NBSIR 88-3094

FIBROUS ALUMINA-SILICA INSULATION BOARD AS A CANDIDATE STANDARD REFERENCE MATERIAL OF THERMAL RESISTANCE

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June 1988

Stimulating America's Progress
1913-1988

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Sponsored, in part, by
U.S. Department of Energy
Oak Ridge National Laboratory
Oak Ridge, Tennessee 37830

U.S. DEPARTMENT OF COMMERCE, C. William Verity, Secretary

NATIONAL BUREAU OF STANDARDS, Ernest Ambler, Director

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Fibrous Alumina-Silica Insulation Board as a Candidate Standard Reference Material of Thermal Resistance

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Measurements of apparent thermal conductivity are reported in order to provide the basis for certifying fibrous alumina-silica insulation board as a Standard Reference Material (SRM) of thermal resistance. These data encompass ranges of temperature from 93 to 746 K, densities from 207 to 308 kg/m^3, and fill-gas pressures from roughing-pump vacuum to atmospheric pressure, in environments of both air and helium. Detailed analyses and intercomparisons of previously published data are given.

Key words: alumina-silica board; apparent thermal conductivity; density; pressure; Standard Reference Material; temperature; thermal insulation; thermal resistance.

This work was funded in part by DOE/ORNL under contract ORNL/IA-21428.

1. INTRODUCTION

The Office of Standard Reference Materials (OSRM) of the U.S. National Bureau of Standards (NBS) establishes Standard Reference Materials (SRMs) needed to improve reliability in measurement of physical properties. The Properties of Solids Group within the Center for Chemical Engineering (CCE) has actively participated for about 25 years in the effort to establish SRMs of thermal resistance over a broad range of conductivities and temperatures. The status of this work has been summarized by Hust [1].

During the mid-1970's, Committee C-16 of the American Society for Testing and Materials recognized the great need for SRMs of thermal insulation. As a consequence, a task-group was established under the auspices of ASTM Subcommittee C16.30 on thermal measurements. Recommendations for establishing thermal insulation SRMs were published in 1978 [2].

Clay-bonded fibrous alumina-silica insulation is being investigated for possible use as a high-temperature SRM of thermal resistance. We report measurements of the apparent thermal conductivity of several specimens of this material using two different guarded-hot-plate apparatus (GHP). The low-temperature GHP obtained data over a range of mean specimen temperature from 93 to 311 K; the high-temperature GHP covered the range of mean temperatures from 313 to 746 K. At the present time no SRM of thermal resistance for temperatures above 330 K is available from OSRM, in spite of the strong need for such SRMs.

2. MATERIAL CHARACTERIZATION

The material studied is produced as rigid boards from clay-bonded fibers of alumina-silica. The specimens obtained from the producer are nominally 2.5 cm (1 in) thick and about 30 cm (1 f) square. The alumina-silica fibers are oriented approximately parallel to the faces of the boards. The bulk densities of the specimens ranged from 207 to 308 kg/m^3.

This material was investigated because of the recommendations of the ASTM C16.30 task-group. The producer of this material had decided to establish it as an in-house standard and to cooperate with us by providing carefully selected specimens for determining the suitability of the material as an SRM.

3. MEASUREMENTS

For brevity we shall use the term "thermal conductivity" to denote "apparent thermal conductivity" in the following text. Analysis of our data in the following section suggests that radiative and convective heat transfer in this fibrous alumina-silica board contribute only a small amount in comparison to conductive heat transfer. "Thermal conductivity" seems to be a valid descriptor of the heat-transfer behavior of this material.

Thermal conductivity data reported here were obtained with the high-temperature GHP, described by Hust, Filla, Hurley, and Smith [3,4], and with the low-temperature GHP, described by Smith, Hust, and Van Poolen [5]. The diameters of the circular stack and metered main heater areas are respectively 20 and 10 cm for the low-temperature GHP, and are 25 and 12.5 cm for the high-temperature GHP.

Thermal conductivity at low temperatures was measured in dry nitrogen gas at atmospheric pressure (83 kPa; 623 Torr), for a single pair of specimens whose mean bulk density was 259 kg/m^3. Table 1 lists the thermal conductivity measurements on this pair under the two-sided mode of operation of the low-temperature GHP, at mean temperatures ranging from 93 to 311 K (-180 to +38°C).

Measurements of thermal conductivity at high temperatures were performed initially on an additional set of eight carefully selected specimens in an atmosphere of air at ambient pressure, 83 kPa. Each specimen was individually measured in the single-sided mode of operation of the high-temperature GHP to determine the variability of thermal conductivity within the set. The first block of data in table 2 lists thermal conductivity data for a mean temperature of 313 K. Because multiple measurements were made on some of the specimens there are more than eight data points in this first block.

From the set of eight specimens we selected two, matched in density; this matched pair was then measured in air at 83 kPa, at mean temperatures ranging from 313 to 746 K (second block of table 2). In addition, the thermal conductivity of this pair was measured at various air pressures from ambient to low vacuum. Table 3 gives the data at mean temperatures of 313 and 693 K and for various pressures ranging from 83.6 to 0.0047 kPa (0.035 Torr).

Thermal conductivity of this matched pair was also measured in an environment of helium gas at 84 to 87 kPa at five different mean temperatures from 313 to 692 K (table 4). The variation in pressure was due to the rise in temperature of the sealed system.

Because the bulk densities of the group of eight specimens covered only a very small range (see table 5a), four additional specimens were obtained with appreciably different bulk densities. These specimens were individually measured in the single-sided mode to determine how the thermal conductivity depends on density. Finally, measurements were included from a study of thirteen more specimens which were used in a high-temperature interlaboratory comparison [6]. The results of single-sided thermal conductivity measurements on all the additional seventeen specimens, at mean temperatures of 333 K, are also presented here (table 5b) to aid in assessing specimen variability and dependence on density. All these measurements were conducted in air at 84 kPa. Multiple measurements performed on some of the specimens are responsible for the presence of more data points in tables 5a and 5b than the number of specimens.

4. DATA ANALYSIS

The data were analyzed to determine the dependence of thermal conductivity on temperature, density, and environmental gas pressure and species.

A. Conductivity as a Function of Temperature.

The first matched pair of specimens, measured in dry nitrogen gas at 83 kPa (623 Torr) in the low-temperature apparatus, had a mean density of 259 kg/m^3. The temperature dependence of thermal conductivity for temperatures from 93 to 311 K was represented by

$$k(T) = 6.932 + 0.1769 \cdot T - 0.3070 \times 10^{-6} \cdot T^3, \qquad (1)$$

where k is in mW/(m·K) and T is in K. This correlation was obtained using the thermal conductivity integral method [7] and a weighted least-squares fit, as were all the correlations obtained in the following analysis. The weighting gives approximately equal percentage deviations, to reflect the usual experimental practice of holding the relative error of the measurements constant. The data used to determine this correlation, along with values calculated from it, are listed in table 1 and illustrated in figure 1. Deviations of the data from eq(1) are shown in figure 2.

The dependence of thermal conductivity on temperature for a different matched pair of specimens, each having a density of about 247 kg/m^3, and measured in air at atmospheric pressure in the high-temperature apparatus, was represented by

$$k(T) = 15.12 + 0.09489 \cdot T + 2.888 \times 10^{-8} \cdot T^3, \qquad (2)$$

where k is in mW/(m·K) and T is in K. This correlation is valid for mean temperatures from 313 to 746 K and for specimens in air at 83 kPa. The data used to determine this relation are listed in table 2 and illustrated in figure 3. The deviations of the data from eq(2) are illustrated in figure 4.

The very small positive value of the coefficient of the T^3 term in eq(2) correlates with the slight upward curvature evident in figure 3. At T = 310 K the T^3 term contributes 0.86 mW/(m·K) to the total thermal conductivity value of 45.4 mW/(m·K), or only 2%. At the upper temperature limit of this study, 750 K, the T^3 term represents 12% of the total thermal conductivity. On theoretical grounds the physical origin of this relatively small T^3 term in the k(T) function is probably radiative heat transfer. The material is dense enough that convective heat transfer is negligible at room temperature. Thus conductive heat transfer through the solid fibers and through the environmental gas (air) between the fibers is the major contributor to the total heat transfer.

At a typical temperature of 312 K, eq(1) yields a thermal conductivity of 52.8 mW/(m·K) for one pair, while eq(2) yields 45.6 mW/(m·K) for the other pair, a difference of 14%. The low-temperature and the high-temperature apparatus each have an estimated accuracy of 2% at 312 K, and the experimental repeatability for removal and re-installation of specimens is about 0.5% for each apparatus. The dependence of the thermal conductivity on density is not known very precisely, as will be discussed in the next two paragraphs. It is quite possible that differences in density between the two pairs are responsible for the lack of agreement in the values of k at the same temperature. The second pair was manufactured several years after the first pair, and was measured 6 years later.

B. Conductivity as a Function of Density

The data used to determine the dependence of thermal conductivity on density are illustrated in figure 5 and listed in table 5b. The dependence of thermal conductivity on density for specimens at a temperature of 333 K and in air at 83 kPa was represented by

$$k(D) = 42. + 0.033 \cdot D, \qquad (3)$$

where k(D) is in mW/(m·K) and D is in kg/m^3. This correlation is valid for a range of densities from 207 to 308 kg/m^3.

The large scatter of data in this figure (± 8% at the low end of the curve) shows that unknown factors are present. Some of these specimens, used in the round-robin study, were not as carefully selected as the specimens selected as candidates for SRM certification. The imprecision caused by the measurement process is thought to be less than 1%. As a consequence of the large scatter, the correlation with density is highly uncertain. The deviations of the data from eq(3) are illustrated in figure 6. The relatively large deviations, and concomitant large uncertainty in the k(D) correlation, are attributed to specimen variations of unknown origin.

C. Conductivity as a Function of Pressure

The dependence of thermal conductivity on pressure for specimens at a temperature of 313 K and having a density of 247 kg/m^3 was represented by

$$k(P) = k_o + \frac{A \cdot P}{(1 + [P/P_o]^n)^{1/n}} , \qquad (4)$$

where k and k_o are in mW/(m·K), and P is in kPa; k_o and A are constants. P_o is a pressure parameter which determines the location of the transition region where k rises rapidly with increasing P. The parameter k_o models the constant value approached by k at very low values of P ($P \ll P_o$). Thus the value of k_o represents conduction by the solid fiber matrix. This contribution is independent of gas pressure and is what remains at zero pressure. To match the observed behavior k also approaches a different constant, $k_o + A \cdot P_o$, at high values of P ($P \gg P_o$). At $P = P_o$, $k(P_o) = k_o + A \cdot P_o/2^{(1/n)}$.

