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EXPANDED POLYSTYRENE BOARD AS A STANDARD REFERENCE MATERIAL FOR THERMAL RESISTANCE MEASUREMENT SYSTEMS

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ABSTRACT: Thermal conductivity measurements at room temperature are presented as the basis for certified values of Standard Reference Material 1453, Expanded Polystyrene Board. The measurements have been conducted in accordance with a randomized full factorial experimental design of two variables, bulk density and temperature, using the National Institute of Standards and Technology one-meter line-heat-source guarded hot plate. Uncertainties of the measurements, consistent with current international guidelines, have been prepared. The thermal conductivity measurements were conducted over a range of bulk density of 37.4 to 45.8 kg/m^3 and mean temperature of 281 to 313 K. Statistical analyses of the physical properties of Standard Reference Material 1453 are presented and include variations between boards, as well as within board.

KEYWORDS: expanded polystyrene, fenestration, foam, guarded hot plate, standard reference material (SRM), thermal conductivity, thermal resistance, thermal insulation, window test methods

For several years, there has been a significant effort in North America to develop standard test methods for the thermal evaluation of fenestration systems. As a result, the ASTM Committee C-16 on Thermal Insulation has formally adopted ASTM Test Method for Measuring the Steady State Thermal Transmittance of Fenestration Systems Using Hot Box Methods (C 1199). This test method requires a large calibration test panel with known thermal transmission properties in order to estimate the surface heat transfer coefficients of more complex fenestration systems. Recent work [1,2] has advocated a panel design consisting of 13-mm thick expanded polystyrene foam laminated between 3-mm glass sheets on either side. In order to provide a common basis for calibration, a suitable reference material was sought by potential users of ASTM C 1199.

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In 1993, representatives from the National Fenestration Rating Council, private industry, and the National Voluntary Laboratory Accreditation Program met at the National Institute of Standards and Technology (NIST) to discuss the development of a new SRM for this purpose. Based on their recommendations, NIST evaluated a candidate material and subsequently purchased 300 boards of a commercial grade of molded polystyrene foam, Figure 1. The foam boards, nominally 660 by 930 mm, were manufactured by heating expanded polystyrene beads under pressure in a plank mold until the beads fused together. The surfaces of the boards were subsequently sanded to a nominal thickness of 13 mm.

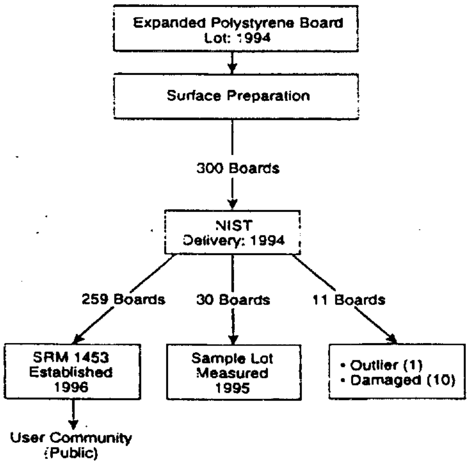

FIG. 1 - SRM 1453 Chronology

NIST completed development of SRM 1453 in 1996 [3]. The primary purpose of SRM 1453 is to provide the users of standard fenestration test methods with a reference material for calibration purposes. Single units of SRM 1453 may also be used for the calibration of heat-flow-meter apparatus or checking the operation of guarded-hot-plate apparatus. However, due to increased transmission of long-wave thermal radiation [4,5], stacked units at larger thicknesses are not recommended and certified values of thermal resistance for stacked units of SRM 1453 are invalid. This paper describes the test specimens, experimental design, measurement procedures, test results, and certified values for SRM 1453.

SPECIMENS

Test specimens for characterizing the thermal transmission properties of SRM 1453 were selected based on a randomized full factorial experimental design that required 30 test specimens (15 pairs) covering three nominal levels of density. The breakdown consisted of five pairs having the lowest density, five pairs about the median density, and five pairs having the highest density. Each pair was selected to have nearly the same bulk density (within 2 percent after final cutting to dimensions of 657 mm square). The selection of specimens required the bulk density of each board of polystyrene foam. Table 1 gives summary statistics for the mass, length, width, thickness, and bulk density of the 300 boards. One board had an unusually low density (Table 1) that was subsequently identified as an outlier and removed.

