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ROUND-ROBIN MEASUREMENTS OF THE APPARENT THERMAL CONDUCTIVITY OF TWO REFRACTORY INSULATION MATERIALS, USING HIGH-TEMPERATURE GUARDED-HOT-PLATE APPARATUS

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Round-Robin Measurements of the Apparent Thermal Conductivity of Two Refractory Insulation Materials, Using High-Temperature Guarded-Hot-Plate Apparatus

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This report presents the test results and analysis of round-robin measurements of apparent thermal conductivity for two kinds of refractory insulation board using high-temperature guarded-hot-plate apparatus. The round robin was carried out under the sponsorship of the American Society for Testing and Materials (ASTM) Subcommittee C-16.30 on Thermal Measurements. To complete the measurement program in a timely manner the participants chose to measure different specimens, selected, however, from the same production lot. The test results for apparent thermal conductivity illustrate the interlaboratory reproducibility as well as the temperature and density dependence. The data include the temperature range from 297 to 773 K. The standard deviation is 7.4% for the 48 test results reported by seven participating laboratories for fibrous alumina-silica. The standard deviation is 8.0% for the 58 test results reported for calcium silicate.

Key words: apparent thermal conductivity; guarded-hot-plate apparatus; high-temperature; refractory thermal insulation; round robin.

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1. Introduction

During the last 20 years considerable progress has been made in developing and improving equipment and techniques for measuring the thermal resistance of thermal insulations, particularly at ambient temperatures. However, recent unpublished intercomparisons of measurements of apparent thermal conductivity obtained with the C177 test method [1] suggest that considerably larger uncertainties may exist in measurements made with apparatus designed for higher temperatures. As a consequence, a task group was formed under the auspices of the American Society of Testing and Materials, Subcommittee C-16.30, to perform a round-robin measurement program using guarded-hot-plate apparatus at temperatures between ambient and about 775 K (500°C).

Because of the urgency of the need for this information, the original plan, formulated in the fall of 1986, was to include only three laboratories in the study. However, as interest grew the task force decided in the spring of 1987 to include other laboratories, as long as they finished the measurements by July of 1987. The objective was to have the preliminary analysis completed by the 1987 fall ASTM meeting in Toronto, Canada. Such an ambitious schedule for a round robin seemed unrealistic at the time, but because of the intense interest and cooperation of the participants the schedule has been achieved.

The participants in this round robin did not measure the same specimen. Experience indicates that it usually takes a year or longer for a single specimen to make the rounds of each laboratory. Instead, round-robin specimens chosen from the same production lot of one manufacturer were distributed to the participants at the same time. This was felt by the participants to be desirable in order to obtain data for comparing the performance of the different laboratories in a timely manner.

2. Scope

This report presents the results and analysis of apparent thermal conductivity data obtained on two refractory insulation boards: calcium silicate of two nominal densities and a fibrous alumina-silica insulation. The fibrous alumina-silica is also under consideration for use as a Standard Reference Material (SRM) of thermal resistance [2].

The specimens of these materials were supplied by two of the participants. Prior to shipping the specimens to the participants, the bulk density of each specimen was measured at the National Bureau of Standards, Boulder, Colorado (NBS/B). After the specimens were measured by the participants and returned to NBS/B, the apparent thermal conductivity of each specimen was measured at 333 K using the NBS/B high-temperature guarded-hot-plate apparatus in the single-sided mode.

The plate sizes of the guarded-hot-plate apparatus used by the participants are listed in Table 1. The direction of heat flow was vertical for each of the apparatus with the exception of that having a plate diameter of 40.6 cm; for it the direction of heat flow was horizontal.

Table 1. Sizes of plates in apparatus used by seven participants in the round-robin measurement program.

Plate Size (cm)	Metered Size (cm)
61.0x61.0	30.5x30.5
40.6 dia.	20.3 dia.
30.5x35.6	15.2x15.2
30.5x30.5	15.2x15.2
25.4 dia.	12.7 dia.
25.4 dia.	10.2 dia.
20.3 dia.	10.2 dia.