Values of k_o and A were obtained by an unweighted least squares fit with n and P_o chosen by trial and error to yield the minimum standard deviation of the fit. In performing this fit it was found that, for the somewhat limited range of pressure for which we obtained data, the minimum standard deviation of the fit (1.26) is relatively insensitive to the values of n and P_o. Thus for simplicity we forced n = 0.5 (1/n = 2) and then found k_o = 5.75 mW/(m·K), A = 778, and P_o = 0.054 kPa (0.40 Torr), with a resulting standard deviation of 1.34, very close to the global minimum.

The data used to determine this dependence on air pressure, along with the smooth curve calculated from eq(4), are listed in table 3 and shown in figure 7. Deviations of the data from eq(4) are illustrated in figure 8. The relatively large variations exhibited at low pressures are attributed to large relative uncertainties in the measurement and control of the air pressure.

This pressure dependence of k indicates a reduction of -0.9% in thermal conductivity in the value at the 1650 m (5400 ft) elevation of our laboratory at Boulder, Colorado, in comparison to the value at sea level.

Using kinetic theory we can also estimate, from the value of P_o obtained above, the effective size of the pores in the material. The transition region, passing from the upper constant value to the lower constant value in the k(P) correlation as the air pressure is reduced, should be found where the mean free path (**mfp**) of the air molecules becomes about equal to the pore size. In this region, the probability of a collision with another air molecule becomes approximately equal to the probability of a collision with a fiber of insulation material. Reference [**8**] derives a relation showing the mfp to be inversely proportional to pressure, and estimates the mfp of oxygen molecules to be about 8 x 10^{-8} m at standard conditions (101.3 kPa and 273 K). At 313 K and 0.054 kPa (0.4 Torr) the mfp of oxygen molecules is estimated to be 0.15 mm. The atmosphere is composed of 20% O_2 and 79% N_2; nitrogen has a molecular mass only 12% less than that of oxygen, so for our purposes the estimated mfp of air should be about the same as the estimate for oxygen. Thus the estimated pore size in the material is also about 0.15 mm. We can see no pores larger than an upper limit of about 0.2 mm.

D. Conductivity as a Function of Environmental Gas

The temperature dependence of thermal conductivity for the matched pair in an atmosphere of pure helium gas was represented by a relation similar in form to that used for the conductivity in air:

$$k_{He} = 86.166 + 0.2940 \cdot T - 0.13783\text{x}10^{-7} \cdot T^3 . \qquad (5)$$

The data used to determine this correlation are listed in table 4 and plotted in figure 9. The standard deviation of the data from the solid curve is only 0.03%.

At 293 K (20°C) pure helium gas at atmospheric pressure has a thermal conductivity of 147.1 mW/(m·K). For the fibrous alumina-silica insulation in pure helium gas at the same temperature and pressure, eq(5) gives a thermal conductivity value of 172.0 mW/(m·K). The pressure dependence of conductivity at low pressure suggested that k_o = 5.75 mW/(m·K) is the contribution to the thermal conductivity by the solid fiber matrix alone. The conductivity of the fiber matrix in helium is greater than that for pure helium alone by a difference of 24.9 mW/(m·K), which is significantly greater than k_o.

A similar comparison is possible using the corresponding data for air. For specimens in air at 293 K and atmospheric pressure, we used eq(2) as the correlation (by extrapolation) because this relation was obtained for data from the same high-temperature GHP used to obtain the helium correlation, eq(5). Eq(2) gives a value of 43.7 mW/(m·K) for the thermal conductivity. At the same temperature and pressure pure air has a conductivity of 25.1 mW/(m·K). The conductivity of the fiber matrix in air is greater than the conductivity of pure air alone by a difference of 18.6 mW/(m·K), which again exceeds the conductivity of the fiber matrix alone, and by approximately the same magnitude as the difference found for helium gas. This increase in conductivity between a pure gas and the same gas in the solid fiber matrix should depend on the density of the solid fibers, the porosity of the fiber matrix, and on the conductivities of the solid fibers and of the environmental gas. Analysis of the interaction between the environmental gas and solid fiber matrix will be left as the subject of a separate paper.

5. COMPARISONS

The high-temperature results obtained by this investigation can be compared to two other sources of thermal conductivity data: (a) the results [6] of a recently completed round robin sponsored by ASTM Committee C 16.30, and, (b) data published [9] by the producer of this material. The round-robin data, for a set of specimens having a mean density of 238 kg/m^3, are compared to eq(1) in figure 10. The results reported here lie within the band of measurements reported by the round robin participants. The effect of variation in density for the round-robin specimens is known [6] to be negligible here.

The high-temperature measurements reported by the producer, using five different apparatus, are compared in figure 11. The spread of the results from these five apparatus was reported to be 10%. A least-squares fit to the producer's data gave the relation

$$k(T) = 14.2 + 0.0916\ T + 2.776 \times 10^{-8}\ T^3 \qquad (6)$$

which is plotted as the solid line in figure 11. The standard deviation of eq(5) from the NBS data (circles in figure 12) for the SRM candidate material is -4.4%, well within the 10% spread of the results found by the producer. Visually the line appears to be parallel to the data points, showing the deviation to be systematic.

6. RECOMMENDATIONS

Measurements of the thermal conductivity of the eight specimens carefully selected for possible use as an SRM reveal a low variability for this material. This suggests that this material can be supplied with a sufficiently small variability to serve as an excellent SRM. However, the specimens used in the round robin study exhibited a much larger variability. If a large lot of this material (100 to 200 specimens) can be obtained with a variability similar to that of the originally supplied ten specimens, this material would be recommended for use as an SRM. If on the other hand the larger variability is more typical of this material, each specimen would need to be individually measured by NBS to be useful, and would then be certified individually as calibrated transfer specimens.

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Table 1. Thermal conductivity of one pair of fibrous alumina-silica insulation board with a density of 259 kg/m^3, at mean temperatures of 93 to 311 K. Measurements were performed in dry nitrogen gas at a pressure of 83 kPa (623 Torr) using the NBS low-temperature guarded hot plate.

Thi (K)	Tlo (K)	Tmean (K)	Kdat mW/(m.K)	AREA (cm^2)	DELX (cm)	DENSITY (kg/m^3)	PRESSURE (kPa)
147.292	121.818	134.555	30.43	83.1	2.531	259.60	.826E+02
159.939	134.593	147.266	32.19	83.2	2.531	259.50	.826E+02
172.069	146.907	159.488	34.02	83.2	2.531	259.50	.826E+02
185.024	159.714	172.369	35.88	83.3	2.532	259.50	.826E+02
106.266	80.793	93.530	22.75	83.0	2.529	259.70	.826E+02
121.561	96.019	108.790	25.77	83.1	2.530	259.70	.826E+02
134.154	108.346	121.250	28.13	83.1	2.530	259.60	.826E+02
197.521	172.114	184.818	37.81	83.3	2.532	259.40	.826E+02
210.219	184.973	197.596	39.44	83.3	2.533	259.40	.826E+02
222.916	197.561	210.239	41.20	83.4	2.533	259.30	.826E+02
235.513	210.235	222.874	42.49	83.4	2.533	259.30	.826E+02
247.982	222.836	235.409	44.09	83.5	2.534	259.20	.826E+02
247.966	222.829	235.398	44.85	83.5	2.534	259.20	.826E+02
260.591	235.438	248.015	46.04	83.5	2.534	259.20	.826E+02
273.216	247.996	260.606	47.70	83.6	2.535	259.20	.826E+02
285.723	260.569	273.146	49.01	83.6	2.535	259.10	.826E+02
298.308	273.177	285.743	49.89	83.7	2.536	259.10	.813E+02
310.859	285.696	298.278	51.65	83.7	2.536	259.00	.826E+02
323.394	298.310	310.852	53.15	83.8	2.537	259.00	.826E+02

Table 2. Thermal conductivity of eight specimens of fibrous alumina-silica insulation board with densities of 236 to 249 kg/m^3, at mean temperatures of 313 to 746 K. Measurements were performed in air at 83 kPa (623 Torr), using the NBS high-temperature guarded hot plate.

Thi (K)	Tlo (K)	Tmean (K)	Kdat mW/(m.K)	AREA (cm^2)	DELX (cm)	DENSITY (kg/m^3)	PRESSURE (kPa)
323.042	303.114	313.078	45.44	128.4	2.537	242.70	.836E+02
323.050	303.127	313.089	45.63	128.4	2.537	249.40	.836E+02
323.050	303.049	313.050	45.56	128.4	2.537	244.70	.836E+02
323.024	303.095	313.060	45.29	128.4	2.537	236.40	.836E+02
323.069	303.129	313.099	45.94	128.4	2.537	242.70	.836E+02
323.066	303.077	313.072	45.81	128.4	2.537	247.00	.836E+02
323.080	303.061	313.071	45.89	128.4	2.537	245.40	.836E+02
323.041	303.063	313.052	45.02	128.4	2.537	244.70	.836E+02
323.068	303.036	313.052	45.85	128.4	2.537	247.80	.836E+02
323.055	303.134	313.095	45.77	128.4	2.537	247.00	.836E+02
323.027	303.137	313.082	45.51	128.4	2.537	247.00	.836E+02
323.036	303.147	313.092	45.47	128.4	2.537	247.00	.836E+02
323.034	303.146	313.090	45.51	128.4	2.537	247.00	.836E+02
323.073	303.146	313.110	45.79	128.4	2.537	247.00	.836E+02
323.055	303.120	313.088	45.66	128.4	2.537	247.00	.836E+02
323.008	303.099	313.054	46.18	128.4	2.537	247.40	.836E+02
323.090	303.131	313.111	45.81	128.4	2.537	247.40	.836E+02
323.167	303.125	313.146	45.68	128.4	2.537	247.40	.833E+02

Table 2. (cont.)