Table 1 -- Summary Statistics of Expanded Polystyrene Board (n = 300)

	Mass (g)	Length (mm)	Width (mm)	Thickness (mm)	Bulk Density (kg/m^3)
Average	328.3	930.65	656.90	13.23	40.60
Std. Dev.	16.9	0.04	0.13	0.13	2.05
Maximum	371.1	931.5	658.0	14.12	45.7
Minimum	285.1	927.5	636.5	12.71	35.2

Density Variations Between Boards

The underlying statistical assumptions for the data in Table 1 were analyzed graphically using a four-step method, Figure 2. The method consisted of 1) a run-sequence plot that checked for systematic and random changes; 2) a lag plot that checked for randomness; 3) a histogram that checked the frequency distribution; and, 4) a normal probability plot that checked for the normality assumption. The run sequence plot shows that the bulk density is consistent from board-to-board. However, the lag plot reveals localized clusters of data points indicating that the distribution of data is skewed, particularly toward lower densities. The histogram confirms two peaks, a large peak at about 39 kg/m^3 and a smaller peak near 43 kg/m^3. The normality plot was used to identify one board as an outlier, Figure 2.

Density Variations Within a Board

The density variation with respect to position within a board was examined by dividing the anomalous board identified in Figure 2 into 35 equal-size sections, each 127 mm square. The bulk density of each 127 mm square section was determined and the variation examined with the contour plot shown in Figure 3. The contour plot shows that the higher values of bulk density were near the center of the board and the lower values of bulk density were near the edges and corners of the board. The mean bulk density for the board was 35.09 kg/m^3 (slightly lower than the minimum value in Table 1) and the standard deviation was 2.26 kg/m^3. This variation, although significant, was not important since the thermal conductivity was found to be only slightly sensitive to bulk density.