3. Experimental Data

The experimental data submitted by the participants were compiled into tabular files for analysis by computer from the standardized forms provided to the participants. Data submitted in engineering units were converted to SI units for uniformity and ease of intercomparison. Tables 2 and 3 respectively contain the data supplied by the participants for apparent thermal conductivity of fibrous alumina-silica and of calcium silicate. Throughout this report the same symbol was used to represent the data from a given participant. These symbols are listed below:

Lab 1 = o   Lab 2 = △   Lab 3 = □   Lab 4 = ▽
Lab 5 = ◇   Lab 6 = +   Lab 7 = ×

4. Reference Equations and Data Analysis

For brevity, the term "thermal conductivity" will be used in place of "apparent thermal conductivity" in the following text and figures.

In the analyses below, the integral method [3] was used in fitting the equations. The deviations shown in the tables and the deviation plots are also calculated by the integral method. This was done to remove any potential inconsistency caused by the presence of both large and small temperature differences in the data set.

When fitting curves to experimental conductivity data we used weighted least-squares fits; the weighting was chosen to minimize the sum of the squares of the relative deviations, rather than the sum of the absolute deviations. This is considered to be preferable because when measuring thermal conductivity the experimentalist tends to keep the relative (percentage) errors constant.

4.1 Fibrous alumina-silica

The reference equation used to analyze the round-robin data for the fibrous alumina-silica specimens was based on measurements of thermal conductivity performed by NBS on similar specimens in conjunction with an effort to establish this material as an SRM [2]. The measurements of the candidate SRM specimens were performed on the same high-temperature guarded-hot-plate apparatus at NBS/B used in measuring the round-robin specimens. The variation of thermal conductivity with temperature for the candidate SRM specimen is

$$k = 15.13 + 0.09489\ T + 2.888\times10^{-8}\ T^3, \qquad (1)$$

where k is in mW/(m·K) and T is in K. The coefficients in eq(1) were obtained from a weighted least-squares fit of the data for a candidate SRM, for a specimen having a density of 247 kg/m³, over a range of mean temperatures from 313 to 773 K. Since the densities of the participants' round-robin specimens varied from 207 to 237 kg/m³, we assume that the dependence of thermal conductivity on temperature for the round-robin specimens should be similar to that of the SRM candidate material.

Equation (1) was fitted to the participants' uncorrected data listed in table 2, with a multiplicative coefficient determined by a weighted least-squares fit to be 1.057. These data, along with the fitted curve, eq(2), are shown in figure 1. The deviations of the data from the curve are shown in figure 2. The standard deviation of the data from the curve is 9.4%.

$$k = 1.057(15.13 + 0.09489\ T + 2.888\times10^{-8}\ T^3), \qquad (2)$$

with k defined by this correlation for T varying from 313 to 773 K.

The data shown in figures 1 and 2 contain two broad classes or components of variability, assumed to be independent. One component is due to the variability of measurement among different apparatus and associated procedures, and the other is due to variability among the specimens. It is desirable to minimize the second component (specimen variability) so that the variability can be accurately determined for the different apparatus used by the participants in the round robin. NBS measured the thermal conductivity of each round-robin specimen at a temperature of 333 K to permit correcting for the variability among specimens. The resulting data (thermal conductivity measured by NBS) are listed in table 4.

To perform these corrections, the mean value of the NBS data was first obtained. The mean value of thermal conductivity for the specimens used in the round robin (last thirteen results listed in table 4) is 49.847 mW/(m·K). Next we calculated the percentage difference between the thermal conductivity of each participant's specimen (or pair, more commonly) as measured by NBS, and the mean value of the NBS data for all specimens. These percentage corrections, listed in table 6, represent estimates of the specimen variability and were applied to the participants' reported data to remove the effect of this variability. For example, if the thermal conductivity of a given specimen, as measured by NBS, deviated by +5% from the mean value for all specimens, the value reported by the participant was corrected by dividing it by a factor of 1.05.