Thi (K)	Tlo (K)	Tmean (K)	Kdot mW/(m.K)	AREA (cm)	DELX (cm)	DENSITY (kg/m)	PRESSURE (kPa)
343.207	323.167	333.187	47.97	128.4	2.539	247.40	.833E+02
392.895	373.102	382.999	53.20	128.5	2.541	247.20	.833E+02
393.149	373.124	383.137	53.18	128.5	2.541	247.20	.833E+02
483.262	463.197	473.230	63.71	128.7	2.544	246.80	.833E+02
591.999	553.118	572.559	75.03	128.9	2.549	246.40	.833E+02
622.470	523.118	572.794	74.55	129.0	2.549	246.40	.833E+02
671.898	493.743	582.821	75.56	129.1	2.549	246.30	.833E+02
612.959	573.066	593.013	77.69	128.9	2.550	246.30	.833E+02
633.178	593.161	613.170	80.13	129.0	2.551	246.20	.833E+02
653.224	613.126	633.175	82.73	129.0	2.552	246.10	.833E+02
673.212	633.088	653.150	85.26	129.1	2.553	246.00	.833E+02
692.745	653.134	672.940	87.86	129.1	2.554	245.90	.833E+02
712.137	672.899	692.518	91.82	129.1	2.555	245.80	.833E+02
713.045	673.111	693.078	91.94	129.1	2.555	245.80	.833E+02
763.373	728.645	746.009	96.89	129.2	2.557	245.60	.833E+02
712.512	673.096	692.804	89.75	129.1	2.555	245.80	.833E+02
343.187	323.111	333.149	47.77	128.4	2.538	247.30	.833E+02
363.220	343.159	353.190	49.84	128.5	2.539	247.30	.833E+02
383.227	363.068	373.148	51.94	128.5	2.540	247.20	.833E+02
403.241	383.245	393.243	54.34	128.5	2.541	247.10	.833E+02
423.173	383.018	403.096	55.15	128.6	2.541	247.10	.833E+02
443.123	383.149	413.136	56.16	128.6	2.541	247.00	.833E+02
463.157	383.201	423.179	57.25	128.7	2.542	247.00	.833E+02
482.963	383.211	433.087	58.29	128.7	2.542	246.90	.833E+02
502.896	383.163	443.030	59.40	128.7	2.543	246.90	.833E+02
522.995	383.157	453.076	60.52	128.8	2.543	246.90	.833E+02
542.784	383.222	463.003	61.66	128.8	2.543	246.80	.833E+02
562.750	383.205	472.978	62.79	128.8	2.544	246.80	.833E+02
582.598	383.137	482.868	63.98	128.9	2.544	246.70	.833E+02
622.635	403.204	512.920	67.38	129.0	2.546	246.60	.833E+02
662.267	402.976	532.622	69.62	129.0	2.547	246.50	.833E+02
403.221	383.096	393.159	54.44	128.5	2.540	247.10	.833E+02
423.294	403.295	413.295	56.74	128.6	2.541	247.00	.833E+02
443.185	403.088	423.137	57.53	128.6	2.542	247.00	.833E+02
483.279	443.028	463.154	62.03	128.7	2.543	246.80	.833E+02
523.221	481.285	502.253	66.51	128.8	2.545	246.70	.833E+02
323.101	303.125	313.113	45.97	128.4	2.537	247.40	.833E+02
523.295	483.055	503.175	66.44	128.8	2.545	246.60	.833E+02
563.183	522.134	542.659	70.91	128.8	2.547	246.50	.833E+02
603.096	562.959	583.028	75.94	128.9	2.549	246.30	.833E+02
642.828	602.915	622.872	80.46	129.0	2.551	246.20	.833E+02
682.820	642.974	662.897	85.13	129.1	2.553	246.00	.833E+02
323.121	303.098	313.110	46.00	128.4	2.538	247.50	.833E+02
323.140	303.157	313.149	46.25	128.4	2.538	247.50	.833E+02
323.637	303.184	313.411	46.45	128.4	2.538	247.50	.833E+02
583.149	563.174	573.162	75.53	128.9	2.549	246.40	.833E+02
583.174	563.105	573.140	75.55	128.9	2.549	246.40	.833E+02
332.357	312.336	322.347	46.98	128.4	2.538	247.40	.833E+02
333.150	313.150	323.150	46.98	128.4	2.538	247.40	.833E+02
583.140	563.083	573.112	75.87	128.9	2.549	246.40	.833E+02
588.178	568.141	578.160	76.45	128.9	2.549	246.40	.833E+02
583.168	563.151	573.160	75.86	128.9	2.549	246.40	.833E+02

Table 3. Thermal conductivity of a selected pair of fibrous alumina-silica insulation boards with densities of 236 to 249 kg/m^3, at mean temperatures of 313 and 693 K. Measurements were performed in air at pressures from 84 to 0.0047 kPa, using the NBS high-temperature guarded hot plate.

Thigh (K)	Tlow (K)	Tmean (K)	Kdat mW/(m.K)	Pressure (kPa)	Percent Deviation
323.042	303.114	313.078	45.44	.836E+02	-.70
323.050	303.127	313.089	45.63	.836E+02	-.29
323.050	303.049	313.050	45.56	.836E+02	-.45
323.024	303.095	313.060	45.29	.836E+02	-1.04
323.069	303.129	313.099	45.93	.836E+02	.38
323.066	303.077	313.072	45.81	.836E+02	.11
323.080	303.061	313.071	45.89	.836E+02	.28
323.041	303.063	313.052	45.02	.836E+02	-1.63
323.068	303.036	313.052	45.85	.836E+02	.19
323.055	303.134	313.095	45.77	.836E+02	.02
323.027	303.137	313.082	45.51	.836E+02	-.55
323.036	303.147	313.092	45.47	.836E+02	-.64
323.034	303.146	313.090	45.51	.836E+02	-.55
323.073	303.146	313.110	45.79	.836E+02	.05
323.055	303.120	313.088	45.66	.836E+02	-.22
323.008	303.099	313.054	46.18	.836E+02	.92
323.090	303.131	313.111	45.81	.836E+02	.10
323.063	303.066	313.065	45.54	.667E+02	.13
323.087	303.151	313.119	45.00	.400E+02	.55
323.119	303.148	313.134	43.03	.133E+02	1.05
323.131	303.100	313.116	39.33	.400E+01	.77
323.121	303.175	313.148	35.20	.133E+01	2.15
323.122	303.145	313.134	27.92	.400E+00	-.63
323.150	303.146	313.148	22.38	.133E+00	3.37
323.137	303.033	313.085	14.04	.400E-01	-7.00
323.089	303.117	313.103	8.04	.467E-02	3.22
323.097	303.018	313.058	7.84	.467E-02	.74
323.167	303.125	313.146	45.67	.833E+02	-.18
323.101	303.125	313.113	45.97	.833E+02	.47
323.121	303.098	313.110	46.00	.833E+02	.53

Standard Deviation = 1.69

Thigh (K)	Tlow (K)	Tmean (K)	Kdat mW/(m.K)	Pressure (kPa)	Percent Deviation
712.512	673.096	692.804	89.75	.833E+02	
712.522	673.042	692.782	89.52	.666E+02	
712.483	671.335	691.909	80.08	.400E+01	
713.057	673.109	693.083	56.10	.173E+00	

Table 4. Thermal conductivity of the selected pair of fibrous alumina-silica insulation board with a density of 247 kg/m^3, at mean temperatures of 313 to 692 K. Measurements were performed in helium gas at pressures of 84 to 87 kPa (630 to 650 Torr) using the NBS high-temperature guarded hot plate.

Thi (K)	Tlo (K)	Tmean (K)	Kdat mW/(m.K)	AREA (cm^2)	DELX (cm)	DENSITY (kg/m^3)	PRESSURE (kPa)
323.066	303.152	313.109	177.74	128.4	2.537	247.40	.840E+02
343.066	323.134	333.100	183.71	128.4	2.538	247.30	.840E+02
363.100	343.154	353.127	189.34	128.5	2.539	247.30	.840E+02
383.119	363.154	373.137	195.14	128.5	2.540	247.20	.840E+02
711.169	673.166	692.168	285.10	129.1	2.555	245.80	.866E+02

Table 5a. Thermal conductivity of eight different specimens of fibrous alumina-silica insulation board with densities of 236 to 249 kg/m^3, at a mean temperature of 313 K. Measurements were performed in air at 84 kPa using the NBS high-temperature guarded hot plate.

Thi (K)	Tlo (K)	Tmean (K)	Kdat mW/(m.K)	AREA (cm^2)	DELX (cm)	DENSITY (kg/m^3)	PRESSURE (kPa)
323.042	303.114	313.078	45.44	128.4	2.537	242.70	.836E+02
323.050	303.127	313.089	45.63	128.4	2.537	249.40	.836E+02
323.050	303.049	313.050	45.56	128.4	2.537	244.70	.836E+02
323.024	303.095	313.060	45.29	128.4	2.537	236.40	.836E+02
323.069	303.129	313.099	45.94	128.4	2.537	242.70	.836E+02
323.066	303.077	313.072	45.81	128.4	2.537	247.00	.836E+02
323.080	303.061	313.071	45.89	128.4	2.537	245.40	.836E+02
323.041	303.063	313.052	45.02	128.4	2.537	244.70	.836E+02
323.068	303.036	313.052	45.85	128.4	2.537	247.80	.836E+02
323.055	303.134	313.095	45.77	128.4	2.537	247.00	.836E+02
323.027	303.137	313.082	45.51	128.4	2.537	247.00	.836E+02
323.036	303.147	313.092	45.47	128.4	2.537	247.00	.836E+02
323.034	303.146	313.090	45.51	128.4	2.537	247.00	.836E+02
323.073	303.146	313.110	45.79	128.4	2.537	247.00	.836E+02
323.055	303.120	313.088	45.66	128.4	2.537	247.00	.836E+02
323.008	303.099	313.054	46.18	128.4	2.537	247.40	.836E+02
323.090	303.131	313.111	45.81	128.4	2.537	247.40	.836E+02

Table 5b. Thermal conductivity of fibrous alumina-silica insulation board (round-robin material) with densities of 207 to 308 kg/m^3, at a mean temperature of 313 K. Measurements were performed in air at 84 kPa using the NBS high-temperature guarded hot plate.