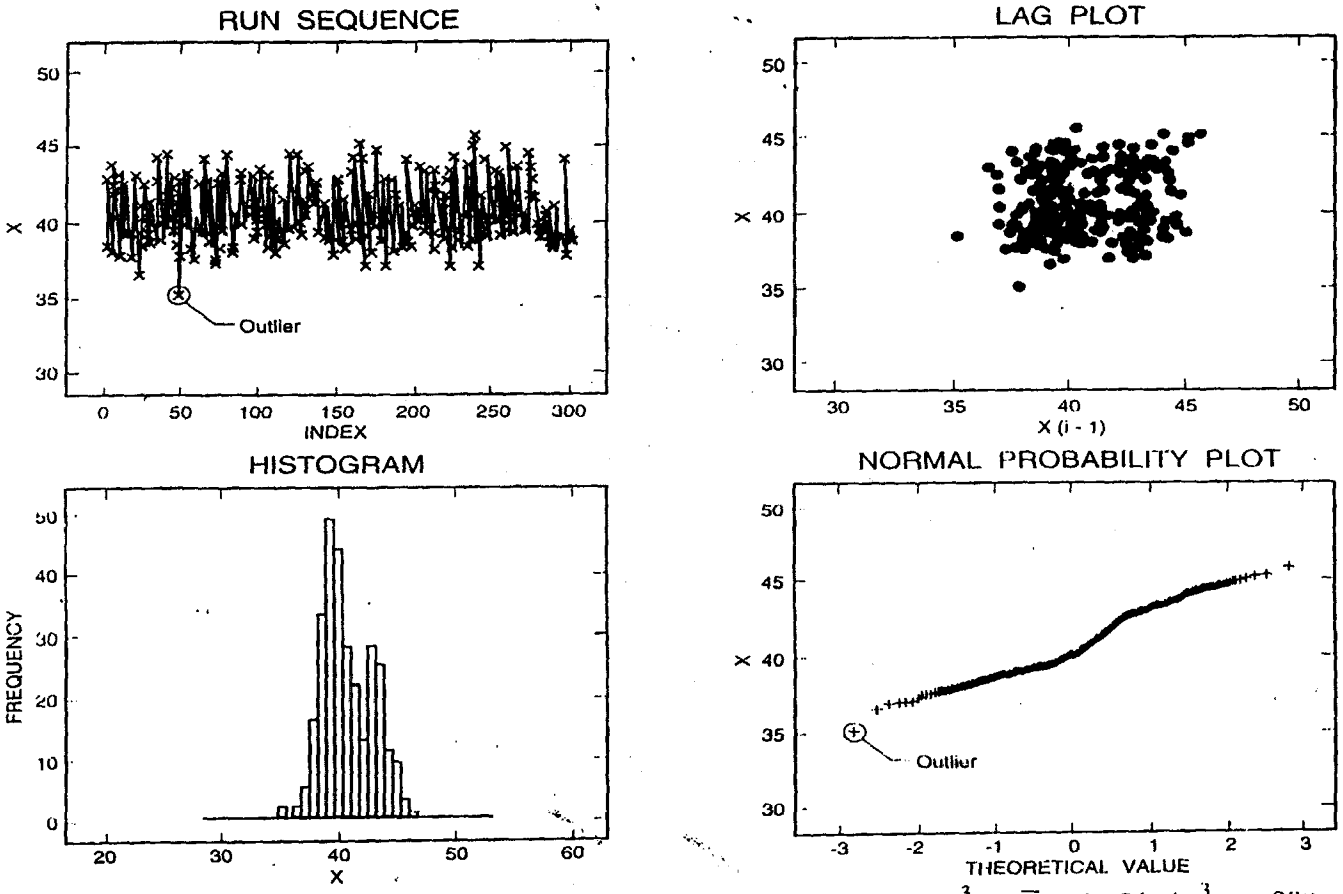

FIG. 2 - Global (between boards) variations of bulk density; $\overline{\rho} = 40.60$ kg/m^3; $s(\overline{\rho}) = 2.05$ kg/m^3; $n = 300$.

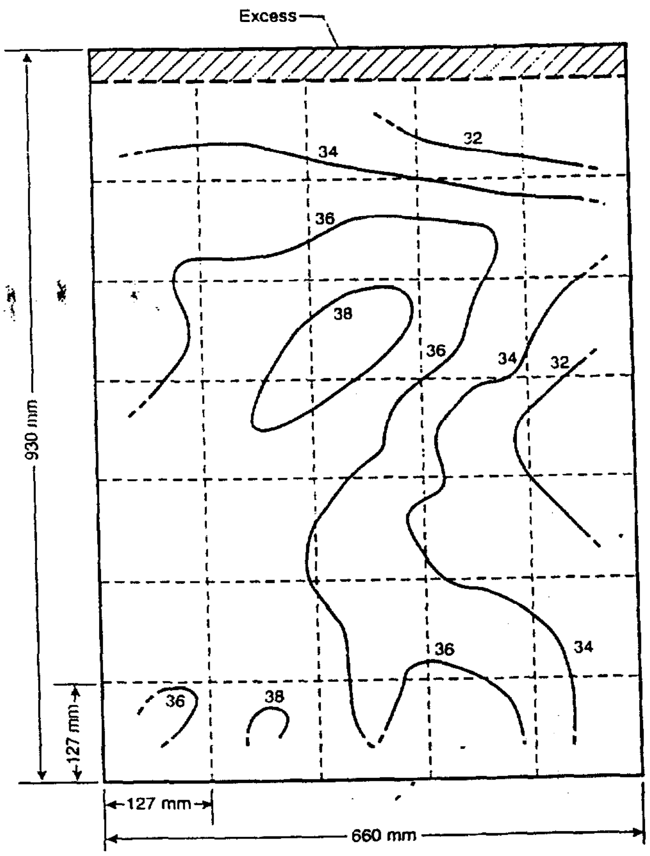

FIG. 3 - Contour plot for density variations (in kg/m^3) within board.

