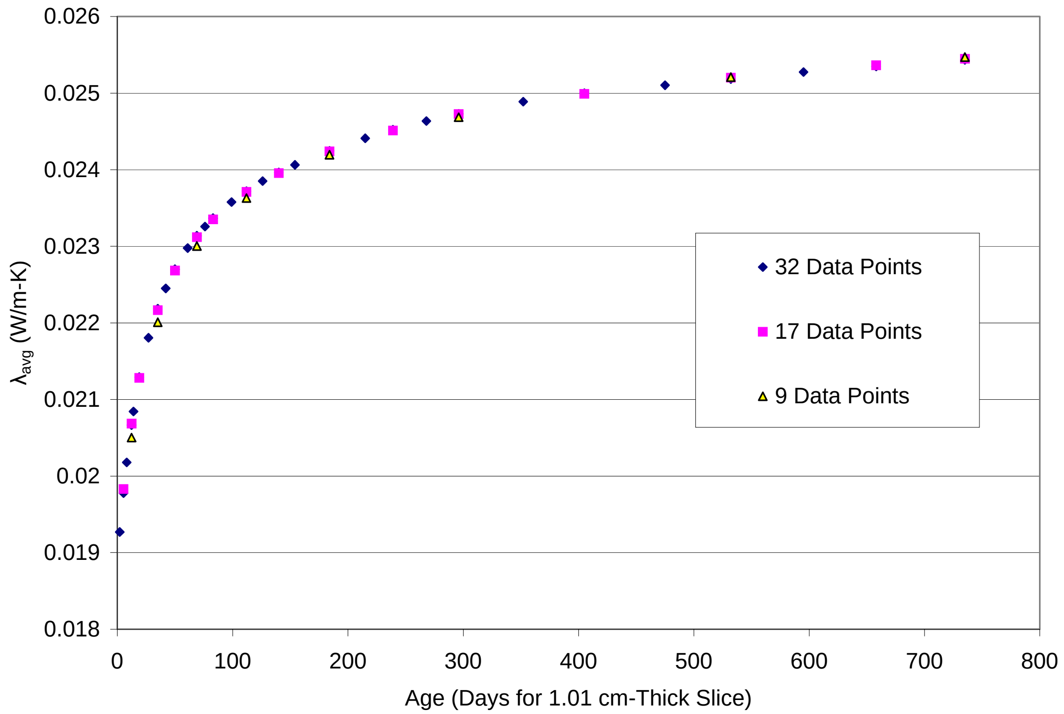

Figure 2. *A Comparison of the Average Apparent Thermal Conductivity for Varying Amounts of Test Data, for Polyurethane Foam Blown With HCFC 141b, Aging in a 32 °C Environment [5]*

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Table 7A – *Example of the Application of the Trapezoidal Integration Method to Determine $\lambda_{5\text{-year}}$ for S 770 Rating Conditions, Data from [5]*

Time Since Slicing (days)	Normalized Time (day/cm^2)	λ (W/m-K)	λ_{avg} (W/m-K)
0.05	0.05	.01899	
5.35	5.16	0.02067	0.02050
19	18.33	0.02277	0.02201
	32.4=5x365/7.5/7.5	**0.02325**	
69	66.58	0.02440	0.02300
	73.=5x365/5/5	**0.02450**	
83	80.09	0.02461	0.02363
140	135.1	0.02501	0.02420
296	285.6	0.02570	0.02469
	292=5x365/2.5/2.5	**0.02570**	
405	390.8	0.02572	0.02521
735	709.24	0.02628	0.02547

Table 7B – *Example of the Application of the Trapezoidal Integration Method to Determine λ_{avg} for S 770 Rating Conditions, Data from [5]*

Time Since Slicing (days)	Normalized Time (day/cm^2)	λ (W/m-K)	λ_{avg} (W/m-K)
0.05	0.05	.01899	
5.35	5.16	0.02067	0.02050
19	18.33	0.02277	0.02201
69	66.58	0.02440	0.02300
83	80.09	0.02461	0.02363
	97.3=15x365/7.5/7.5		**0.02356**
140	135.1	0.02501	0.02420
	219=15x365/5/5		**0.02400**
296	285.62	0.02570	0.02469
405	390.8	0.02572	0.02521
735	709.24	0.02628	0.02547
	876=15x365/2.5/2.5		**Extrapolation not recommended**

Table 7C– *Summary of Example Problem Using C 1303 Data Analysis to Produce S 770 Type Rating Values*

Product Thickness	Rating Based on $\lambda_{5\text{-year}}$ (W/m-K)	Rating Based on $\lambda_{avg,\ 15\text{-year}}$ (W/m-K)	Difference (%)
25 mm	0.02570	Not available	
50 mm	0.02450 (5.9 R/in.)	0.02400 (6.0 R/in.)	2.0
75 mm	0.02325 (6.2 R/in.)	0.02356 (6.1 R/in.)	1.3

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