Thi (K)	Tlo (K)	Tmean (K)	Kdat mW/(m.K)	AREA (cm^2)	DELX (cm)	DENSITY (kg/m^3)	PRESSURE (kPa)
343.187	323.111	333.149	47.77	128.4	2.538	247.30	.833E+02
343.207	323.167	333.187	47.97	128.4	2.539	247.40	.833E+02
343.197	323.181	333.189	53.02	128.4	2.525	295.10	.853E+02
343.108	323.179	333.144	53.22	128.4	2.512	295.80	.853E+02
343.314	323.067	333.191	50.74	128.4	2.712	306.50	.833E+02
343.376	323.117	333.247	50.62	128.4	2.662	307.70	.833E+02
343.294	323.089	333.192	52.77	128.4	2.600	237.00	.833E+02
343.399	323.157	333.278	50.94	128.4	2.628	221.40	.829E+02
343.316	323.063	333.190	49.26	128.4	2.557	236.40	.826E+02
343.232	323.107	333.170	54.39	128.4	2.628	225.70	.834E+02
343.468	323.028	333.248	52.77	128.4	2.611	223.40	.832E+02
343.440	323.069	333.255	53.65	128.4	2.634	225.00	.842E+02
343.169	323.126	333.148	53.36	128.4	2.611	220.50	.841E+02
343.154	323.113	333.134	46.84	128.4	2.600	220.10	.837E+02
343.341	323.160	333.251	47.23	128.4	2.635	217.40	.833E+02
343.179	323.082	333.131	46.46	128.4	2.649	207.20	.830E+02
343.224	323.076	333.150	46.18	128.4	2.628	207.90	.833E+02
343.506	323.168	333.337	48.03	128.4	2.651	214.20	.830E+02
343.309	323.003	333.156	46.14	128.4	2.610	215.30	.829E+02
343.438	323.185	333.312	46.32	128.4	2.626	209.00	.842E+02
343.273	323.239	333.256	54.65	128.4	2.627	225.80	.840E+02
343.112	323.192	333.152	54.31	128.4	2.627	225.80	.840E+02
343.370	323.184	333.277	53.19	128.4	2.645	222.60	.840E+02
343.190	323.143	333.167	53.03	128.4	2.645	222.60	.840E+02

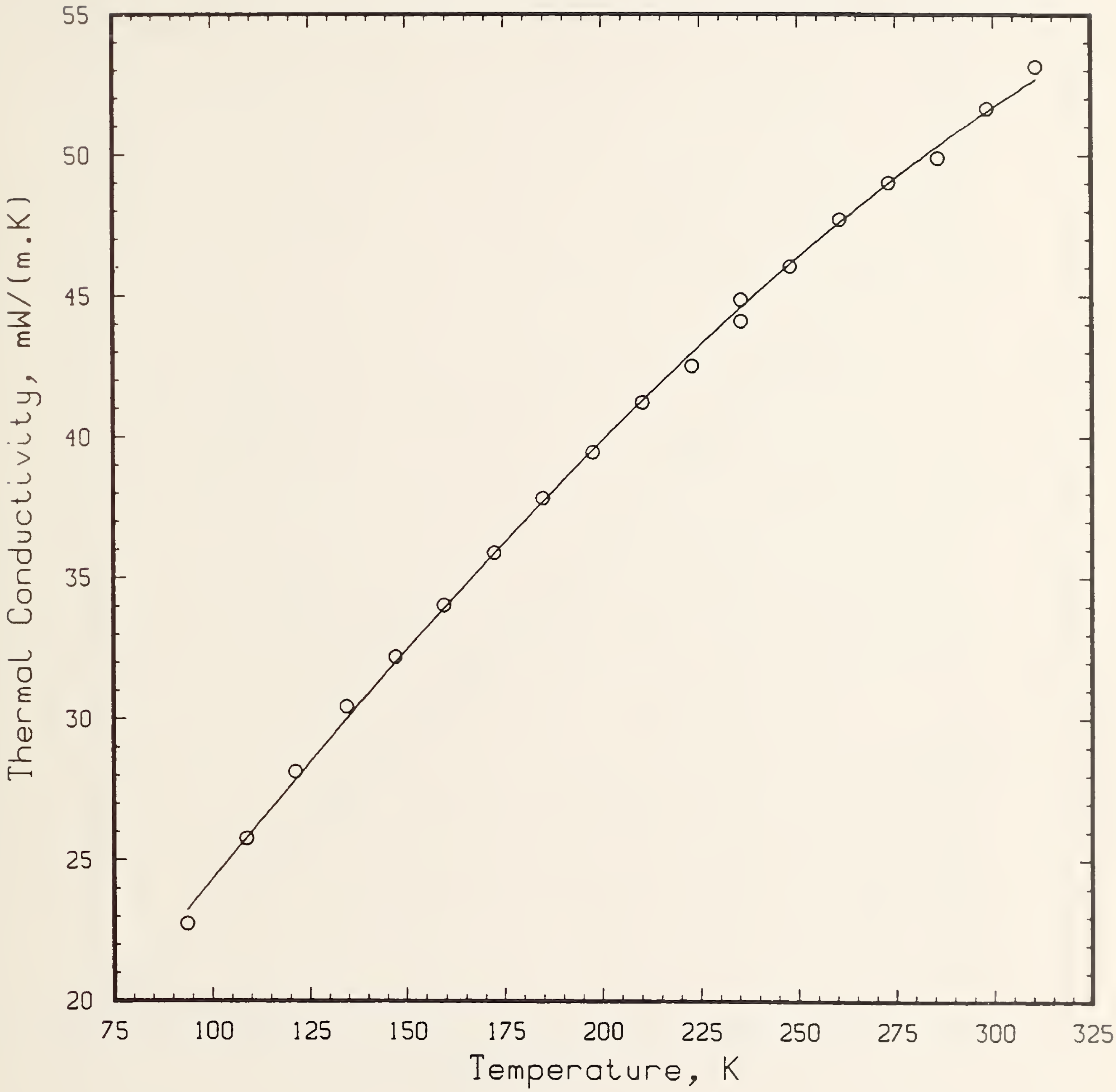

Figure 1. Thermal conductivity of a pair of fibrous alumina-silica insulation boards as measured by NBS/B, at mean temperatures of 93 to 311 K and at ambient atmospheric pressure of 83 kPa. Boards have a density of 259 kg/m³. The solid line was calculated from eq(1).

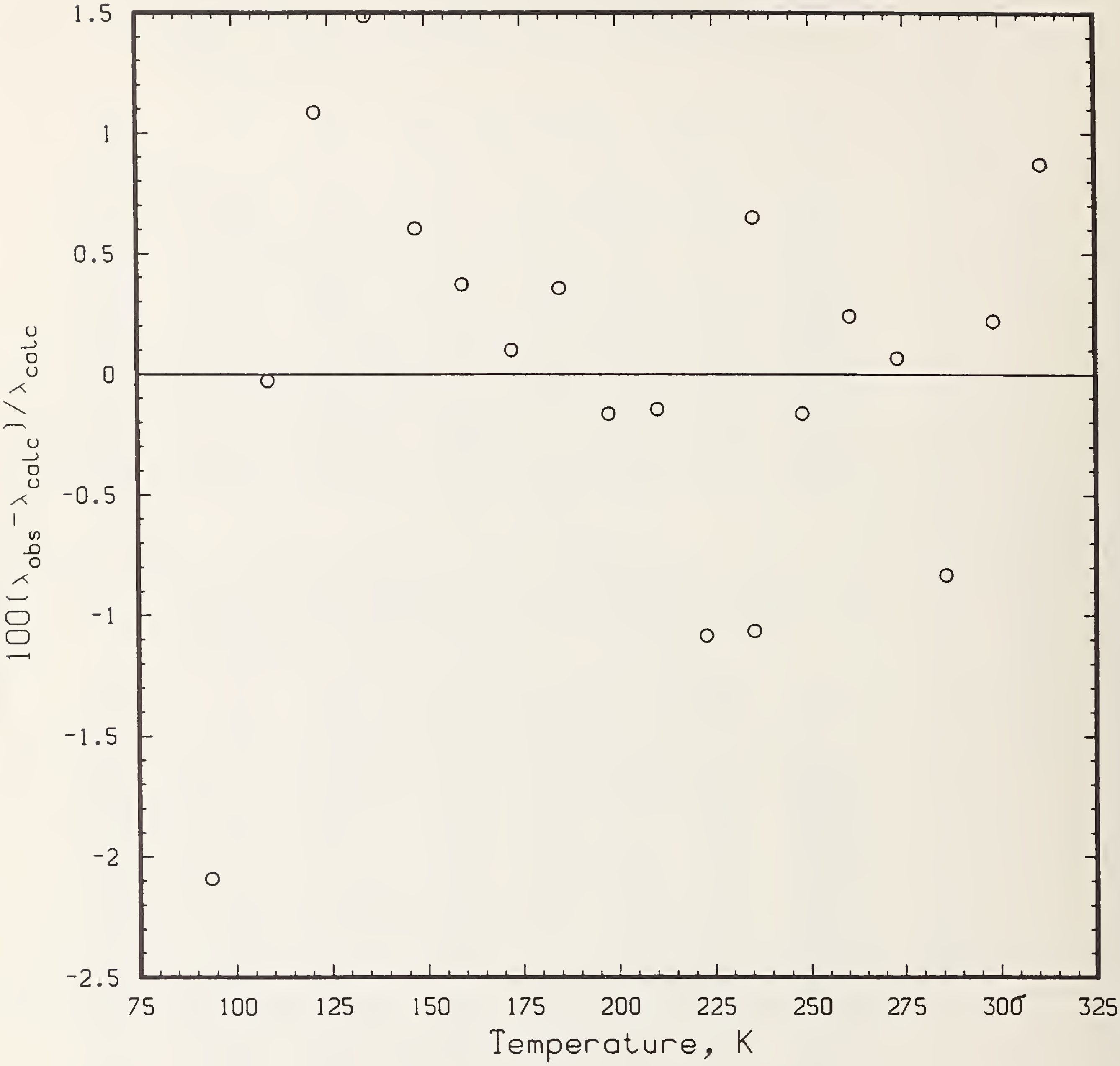

Figure 2. Deviations of the NBS low-temperature thermal conductivity data from eq(1).