EXPERIMENTAL

Thermal conductivity measurements were determined in accordance with ASTM Test Method for Steady-State Heat Flux Measurements and Thermal Transmission Properties by Means of the Guarded-Hot-Plate Apparatus (C 177). Using NIST's one-meter guarded-hot-plate apparatus, each pair of specimens was measured once in a fully randomized sequence in order to minimize the introduction of bias in the test results. The measurements were generally completed in one to two days. The test sequence followed a full factorial experimental design with three nominal levels for bulk density (ρ) and five levels for mean temperature (T). The three levels of ρ included the upper and lower extremes of the SRM lot, thereby reducing the possibility of the user having to extrapolate results. The lower temperature limit was essentially fixed by the limits of the apparatus at 281 K which, unfortunately, was somewhat higher than the low temperature limit specified in ASTM C 1199. An upper temperature limit of 313 K was chosen based on information provided in ASTM Specification for Rigid, Cellular Polystyrene Thermal Insulation (C 578).

Thermal Conductivity Measurements

A schematic of the NIST one-meter line-heat-source guarded hot plate apparatus is shown in Figure 4. The apparatus has been described previously [6,7] and its operation is summarized briefly, here. Two specimens having nearly the same density, size, and thickness are placed on either side of the guarded hot plate and held securely by the circular cold plates. Ideally, the guarded hot plate and cold plates provide constant-temperature boundary conditions to the surfaces of the specimens. With proper guarding in the lateral direction, the apparatus is designed to provide one-dimensional heat flow (Q) through the specimens. Measurements of (apparent)[2] thermal conductivity (λ) were determined in accordance with ASTM C 177 using the following equation.

$$Q = \lambda A \frac{\Delta T}{L} \tag{1}$$

where

Q = heat flow through the meter area of the specimen, W,
A = meter area normal to direction of heat flow, m^2,
ΔT = $T_h - T_c$, average temperature difference across the specimen, K,
T_h = hot plate temperature, K,
T_c = average cold plate temperature, K, and
L = average thickness of specimens, m.

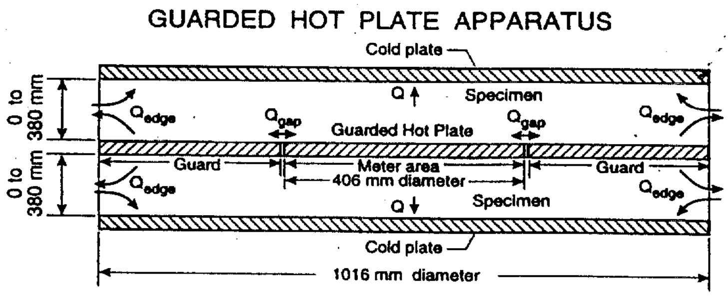

FIG. 4 - Schematic of NIST one-meter guarded hot plate apparatus.

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[2] The thermal transmission properties of heat insulators determined from standard test methods typically include several mechanisms of heat transfer, including conduction, radiation, and possibly convection. For that reason, some experimentalists will include the adjective "apparent" when describing thermal conductivity. However, for brevity, the term thermal conductivity shall be used in this report.

Values of λ were determined at the mean temperature (T) of the hot and cold plates, defined as $T = \frac{1}{2}(T_h + T_c)$. During testing, the foam specimens, which were nominally 657 mm square, were installed in the apparatus and encircled with fibrous polyester blanket insulation. This material was selected because of its compressibility and similar thermal conductivity. The effect of the fibrous polyester insulation on λ was included in the uncertainty analysis described previously [3].

Bulk Density Measurements

The bulk density (ρ) of the specimens was determined in accordance with ASTM Test Method for Apparent Density of Cellular Plastics (D 1622) by dividing the mass (m) of the specimen by its volume (V), or:

$$\rho = \frac{m}{V} \tag{2}$$

The specimen mass was obtained from a precision balance having a resolution of 0.1 g. The length and width of the specimen were measured at three locations using a steel rule having a resolution of 0.5 mm. The thickness was averaged from five measurements taken on a granite flat table with a precision caliper, 0.1 mm resolution. Corrections for the effect of the buoyant force on the polystyrene solid polymer were estimated to be 0.1 percent and neglected.