Equation (1), shifted by a multiplier determined from a weighted least-squares fit to be 1.082, was fitted to the corrected data. The result is

$$k = 1.082(15.13 + 0.09489\ T + 2.888\times10^{-8}\ T^3). \qquad (3)$$

with k defined by this correlation for T varying from 313 to 773 K. These corrected data, along with the curve calculated from eq(3), are shown in figure 3. The deviations of the corrected data from the curve are shown in figure 4 and listed in the last column of table 2. The standard deviation of these data from eq(3) is 7.4%, as compared to the value of 9.4% obtained with the uncorrected data.

The correction procedure is based on two assumptions: (a) the correction is independent of temperature, and (b) the correction is independent of the metered area. The first assumption appears to be approximately valid since the reported data form a family of curves that with one exception are parallel to each other. Data reported by Lab 1 are the exception. The validity of the second assumption is assessed by examining the density dependence of the NBS data at 333 K for the round-robin specimens.

The specimens used to determine the density dependence ranged in density from 207 to 308 kg/m³. A reference equation describing the dependence of thermal conductivity on density is given in reference [2]. This reference equation is

$$k = 41.89 + 0.03344\ D, \qquad (4)$$

where k is in mW/(m·K), and D is in kg/m³. The thermal conductivity data on which this relation is based were obtained on the NBS/B high-temperature guarded-hot-plate apparatus for 16 different specimens varying in density from 218 to 308 kg/m³.

The data in table 4, including the density data, used to obtain the coefficients for eq(4), are those obtained at NBS/B by measuring each of the specimens used in the round robin. These data are illustrated in figure 5. The deviations of the data from eq(4) are shown in figure 6 and listed in the last column of table 4. It was necessary to measure six additional specimens (first six lines of table 4) to obtain information on the depen-dence of thermal conductivity on density; this was not possible using only round-robin specimens because of the large scatter in the data and the limited range of density represented by the round-robin set.

The large amount of scatter in the corrected data illustrated in figures 5 and 6 is evidence that the thermal conductivity of these alumina-silica specimens is strongly affected by characteristics other than bulk density. As a consequence, the second assumption regarding uniformity over various metered areas becomes questionable. This leads to the conclusion that the 7.4% standard deviation of the corrected data may be caused both by variability among specimens as well as procedures of participating laboratories. We are unable to separate these two components at the present time.

It has been suggested that curves of thermal conductivity vs. density for this material may have considerably different slopes at different temperatures; such a conclusion is precluded here because of insufficient information obtained in this round robin and because of the scatter in the data obtained. The desire to obtain "pilot" information quickly left little time for investigating in depth many questions arising from this study. Future round robins involving this material should be planned with time enough to investigate the reasons for the scatter seen here.

4.2 Calcium silicate

A reference equation describing the dependence on temperature of the thermal conductivity for the calcium silicate specimens was obtained. It was based on measurements performed by NBS/B (Lab 7) on one specimen from the same lot from which the participants' round-robin specimens were chosen. The coefficients in eq(5) were obtained from a weighted least-squares fit of these data.

$$k = 68.48 + 0.01820\ T + 5.616\times10^{-8}\ T^3, \qquad (5)$$

where k is in mW/(m·K) and T is in K. This correlation is defined for values of T ranging from 333 to 701 K.

Equation (5) was fitted to the participants' uncorrected data listed in table 3, with a multiplicative coefficient determined by a weighted least-squares fit to be 1.032. These data, along with the fitted curve, eq(6), are shown in figure 7. The deviations of the data from the curve are shown in figure 8. The standard deviation of the data from the curve is 7.9%.

$$k = 1.032(68.48 + 0.01820\ T + 5.616\times10^{-8}\ T^3), \qquad (6)$$

with k defined by this correlation for T varying from 313 to 773 K. The data shown in figures 7 and 8 contain two components of variability. One is due to the apparatus measurement variability, and the other is due to specimen variability. It is desirable to minimize the second component so that the variability can be accurately determined for the different apparatus used by the round-robin participants. NBS/B measured the thermal conductivity of each round-robin specimen to permit correcting for the variability among specimens. The resulting data are listed in table 3. The same method used to perform the corrections for the previously discussed alumina-silica specimens was used at this point to obtain the corrections for the calcium silicate.