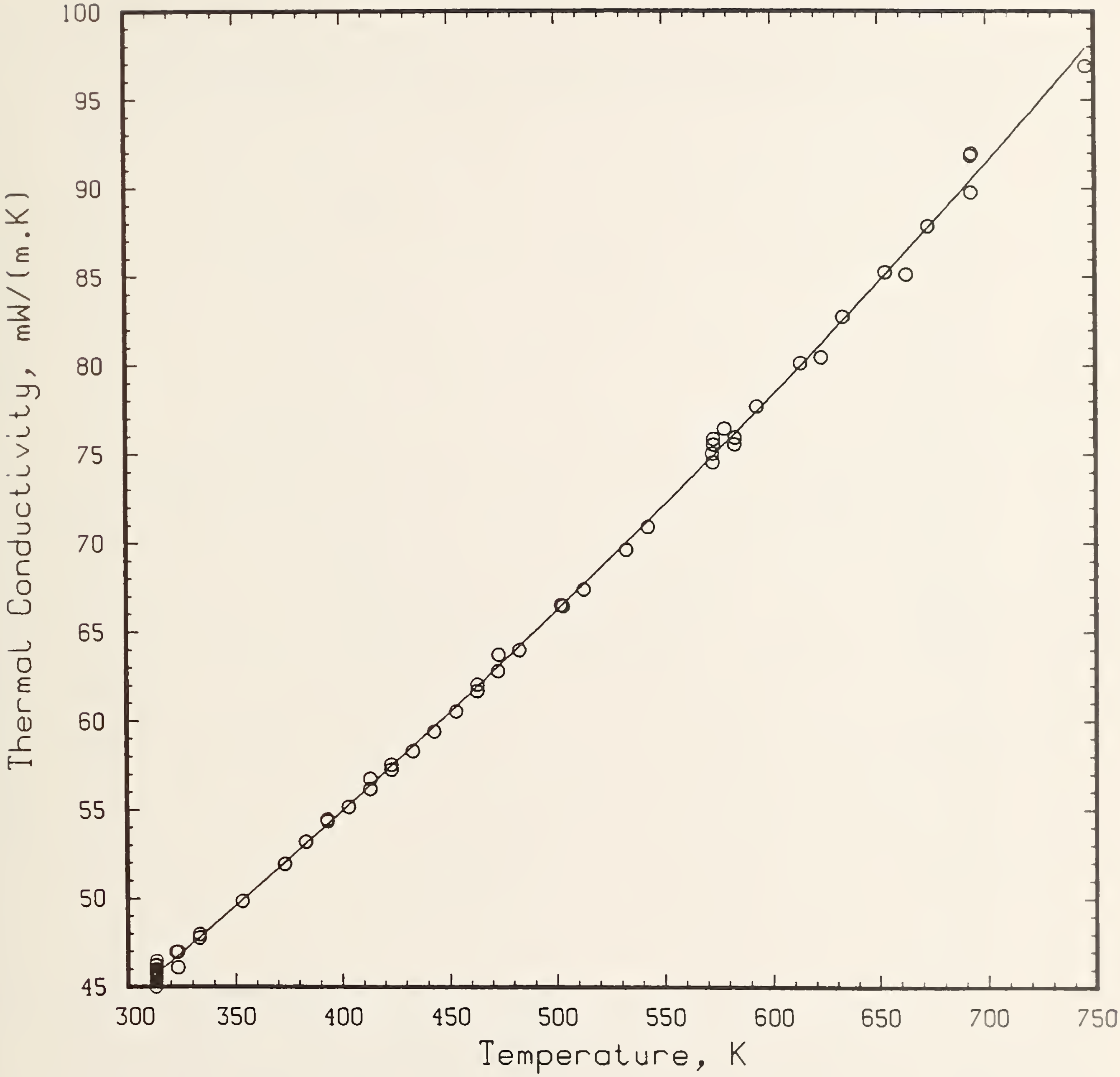

Figure 3. Thermal conductivity of a pair of fibrous alumina-silica insulation boards as measured by NBS/B, at mean temperatures of 313 to 746 K and at ambient atmospheric pressure of 83 kPa. Boards have a density of 247 kg/m^3. The solid line was calculated from eq(2).

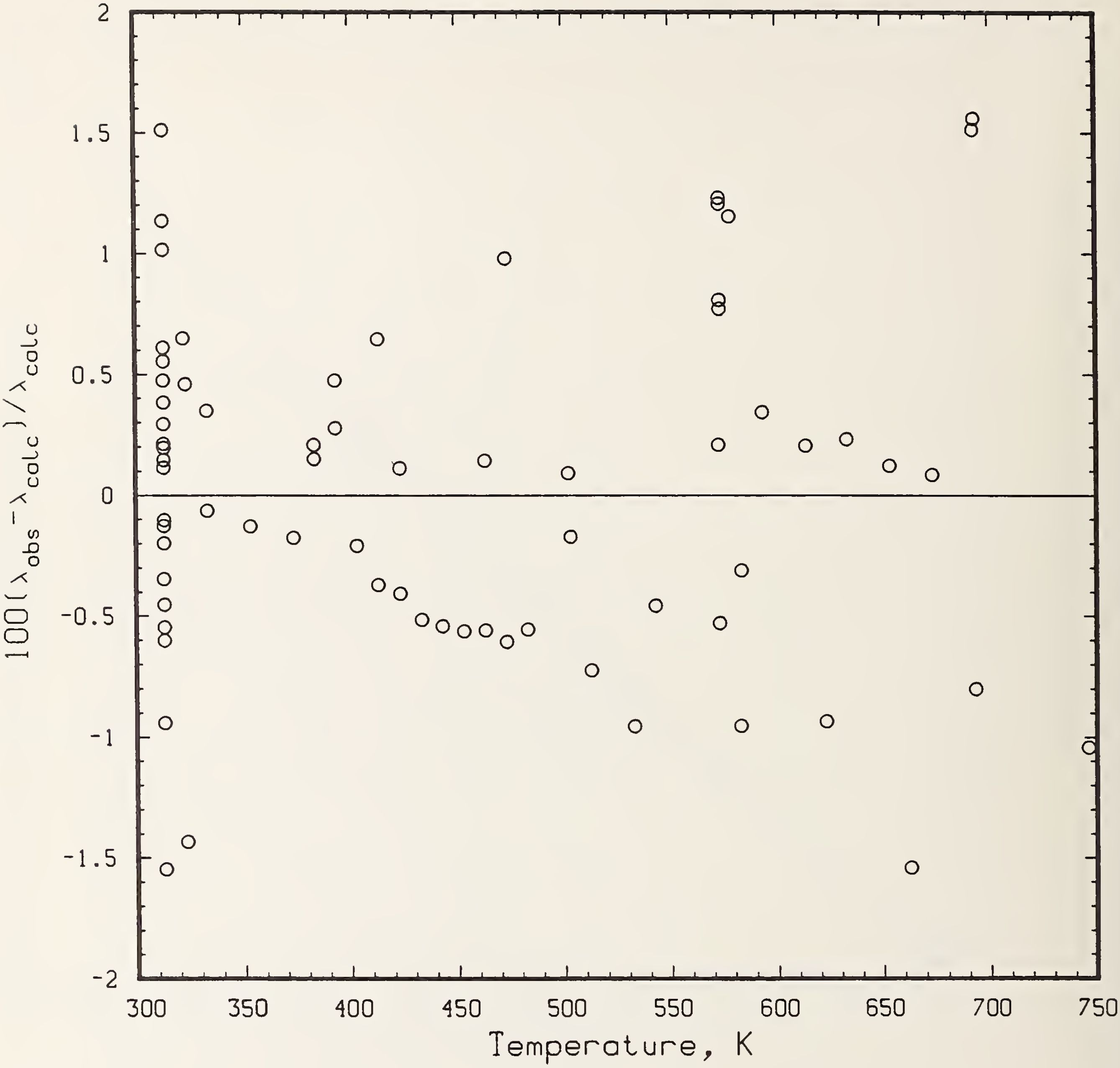

Figure 4. Deviations of the NBS high-temperature thermal conductivity data from eq(2).

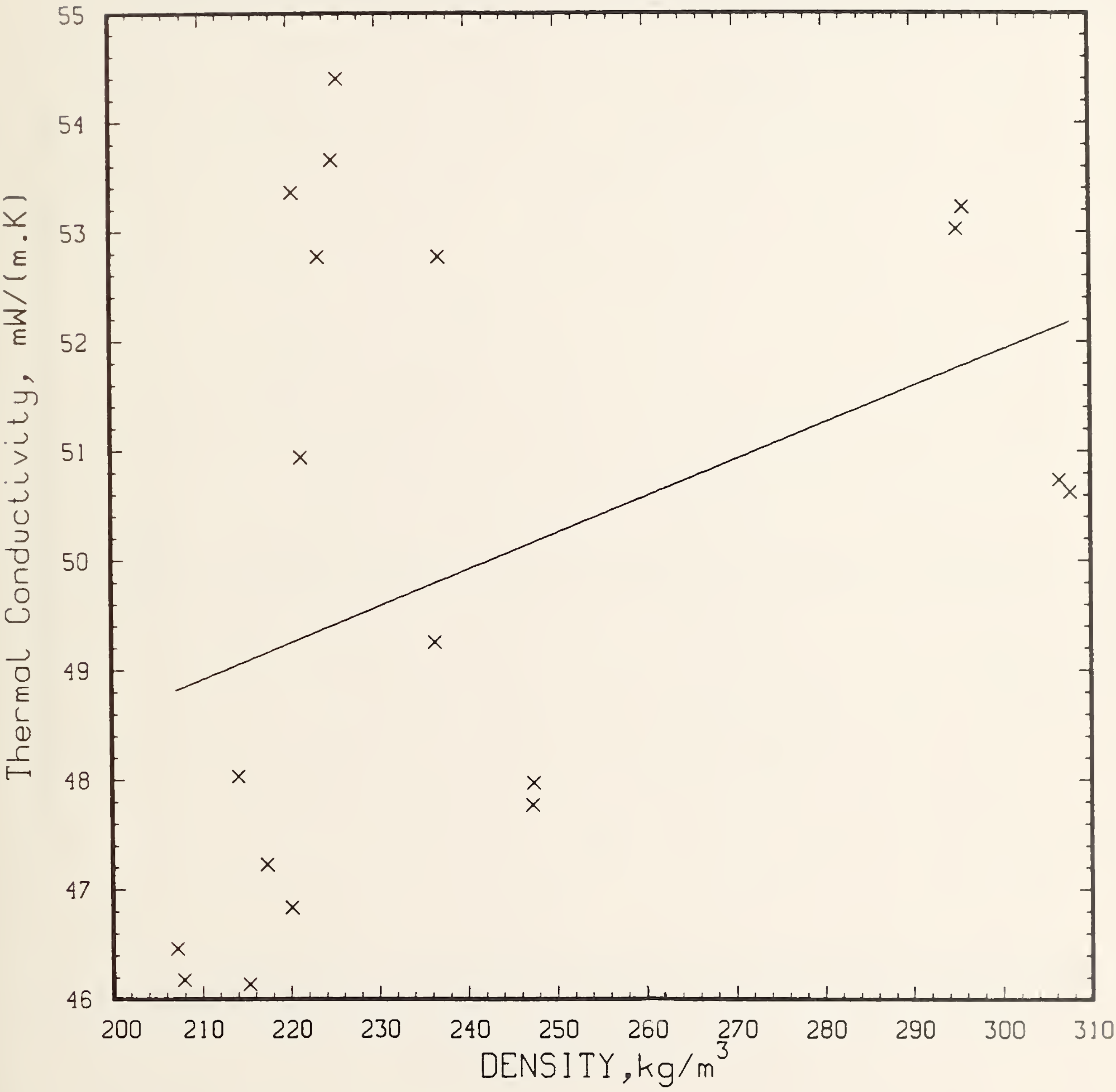

Figure 5. Thermal conductivity of fibrous alumina-silica insulation boards as measured by NBS/B, at a mean temperature of 333 K and at ambient atmospheric pressure of 84 kPa. The solid line was calculated from eq(3).