Uncertainty in Measurements

The measurement uncertainties for thermal conductivity, mean temperature, and bulk density were derived [3] in accordance with current international guidelines [8,9]. The standard uncertainties for the thermal conductivity, mean temperature, and bulk density were 0.00019 W/m·K, 0.034 K, and 0.18 kg/m^3, respectively [3].

RESULTS

Table 2 summarizes the experimental test conditions and measured thermal conductivity (λ) for each pair of specimens. Note that an extra digit is provided for λ to reduce rounding errors. Each test was conducted with heat flow in the vertical direction and a temperature difference of 20 K across the specimens. During a test, the ambient temperature (T_a) of the air surrounding the specimens was maintained at the same value of the mean temperature (T) by means of a temperature-controlled environmental chamber. The ambient air pressure (P_a) was not controlled and varied with barometric conditions. The relative humidity (RH) varied with T_a.

Table 2 -- Thermal Conductivity Measurements of SRM 1453, Expanded Polystyrene Board

Test	T (K)	Average ρ (kg/m^3)	Average L (mm)	Average Load* (N)	T_a (K)	P_a (kPa)	RH (%)	T_h (K)	Average T_c (K)	Measured λ (W/m·K)
1	297	39.9	13.32	407	297.2	100.49	14	307.15	287.15	0.03349
2	313	37.3	13.29	714	313.2	101.15	8	323.15	303.15	0.03541
3	281	43.8	13.25	454	281.2	101.27	24	291.15	271.15	0.03159
4	289	44.7	13.52	140	289.2	101.33	18	299.15	279.15	0.03236
5	281	39.8	13.30	362	281.2	101.37	23	291.15	271.16	0.03170
6	305	37.7	13.38	594	305.2	100.28	10	315.15	295.15	0.03454
7	289	36.7	13.46	297	289.2	101.38	17	299.15	279.15	0.03271
8	313	39.8	13.44	736	313.2	101.11	8	323.15	303.15	0.03552
9	297	36.3	13.53	422	297.2	100.52	13	307.15	287.15	0.03373
10	305	39.9	13.52	685	305.2	100.25	10	315.15	295.15	0.03455
11	289	39.8	13.61	236	289.2	100.46	18	299.15	279.15	0.03263
12	305	44.0	13.48	632	305.2	100.43	10	315.15	295.15	0.03430
13	313	44.3	13.41	715	313.2	100.08	8	323.15	303.15	0.03511
14	281	37.9	13.36	324	281.2	100.79	24	291.15	271.16	0.03163
15	297	44.3	13.53	431	297.2	100.43	12	307.15	287.16	0.03330

* Plate Surface Area = 0.811 m^2.

Several parameters in Table 2 indicate the "average" value for the top and bottom specimen, i.e., bulk density (ρ), thickness (L), clamping load, etc. The average thickness (L) was determined from in-situ measurements of the top and bottom plate separation. The grand average of the test thicknesses was 13.43 ± 0.11 mm (one standard deviation). The grand average of the clamping loads was 477 N. The load varied from test-to-test due to the thermal expansion and contraction of the specimens and the apparatus. The maximum clamping pressure (load divided by the plate surface area) was well below the mechanical yield point of the polystyrene foam [3].

ANALYSIS

ASTM C 177 recommends that, whenever possible, the bulk density of the specimen be determined for the volume corresponding to the meter area of the apparatus. Thus, a nominal 406-mm-diameter cylinder was cut from a limited number of specimens to account for differences in the bulk densities of the meter area and the specimen. In order to reserve a few specimens for future measurements, only eight specimens (four pairs) were selected for cutting. Using a jigsaw, 406-mm-diameter cylinders were cut from the center of each specimen and the bulk density determined using Eq 2. Table 3 summarizes the bulk densities of the specimen and meter area (406-mm-diameter cylinder). The differences ranged from 0.1 to 1.9 kg/m^3 (0.2 to 5.2 percent).