The mean value of thermal conductivity for the specimens used in the round robin (results listed in table 5) is 74.991 mW/(m·K). A value was calculated for the percentage difference between the thermal conductivity, measured by NBS/B, of each specimen (or pair) used by each participant and the mean value for the NBS/B data for all specimens. These percentage corrections, listed in table 6, representing estimates of the specimen variability, were applied to the reported data to remove the effect of this variability.

Equation (6), shifted by a multiplier determined by a weighted least-squares fit to be 1.033, was fitted to the corrected data. The result is

$$k = 1.033(68.48 + 0.01820\ T + 5.616\times10^{-8}\ T^3), \qquad (7)$$

defined for T varying from 313 to 773 K.

These corrected data along with the curve calculated from eq(7) are shown in figure 9. The deviations of the data from the curve are shown in figure 10 and listed in the last column of table 3. The standard deviation of these data from the reference curve is 8.0%.

The correction procedure is based on two assumptions: (a) the correction is independent of temperature, and (b) the correction is independent of the metered area. The first assumption appears to be reasonably valid since the reported data form a family of curves that are parallel to each other, within their scatter with one exception. Data from Lab 5 cross the fitted line as temperature increases, but otherwise lie within the scatter of the band of data.

The validity of the second assumption is assessed by examining the density dependence of the NBS/B data at 333 K for the round-robin specimens. The specimens used in the round robin study ranged in density from 324 to 446 kg/m^3. A reference equation describing the dependence of thermal conductivity on density was obtained. The reference equation chosen is

$$k = 44.37 + 0.07694\ D, \qquad (8)$$

where k is in $mW/(m\cdot K)$, and D is in kg/m^3 and varies over the range from 324 to 446 kg/m^3.

The data in table 5 used to obtain the coefficients for eq(8) are those measured at NBS/B on each of the specimens used in the round robin. These data are illustrated in figure 11. The deviations of the data from eq(8) are shown in figure 12 and listed in the last column of table 5.

From the amount of scatter illustrated in figures 11 and 12, it is suggested that the thermal conductivity of these calcium silicate specimens is affected mainly by their bulk density and not appreciably by other characteristics as were the specimens of fibrous alumina-silica. The second assumption involves the implicit assumption that density does not vary appreciably with metered area.

To shed light on this question, the variation of density within one large, square specimen of calcium silicate was measured. Its edges originally measured 61 cm. It had been cut into four square pieces measuring 25.4 cm on each side, four rectangular pieces 25.5 cm by 9.8 cm, and one square piece measuring 10 cm on each side. The densities of these pieces ranged from 443.5 to 449.0 kg/m^3, with a mean density of 447.4 kg/m^3 and standard deviation of 0.6%. This standard deviation in density corresponds to a standard deviation of about 0.3% in apparent thermal conductivity, according to eq(8) or figure 11. This suggests that only a small portion of the 8% standard deviation of the corrected data is caused by residual variations in density of the specimens.

It is puzzling that the standard deviation for the corrected data, 8.0%, is not less than that of the uncorrected data, 7.9%. It is known that calcium silicate insulation board contains not only adsorbed moisture (as do all porous materials), but also water of crystallization. Adsorbed moisture can be driven off reversibly by heating a specimen to a temperature somewhat above 100°C. Water of crystallization, on the other hand, is chemically bonded and requires higher temperatures to remove; its removal is an irreversible process. This means that the thermal conductivity obtained for this material could depend on the history of the material: its past temperature and environmental humidity could influence the amount of adsorbed moisture present as well as the amount of water of crystallization.

The fact that the correction procedure does not bring the round-robin data closer together may be evidence of variation among different preparation and measurement procedures used by the partipants. The mean value of thermal conductivity measurements on the specimens by NBS, 75 mW/(m·K) at 333 K, differed from the mean value by the participants. This mean value can be estimated from the fitted curve in figure 9 to be approximately 79 mW/(m·K) at 333 K, greater by about 5% than the mean of the NBS measurements.