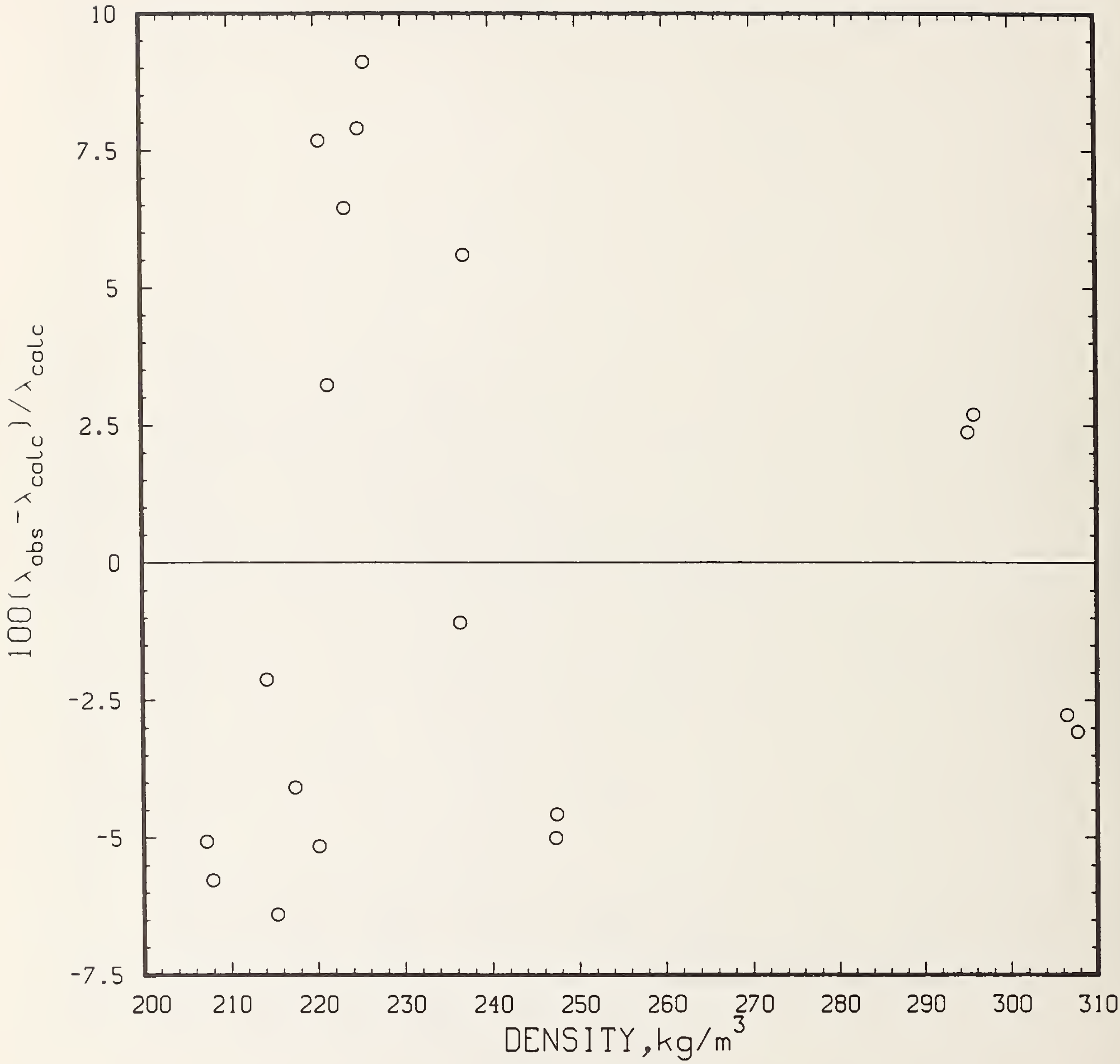

Figure 6. Deviations of the NBS thermal conductivity data from eq(3).

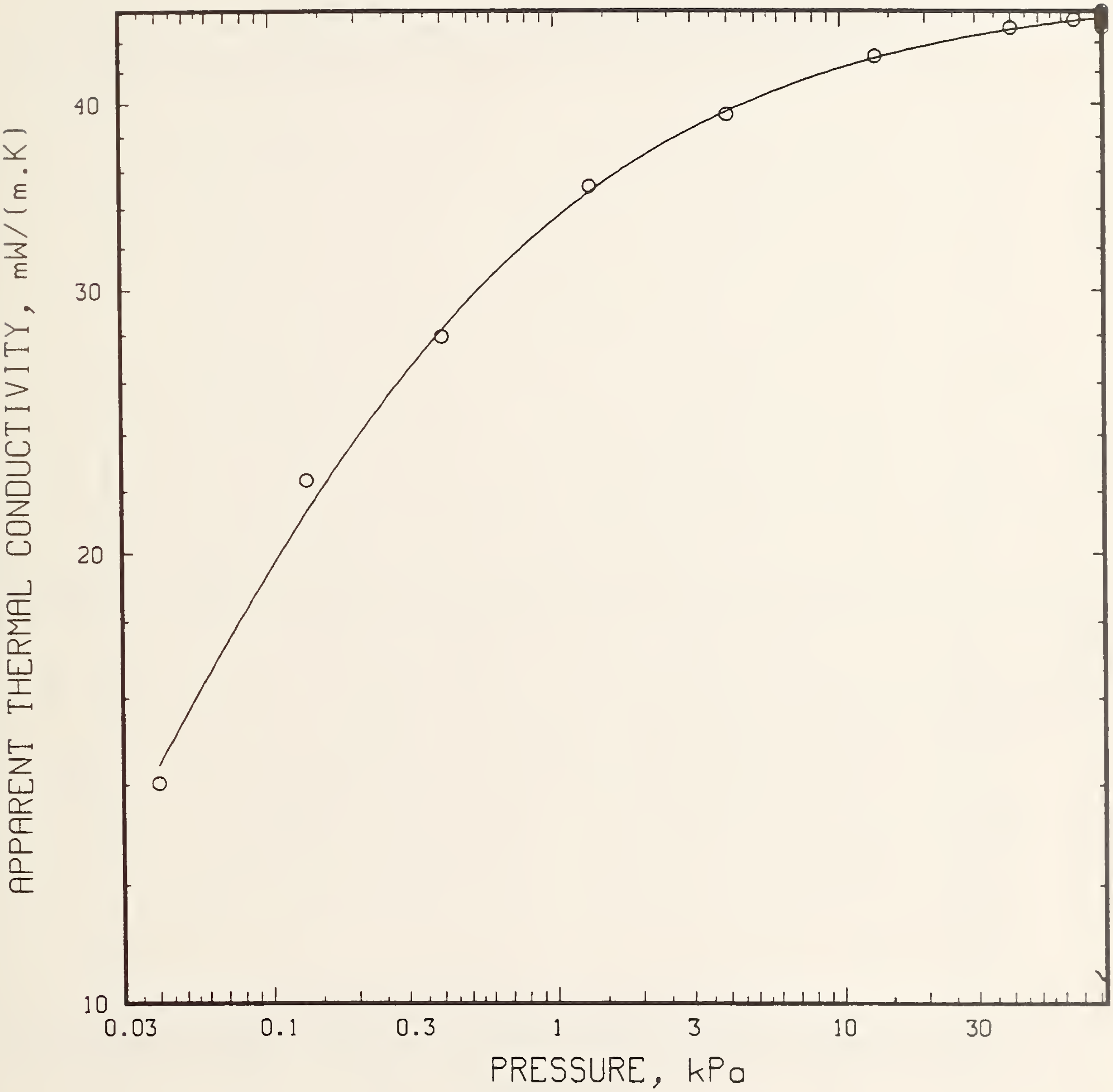

Figure 7. Thermal conductivity of fibrous alumina-silica insulation boards as measured by NBS/B, at a mean temperature of 313 K. The boards have a density of 247 kg/m³. The solid line was calculated from eq(4) with k_o = 5.75, A = 778, P_o = 0.054 kPa and n = 0.5.