Table 3 -- Comparison of Specimen and Meter Area Bulk Densities

ID	Density Level	Specimen Density (kg/m^3)	Meter Area Density (kg/m^3)	Difference (kg/m^3)	Difference (%)
059	Low	37.6	38.6	1.0	2.8
072	Low	37.7	38.4	0.7	1.9
168	Low	36.8	38.5	1.7	4.7
176	High	44.2	45.4	1.2	2.6
239	High	44.4	45.4	0.9	2.1
240	High	45.0	45.1	0.1	0.2
242	Low	36.6	38.5	1.9	5.2
260	High	43.8	45.2	1.4	3.3

The grand average of the differences and the standard deviation were 1.12 kg/m^3 and 0.57 kg/m^3, respectively. A 95 percent confidence interval for the "true" density difference was determined from the following equation

$$\bar{\rho} \pm t_{\alpha/2,DoF}\frac{s}{\sqrt{n}} \tag{3}$$

where $\bar{\rho}$ and s are the grand average and standard deviation, respectively, (Student's) t for 95 percent and 7 degrees of freedom (DoF) is 2.36, and n is the number of measurements. The corresponding interval was 1.12 ± 0.48 kg/m^3 which does not contain zero. Therefore, the difference in densities for the meter area and the entire specimen was statistically significant and a value of 1.12 kg/m^3 was added to the (uncorrected) specimen bulk densities given in Table 2.

Multiple Variable Regression Analysis

Plots of the specimen thermal conductivity as a function of specimen bulk density and mean temperature are shown in Figures 5a and 5b, respectively. The plots indicate that the thermal conductivity was sensitive to changes in (mean) temperature and fairly insensitive to changes in bulk density. For the (corrected) bulk density range of 37.4 to 45.8 kg/m^3, the change in thermal conductivity with respect to bulk density was quite small and decreased slightly as bulk density increased (Figure 5a). For mean temperatures of 281 to 313 K, the thermal conductivity increased in a linear manner from approximately 0.0316 to 0.0354 W/m·K (Figure 5b). At 297 K, the measured thermal conductivity was approximately 0.0335 W/m·K.

As noted in Figure 5a, the change in thermal conductivity was not monotonic at temperature levels of 281 and 313 K. At these temperatures, the thermal conductivity for the mid-density specimens was higher than the value for the low density specimen. These inconsistencies were also present in Figure 5b where the data points were not sequentially arranged from lowest to highest density at 281 and 313 K. The cause of the variabilities was unknown but most likely was due to between-specimen variability such as local within-board density variations noted above.

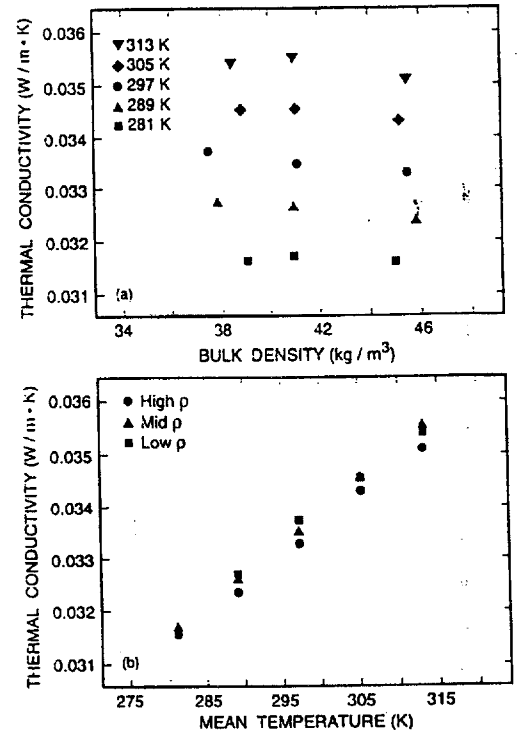

FIG.5 - (a) Thermal conductivity as a function of bulk density.
(b) Thermal conductivity as a function of mean temperature

The data for the (corrected) bulk density, mean temperature and corresponding value of thermal conductivity were fit to a $\lambda(\rho,T)$ model by a multiple variable regression analysis. Higher order temperature terms were determined to be statistically insignificant and a final form, linear in ρ and T, was found adequate. The fitted model is:

$$\hat{\lambda} = 6.3054\times10^{-4} - 4.1993\times10^{-5}\rho + 1.1650\times10^{-4}T \tag{4}$$

The last digit of the coefficients is provided to reduce rounding errors. In the analysis, higher order temperature terms in the model did not improve the results of the curve fit. The author acknowledges that for a larger temperature range, the above model is probably unacceptable.