While specific instructions for preparation of the specimens were given to the participants in the round robin, some participants lacked the equipment required to comply with all the instructions regarding conditioning of the specimens. This might explain some of the scatter in the data about the fitted curve. In this regard, the purpose of the round robin may have been fulfilled: to compare the best efforts of the participating laboratories, as well as to learn how suitable either material would be as an SRM for high temperatures.

Figures 7 through 10 show that both the reported and the corrected data from one lab (squares) for calcium silicate are in considerable disagreement with the other data. For comparison, the standard deviation of the subset of data defined by omitting the results on calcium silicate for Lab 3 was calculated; it is 6.0% for uncorrected data and 5.8% for the corrected data.

5. Summary and Conclusions

Round-robin measurements of thermal conductivity are presented for two refractory insulation materials at temperatures from 297 to 773 K. Reference equations are given describing the temperature and density dependencies of the thermal conductivity of the two materials. These equations are used to analyze the interlaboratory measurement reproducibility of the seven laboratories that participated in the round robin.

The reproducibility, as measured by two times the standard deviation of the corrected data, is 15% and 16% for fibrous alumina-silica and calcium silicate, respectively. As was suggested by previous unpublished data, this is considerably larger than the 2% reproducibility observed with ambient-temperature apparatus [4]. However, the variability of the corrected data for alumina-silica probably contains a significant portion due to residual specimen variability. This excessive residual specimen variability is a consequence of the tight schedule established for this round robin. Discussions with the participants established, however, that the round robin provided useful initial information. Any future high-temperature round robins should be preceded by careful fabrication and selection of the specimens to assure their greater uniformity and thermal stability. Even though the different laboratories had guarded-plate apparatus of different sizes and shapes, it may be possible to arrange a procedure so that several labs measure the same specimen, as is usual.

After the data from the different labs were corrected there remained an equally large scatter about the fitted correlation and inconsistent dependences with temperature; this indicates that a high-temperature SRM for thermal resistance could be very useful to laboratories measuring apparent thermal conductivity at temperatures significantly higher than room temperature.

We gratefully acknowledge the generosity of two companies for donating the insulation specimens for this round robin: Manville Corporation of Denver, CO, for donating the alumina-silica specimens, and PABCO of Fruita, CO, for donating the calcium silicate specimens. We also acknowledge the time and effort spent by the participating laboratories: CertainTeed Corporation, Blue Bell, PA; Dynatech R/D Company, Cambridge, MA; Fiberglas Canada, Inc., Sarnia, Ontario; Manville Corporation, Denver, CO; National Bureau of Standards, Boulder, CO; Owens/Corning Fiberglas Corporation, Granville, OH; and PABCO, Fruita, CO.

6. References

[1] ASTM Standard Test Method C177 for STEADY-STATE HEAT FLUX MEASUREMENTS AND THERMAL TRANSMISSION PROPERTIES BY MEANS OF THE GUARDED-HOT-PLATE APPARATUS, ANNUAL BOOK OF ASTM STANDARDS, Vol. 04.06, pp. 21-36 (ASTM, Philadelphia, 1986)

[2] Hust, Jerome G. and Smith, David R., Fibrous alumina-silica insulation board as a candidate Standard Reference Material, to be published as an NBSIR

[3] Hust, J. G. and Lankford, A. B., Comments on the measurement of thermal conductivity and presentation of a thermal conductivity integral method, International Journal of Thermophysics, Vol. 3, No. 1, pp. 67-77, 1982

[4] Hust, J. G. and Pelanne, C. M., Round robins on the apparent thermal conductivity of low-density glass fiber insulations using guarded hot plate and heat flow meter apparatus, U.S. Nat. Bur. Stand. NBSIR 85-3026 (1985)

Table 2. Round-robin thermal conductivity data for fibrous alumina-silica.