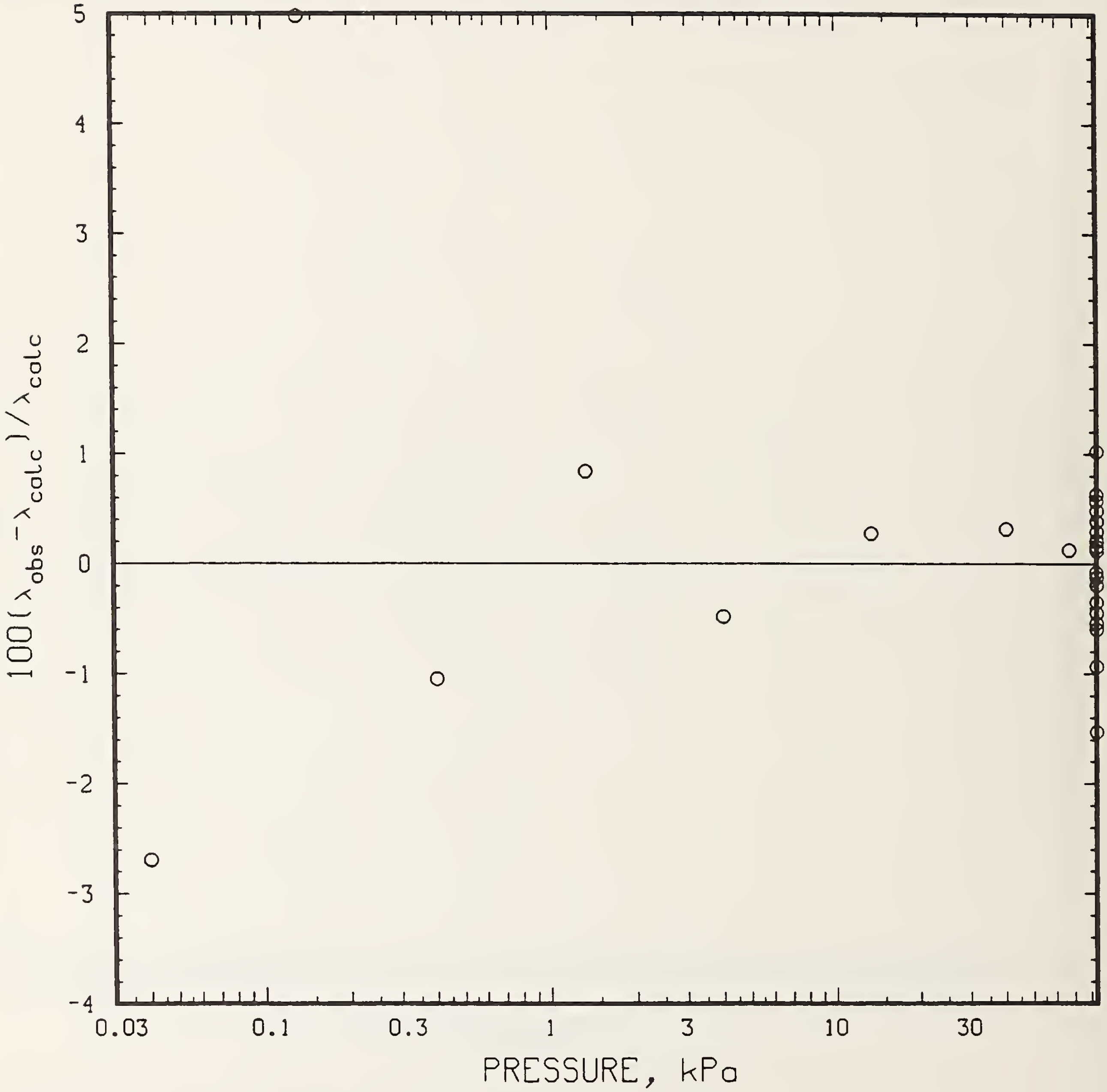

Figure 8. Deviations of the NBS thermal conductivity data from eq(4).

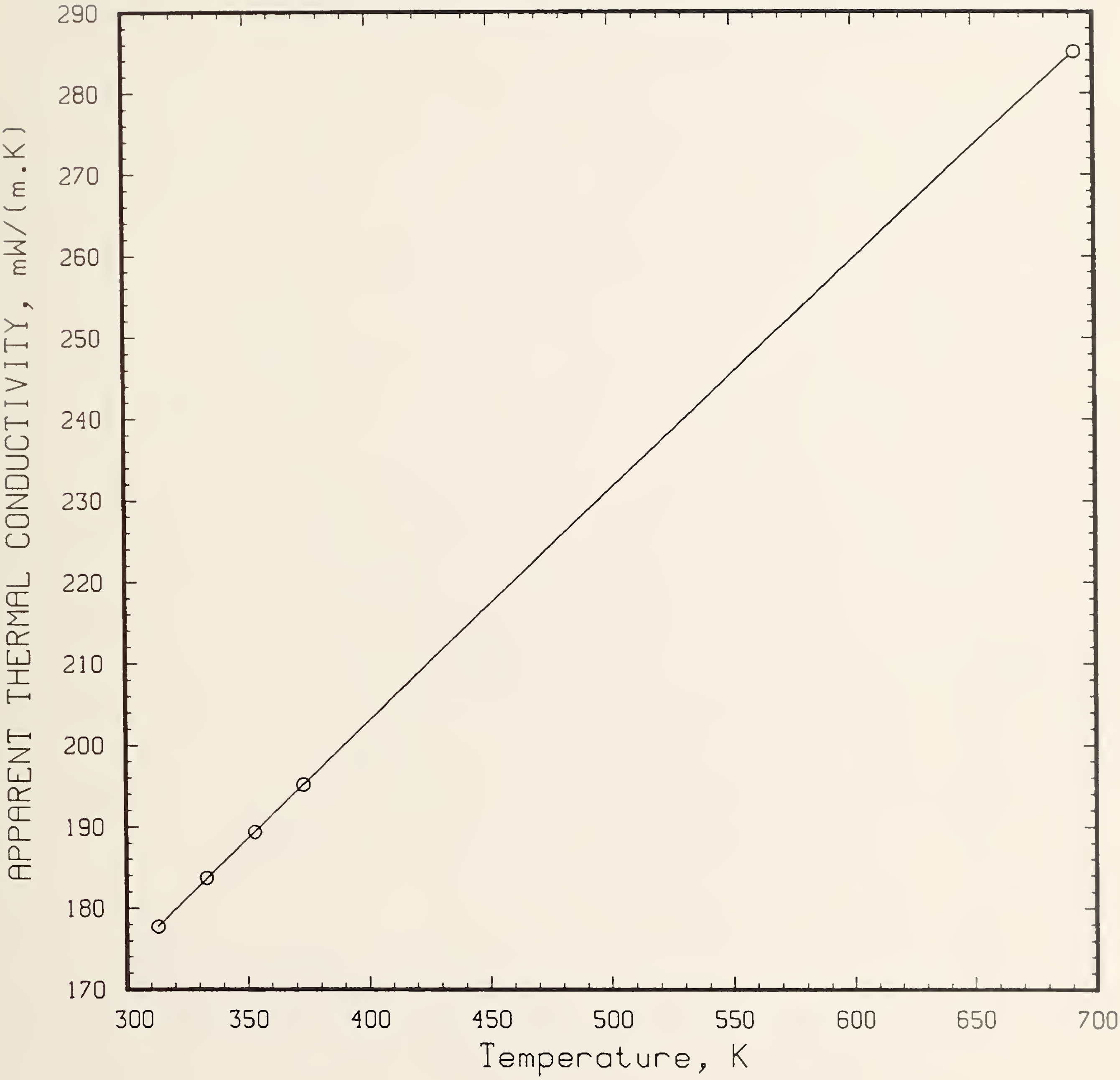

Figure 9. Thermal conductivity of fibrous alumina-silica insulation boards as measured by NBS/B, in an environment of pure helium gas. The board density is 247 kg/m^3. The solid line was calculated from eq(5).

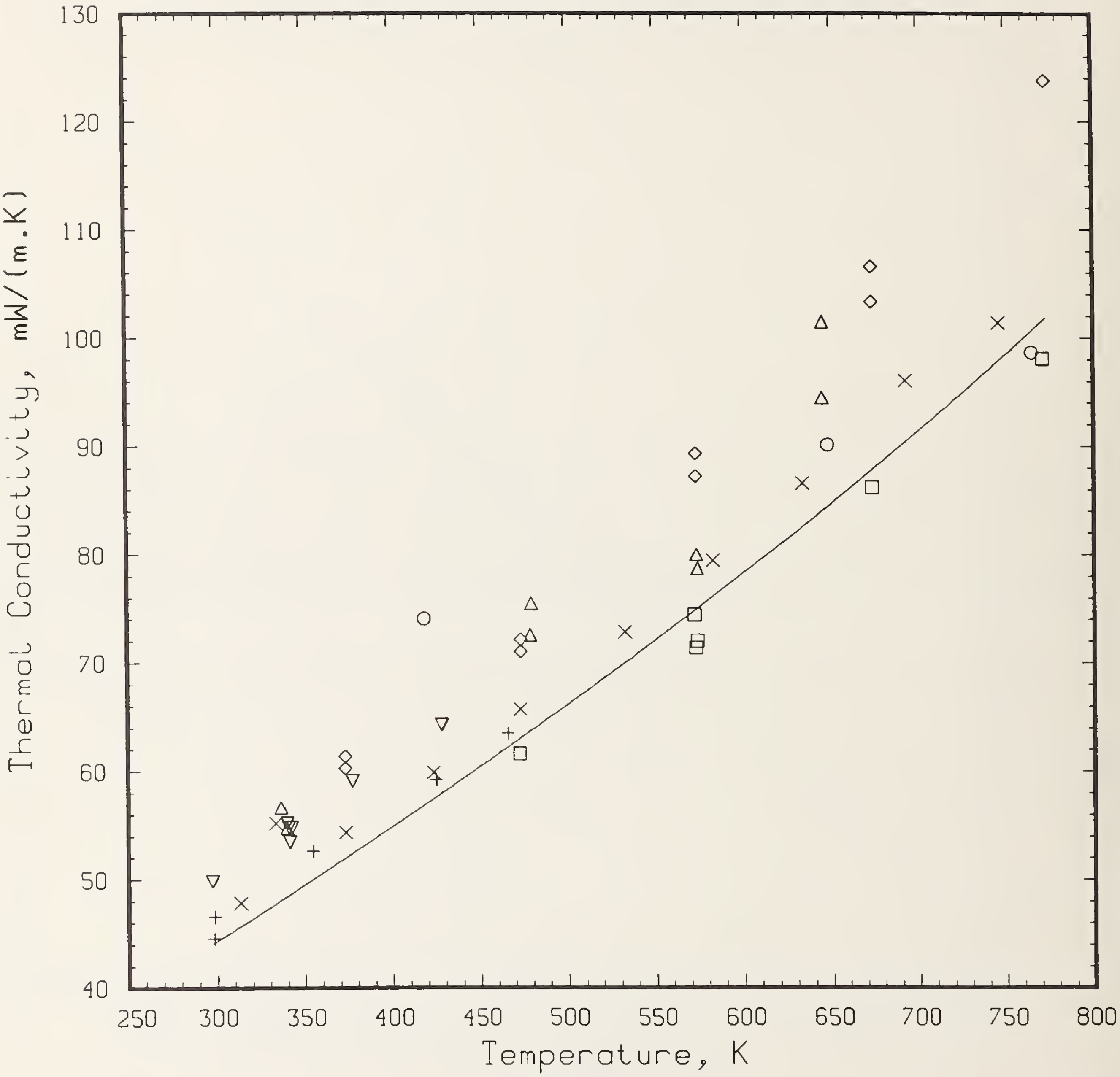

Figure 10. Round-robin measurements, by seven participating labs including NBS/B, of thermal conductivity of fibrous alumina-silica insulation boards, at the local ambient atmospheric pressure of each participating laboratory. The board density is 238 kg/m³. The solid line is calculated from eq (1).