For this reason, extrapolation of the model beyond the temperature range of this study, 281 to 313 K, is not recommended.

The residual standard deviation for the above fit was 0.000079 W/m·K. The adequacy of the fit was examined by plotting the individual deviations (δ), in W/m·K, from the fitted model versus ρ and T. Values of δ were determined from

$$\delta = \lambda - \hat{\lambda} \tag{5}$$

and plotted versus ρ and T in Figures 6a and 6b, respectively. Figures 6a and 6b do not indicate any trends in the deviations, signifying a satisfactory fit. The standard uncertainties for the predicted values of $\hat{\lambda}$ generally increased at the extreme values of ρ and T (i.e., greater precision near the median values of ρ and T). The maximum predicted standard uncertainty was 0.000048 W/m·K at 37 kg/m^3 and 281 K.

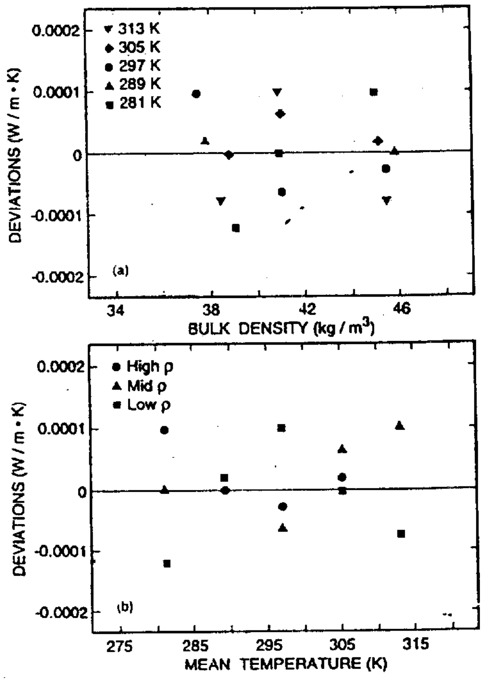

FIG. 6 - Scatter plots.
(a) Deviations versus bulk density.
(b) Deviations versus mean temperature

CERTIFIED VALUES

Based on the regression analysis of the sample lot, certified values of thermal resistance ($\hat{R}$) of SRM 1453 were calculated for a 13.4-mm-thick specimen using the following equation:

$$\hat{R} = \frac{L}{\hat{\lambda}} \tag{6}$$

The thermal conductivity ($\hat{\lambda}$) was computed from Eq 4 and the value of 13.4 mm was the grand average from Table 2. Certified values of $\hat{R}$ are given in Table 4.

Table 4 -- Certified Values of Thermal Resistance of a 13.4 mm Thick Specimen

Temperature	Bulk Density (kg/m^3)				
(K)	38	40	42	44	46
285	0.416	0.417	0.418	0.419	0.420
290	0.408	0.409	0.410	0.411	0.413
295	0.401	0.402	0.403	0.404	0.405
300	0.394	0.395	0.396	0.397	0.398
305	0.388	0.389	0.390	0.390	0.391
310	0.381	0.382	0.383	0.384	0.385

Restrictions and Precautions

The certified values of $\hat{R}$ in Table 4 are restricted to the measured ranges of bulk density, mean temperature, thickness, and thermal conductivity presented herein. This means that certified values of $\hat{R}$ are valid only over a density range of 38 to 46 kg/m^3 and a temperature range of 281 to 313 K. Further, the thermal conductivity of polystyrene foam dramatically increases with specimen thickness due to the increased transmission of long-wave thermal radiation in thicker specimens [4,5]. Consequently, certified values of $\hat{R}$ are *not* valid when specimens of SRM 1453 have been stacked to increase thickness; that is $L \gg 13.4$ mm or, for that matter, $L \ll 13.4$ mm. Values of $\hat{R}$ from thicknesses of 13.2 to 13.6 (13.4 ± 0.2 mm) can be determined from Eqs 4 and 6. As a final note, the boundary conditions of the user application must be comparable to the (normal) emissivity, ϵ, of the surface plates of the guarded hot plate apparatus, $\epsilon = 0.89$.