Lab. No.	Specimen Ident.	Test Density (kg/m3)	High Temp. (K)	Low Temp. (K)	Mean Temp. (K)	Thermal Conduct. (mW/m.K)	Pct. Dev.
1	17A20	232.3	672.039	623.150	647.594	85.019	-1.34
1	17A20	232.3	787.039	742.761	764.900	93.089	-9.37
1	17A20	232.3	443.650	392.706	418.178	69.889	20.28
2	00A24	237.7	361.533	311.283	336.408	55.997	8.78
2	00A24	237.7	504.844	453.744	479.294	74.601	9.39
2	00A24	237.7	669.956	619.522	644.739	100.265	11.58
2	00A24	237.7	598.933	547.856	573.394	79.039	-1.40
2	00A22	241.7	364.872	314.644	339.758	55.954	4.35
2	00A22	241.7	504.444	453.450	478.947	74.154	5.21
2	00A22	241.7	669.800	619.578	644.689	96.518	3.88
2	00A22	241.7	599.456	548.217	573.836	80.436	-3.04
3	05A07	218.2	497.761	447.261	472.511	58.216	-9.59
3	05A07	218.2	597.039	547.317	572.178	70.321	-8.05
3	05A07	218.2	697.594	648.650	673.122	81.417	-9.27
3	05A07	218.2	796.261	746.372	771.317	92.656	-10.73
3	05A07	218.2	623.150	522.817	572.983	67.439	-11.97
3	05A07	218.2	673.539	474.428	573.983	68.015	-11.51
4	02A12	225.9	308.094	286.317	297.206	53.605	4.56
4	02A12	225.9	354.928	324.872	339.900	59.369	5.24
4	02A12	225.9	365.317	315.761	340.539	58.937	4.32
4	02A12	225.9	392.539	292.206	342.372	58.937	3.87
4	02A12	225.9	427.650	326.594	377.122	63.548	4.12
4	02A12	225.9	528.039	327.483	427.761	69.168	2.38
4	02A12	225.9	552.983	303.372	428.178	69.024	1.97
4	02A12	225.9	391.094	291.372	341.233	57.496	1.58
5	23A25	219.6	393.150	353.150	373.150	57.000	8.97
5	23A25	219.6	493.150	453.150	473.150	67.000	5.65
5	23A25	219.6	593.150	553.150	573.150	83.000	10.16
5	23A25	219.6	693.150	653.150	673.150	96.000	8.76
5	23A25	219.6	793.150	753.150	773.150	115.000	12.34
5	23A25	219.6	423.150	323.150	373.150	56.000	7.01
5	23A25	219.6	523.150	423.150	473.150	66.000	4.03
5	23A25	219.6	623.150	523.150	573.150	81.000	7.46
5	23A25	219.6	723.150	623.150	673.150	99.000	12.10
6	06A10	224.3	310.983	286.206	298.594	50.003	-2.64
6	06A10	224.3	422.706	286.817	354.761	56.487	-2.95
6	06A10	224.3	561.983	287.706	424.844	63.548	-5.45
6	06A10	224.3	643.539	288.372	465.956	68.159	-6.36
6	06A10	224.3	310.428	286.261	298.344	47.841	-6.80
7	21A30	237.0	343.294	323.089	333.192	52.767	6.70
7	DXA30	247.0	323.055	303.134	313.095	45.769	-3.22
7	28A30	247.2	383.227	363.068	373.148	51.939	-3.50
7	28A30	247.0	463.157	383.201	423.179	57.251	-3.72
7	28A30	246.8	562.750	383.205	472.978	62.786	-3.91
7	28A30	246.5	662.267	402.976	532.622	69.619	-4.23
7	28A30	246.3	603.096	562.959	583.028	75.939	-3.62
7	28A30	246.1	653.224	613.126	633.175	82.732	-3.10
7	28A30	245.8	712.137	672.899	692.518	91.822	-1.83
7	28A30	245.6	763.373	728.645	746.009	96.895	-4.32

Table 3. Round-robin thermal conductivity data for calcium silicate.