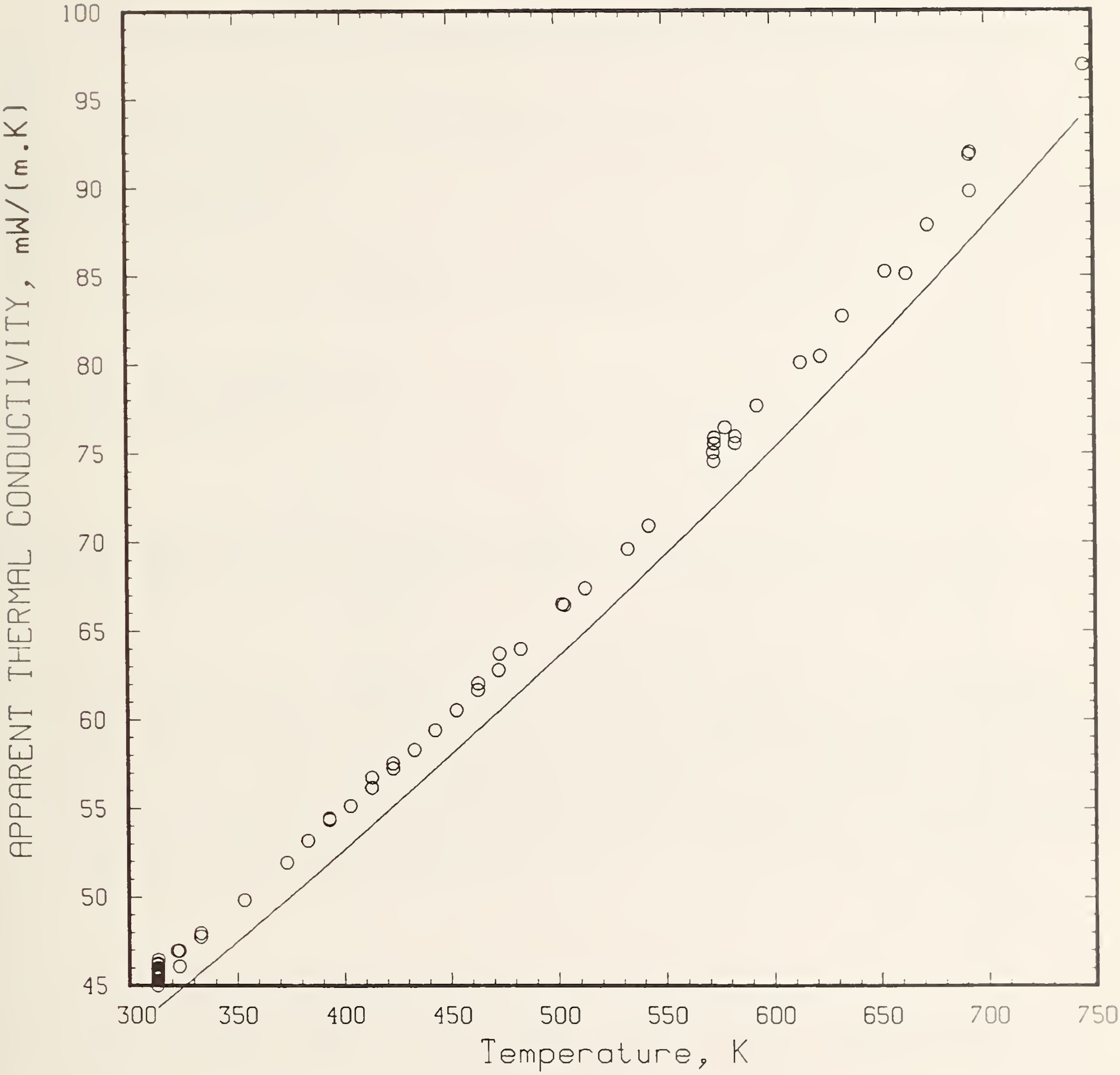

Figure 11. Thermal conductivity of fibrous alumina-silica insulation boards, as measured by the producer (solid line) at a pressure of 84 kPa, for a board with a density of 244 kg/m³. The solid line is given by eq(6). Data points shown are NBS data for a different specimen with a density of 247 kg/m³.

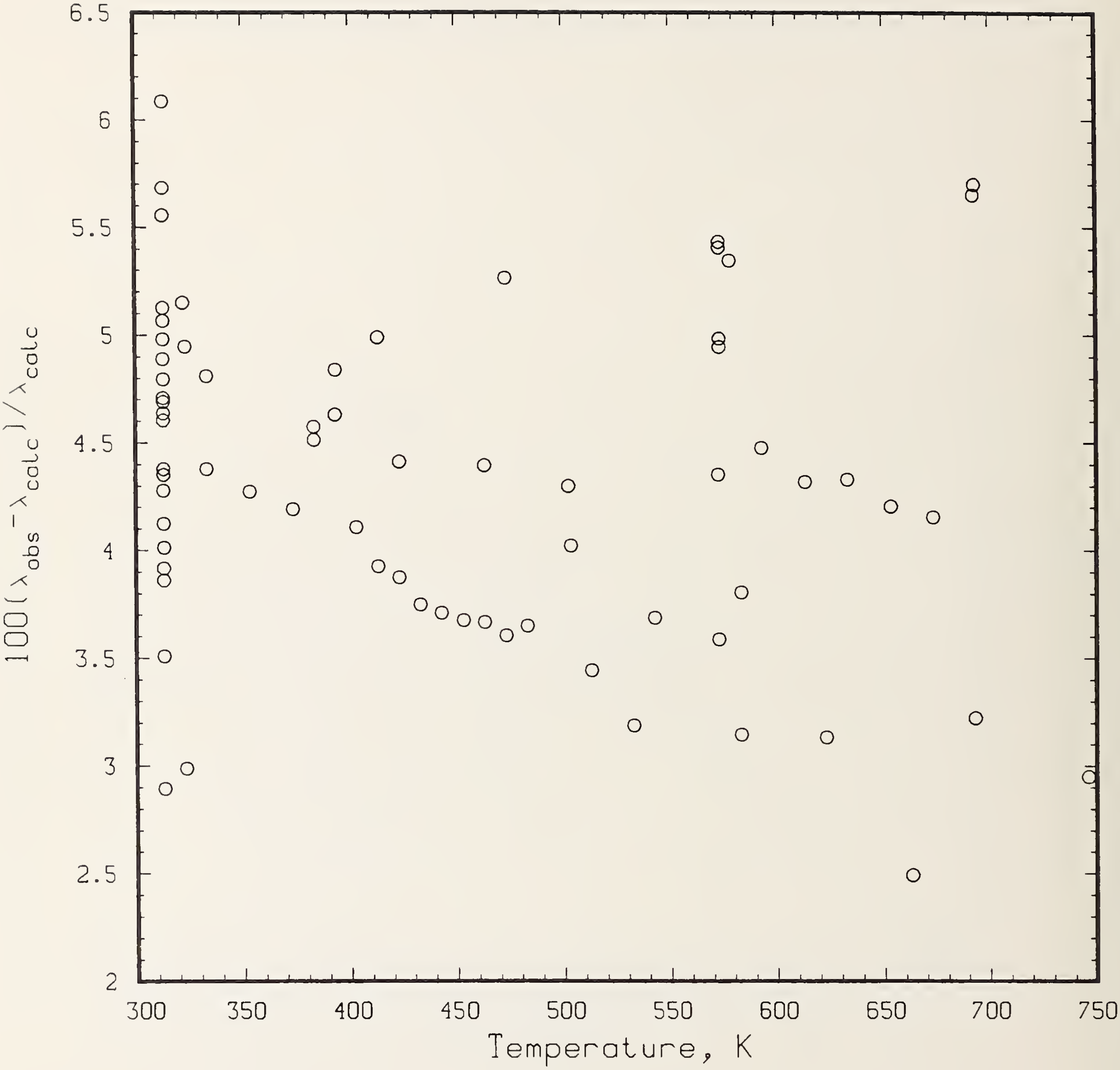

Figure 12. Deviations of the NBS/B thermal conductivity data from the producer's data, eq (6).

NBS-114A (REV. 2-8C)

U.S. DEPT. OF COMM. BIBLIOGRAPHIC DATA SHEET (See instructions)	1. PUBLICATION OR REPORT NO. NBSIR 88-3094	2. Performing Organ. Report No.	3. Publication Date June 1988

4. TITLE AND SUBTITLE

Fibrous Alumina-Silica Insulation Board as a Candidate Standard Reference Material of Thermal Resistance

5. AUTHOR(S)

Hust, Jerome G. and Smith, David R.

6. PERFORMING ORGANIZATION (If joint or other than NBS, see instructions)

NATIONAL BUREAU OF STANDARDS
DEPARTMENT OF COMMERCE
WASHINGTON, D.C. 20234

7. Contract/Grant No.

ORNL/IA-21428

8. Type of Report & Period Covered

9. SPONSORING ORGANIZATION NAME AND COMPLETE ADDRESS (Street, City, State, ZIP)

Dept. of Energy
P.O. Box X
Oak Ridge National Laboratory
Oak Ridge, TN 37830

10. SUPPLEMENTARY NOTES

☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

11. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)

Measurements of apparent thermal conductivity are reported in order to provide the basis for certifying fibrous alumina-silica insulation board as a Standard Reference Material (SRM) of thermal resistance. These data encompass ranges of temperature from 93 to 746 K, densities from 207 to 308 kg/m³, and fill-gas pressures from roughing-pump vacuum to atmospheric pressure, in environments of both air and helium. Detailed analyses and intercomparisons of previously published data are given.

12. KEY WORDS (Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)

alumina-silica board; apparent thermal conductivity; density; pressure; Standard Reference Material; temperature; thermal insulation; thermal resistance.

13. AVAILABILITY

[X] Unlimited

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☐ Order From Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402.

[X] Order From National Technical Information Service (NTIS), Springfield, VA. 22161

14. NO. OF PRINTED PAGES

36

15. Price

USCOMM-DC