With reasonable care, specimens of SRM 1453 should have an indefinite shelf life. Guidelines for providing the proper clamping load during testing are provided in Reference [3]. For thermal testing, the specimens must be in firm contact with the apparatus plates. However, the material should not be compressed more than 0.34 mm (2.5 percent) of its original thickness. Polystyrene foam is insensitive to changes in humidity [3]. In the worst case, the moisture content of the foam at 24 °C was found to be less than 1 percent at a relative humidity of 97 percent [3]. The upper temperature of SRM 1453 is limited to the softening point of the polystyrene polymer which is 74 °C as specified in ASTM C 578. A low temperature limit for SRM 1453 has not been established. General precautions for handling polystyrene foam have been described previously [3].

Uncertainty Statement

The expanded uncertainty, U, for predicted values of $\hat{\lambda}$ was obtained by multiplying the combined standard uncertainty for predicted values of $\hat{\lambda}$, $u_c(\hat{\lambda})$ by a coverage factor of $k = 2$:

$$U = ku_c(\hat{\lambda}) \tag{7}$$

The combined standard uncertainty, $u_c(\hat{\lambda})$ was determined from the individual contributions of: 1) the standard uncertainty for the regression analysis for $\hat{\lambda}$: 2) the standard uncertainty for the measurement of λ; 3) the standard uncertainties for the measurements of ρ and T; and, 4) the correction for the meter area bulk density. The standard uncertainties for $\hat{\lambda}$ and λ were 0.000048 W/m·K and 0.00019 W/m·K, respectively. The standard uncertainties for the measurements of ρ and T, and the correction for the meter area bulk density were 0.18 kg/m^3, 0.034 K, and 0.20 kg/m^3, respectively. Propagation of these uncertainty estimates in Equation (5) yielded a standard uncertainty of 0.000012 W/m·K. For these uncertainty estimates, the expanded uncertainty, U, for predicted values of $\hat{\lambda}$ was 0.00039 W/m·K ($k = 2$). The expanded uncertainty estimate does not include any estimate s for uncertainties introduced by the user or long-term drifts in the material.

The expanded uncertainty, U, for certified values of $\hat{R}$ in Table 7 was based on the following equation:

$$U(\hat{R}) = ku_c(\hat{R}) = k\sqrt{c_{\hat{\lambda}}^2 u_c^2(\hat{\lambda})} \tag{8}$$

where the sensitivity coefficient $c_{\hat{\lambda}} = -(0.0134/\hat{\lambda}^2)$ and $u_c(\hat{\lambda})$ was obtained from Equation (7). Note that the sensitivity coefficient $c_{\hat{\lambda}}$ varies with $\hat{\lambda}$ and therefore the standard uncertainty for $\hat{R}$ also varies. The maximum expanded uncertainty for $\hat{R}$ in Table 7 is ±0.005 m^2·K/W ($k = 2$) In relative terms, at 46 kg/m^3 and 300 K, the maximum relative expanded uncertainty is 1.3 percent. Note that expanded uncertainties for $\hat{R}$ in Table 7 are valid only for the given hypothetical thickness of 13.4 mm.

SUMMARY

Thermal conductivity measurements at room temperature are presented as the basis for certified values of SRM 1453, Expanded Polystyrene Board. The thermal conductivity measurements were conducted over range of bulk density of 37.4 to 45.8 kg/m^3 and mean temperature of 281 to 313 K. A model dependent on these two parameters has been developed that describes the thermal conductivity over the range of the parameters. An expanded uncertainty, consistent with current international guidelines, has been prepared.

ACKNOWLEDGMENTS

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