Lab. No.	Specimen Ident.	Test Density (kg/m3)	High Temp. (K)	Low Temp. (K)	Mean Temp. (K)	Thermal Conduct. (mW/m.K)	Pct. Dev.
1	6A8M12	443.7	757.539	729.872	743.706	119.891	8.76
1	6A8M12	443.7	648.261	617.261	632.761	108.507	9.81
1	6A8M12	443.7	529.983	495.372	512.678	98.564	10.08
1	6A8M12	443.7	430.650	392.539	411.594	90.639	8.19
2	1M12	403.2	376.372	327.078	351.725	89.529	11.95
2	1M12	403.2	503.289	453.111	478.200	96.706	12.22
2	1M12	403.2	669.583	619.567	644.575	108.911	10.55
2	1M12	403.2	598.967	548.422	573.694	95.394	3.02
2	9L12	320.2	377.528	326.678	352.103	78.621	7.79
2	9L12	320.2	503.361	452.367	477.864	86.374	9.93
2	9L12	320.2	669.739	619.789	644.764	101.403	12.85
2	9L12	320.2	598.656	547.867	573.261	85.336	1.10
3	5A7M12	450.1	497.650	446.650	472.150	70.177	−19.50
3	5A7M12	450.1	596.650	548.594	572.622	73.491	−21.79
3	5A7M12	450.1	694.928	647.317	671.122	84.875	−17.28
3	5A7M12	450.1	795.094	747.317	771.206	92.944	−18.29
4	1A2M24	440.5	308.039	286.317	297.178	81.849	.18
4	1A2M24	440.5	354.428	323.428	338.928	86.748	4.13
4	1A2M24	440.5	365.594	316.039	340.817	85.740	2.82
4	1A2M24	440.5	391.539	292.150	341.844	85.740	2.72
4	1A2M24	440.5	427.483	326.761	377.122	89.054	4.76
4	1A2M24	440.5	528.428	327.817	428.122	91.504	4.30
4	1A2M24	440.5	552.094	305.039	428.567	91.359	3.95
4	1A2M24	440.5	391.539	291.706	341.622	84.154	.83
4	1A2L12	358.8	307.817	286.039	296.928	75.076	.87
4	1A2L12	358.8	354.594	324.983	339.789	79.111	4.20
4	1A2L12	358.8	365.761	315.872	340.817	78.679	3.57
4	1A2L12	358.8	391.150	291.372	341.261	78.390	3.12
4	1A2L12	358.8	428.150	326.761	377.456	81.561	5.30
4	1A2L12	358.8	527.817	327.761	427.789	85.019	6.40
4	1A2L12	358.8	552.594	303.317	427.956	84.587	5.68
4	1A2L12	358.8	391.317	292.483	341.900	76.661	.81
5	2A4M12	393.8	393.150	353.150	373.150	75.000	−6.67
5	2A4M12	393.8	493.150	453.150	473.150	88.000	3.11
5	2A4M12	393.8	593.150	553.150	573.150	99.000	7.64
5	2A4M12	393.8	693.150	653.150	673.150	110.000	9.36
5	2A4M12	393.8	793.150	753.150	773.150	126.000	12.98
5	2A4M12	393.8	423.150	323.150	373.150	74.000	−7.96
5	2A4M12	393.8	523.150	423.150	473.150	85.000	−.47
5	2A4M12	393.8	623.150	523.150	573.150	95.000	3.22
5	2A4M12	393.8	723.150	623.150	673.150	108.000	7.29
6	3A9M12	405.3	308.317	286.261	297.289	73.779	−5.71
6	3A9M12	405.3	444.206	287.150	365.678	79.543	−1.78
6	3A9M12	405.3	570.428	288.039	429.233	83.866	−.53
6	3A9M12	405.3	308.539	286.261	297.400	73.203	−6.45
7	4M24AC	443.4	712.221	676.060	694.141	99.568	−4.52
7	4M24AC	443.4	709.587	675.964	692.776	100.543	−3.45
7	4M24AC	446.2	343.094	323.193	333.144	76.586	−4.24
7	4M24AC	446.0	373.165	343.174	358.170	77.854	−3.86
7	4M24AC	445.8	413.320	373.226	393.273	79.620	−3.52
7	4M24AC	445.3	472.770	433.164	452.967	82.649	−3.38
7	4M24AC	444.6	572.831	523.279	548.055	88.069	−3.81
7	4M24AC	444.0	649.749	599.268	624.509	92.888	−4.87
7	4M24AC	444.0	674.786	575.638	625.212	92.408	−5.48
7	4M24AC	443.9	722.322	535.621	628.972	94.149	−4.25
7	4M24AC	443.3	714.678	687.533	701.106	101.322	−3.51
7	4M24AC	444.6	572.532	523.148	547.840	87.593	−4.31
7	4M24AC	446.2	343.097	323.136	333.117	75.778	−5.24

Table 4. Test results for each of the round-robin alumina-silica specimens as obtained by NBS at a mean temperature of 333 K.

Specimen Ident.	Test Density (kg/m3)	High Temp. (K)	Low Temp. (K)	Mean Temp. (K)	Thermal Conduct. (mW/m.K)	Pct. Dev.
3-28/30	247.3	343.187	323.111	333.149	47.771	-5.00
3-28/30	247.4	343.207	323.167	333.187	47.973	-4.57
II-35	295.1	343.197	323.181	333.189	53.019	2.38
II-36	295.8	343.108	323.179	333.144	53.220	2.70
IV-1	306.5	343.314	323.067	333.191	50.737	-2.76
IV-3	307.7	343.376	323.117	333.247	50.622	-3.08
CBRD-21	237.0	343.294	323.089	333.192	52.767	5.59
CBRD-22	221.4	343.399	323.157	333.278	50.941	3.23
CBRD-24	236.4	343.316	323.063	333.190	49.257	-1.09
CBRD-12	225.7	343.232	323.107	333.170	54.394	9.11
CBRD-02	223.4	343.468	323.028	333.248	52.766	6.45
CBRD-10	225.0	343.440	323.069	333.255	53.653	7.90
CBRD-06	220.5	343.169	323.126	333.148	53.359	7.68
CBRD-17	220.1	343.154	323.113	333.134	46.837	-5.15
CBRD-20	217.4	343.341	323.160	333.251	47.229	-4.09
CBRD-23	207.2	343.179	323.082	333.131	46.464	-5.07
CBRD-25	207.9	343.224	323.076	333.150	46.176	-5.77
CBRD-05	214.2	343.506	323.168	333.337	48.033	-2.12
CBRD-07	215.3	343.309	323.003	333.156	46.140	-6.39

Table 5. Test results for each of the round-robin calcium silicate specimens as obtained by NBS at a mean temperature of 333 K.

Specimen Ident.	Test Density (kg/m3)	High Temp. (K)	Low Temp. (K)	Mean Temp. (K)	Thermal Conduct. (mW/m.K)	Pct. Dev.
4M24	446.2	343.097	323.136	333.117	75.778	-3.86
9L12	324.1	343.316	323.236	333.276	68.456	-1.24
1M12	386.2	343.129	323.144	333.137	75.075	1.32
2M12	404.5	343.245	323.145	333.195	75.177	-.42
4M12	404.5	343.252	323.151	333.202	74.036	-1.97
2M24	426.9	343.150	323.131	333.141	79.006	2.27
1M24	425.4	343.137	323.138	333.138	78.408	1.67
2L12	354.9	343.291	323.111	333.201	71.057	-.87
1L12	354.4	343.139	323.125	333.132	72.357	.99
9M12	403.4	343.296	323.084	333.190	74.631	-1.04
3M12	400.5	343.149	323.106	333.128	76.108	1.21
8M12	405.1	343.114	323.097	333.106	75.701	.21
6M12	409.8	343.125	323.126	333.126	76.554	.85
5M12	409.3	343.149	323.140	333.145	75.785	-.10
7M12	412.1	343.225	323.093	333.159	76.731	.85

Table 6. Percentage Corrections Applied to Reported Data to Remove Effect of Specimen Variability

	Percentage Correction	
Lab No.	Alumina-Silica	Calcium Silicate
1	+5.65	-1.52
2*	-2.19 +1.19	+8.71 -0.11
3	+5.54	-1.69
4*	-7.48	+4.38 -4.96
5	+7.08	+0.51
6	-7.33	-0.51
7	+4.39	-1.05

*Two separate specimens were measured by lab 2 (both types of specimen) and by lab 4 (calcium silicate only)

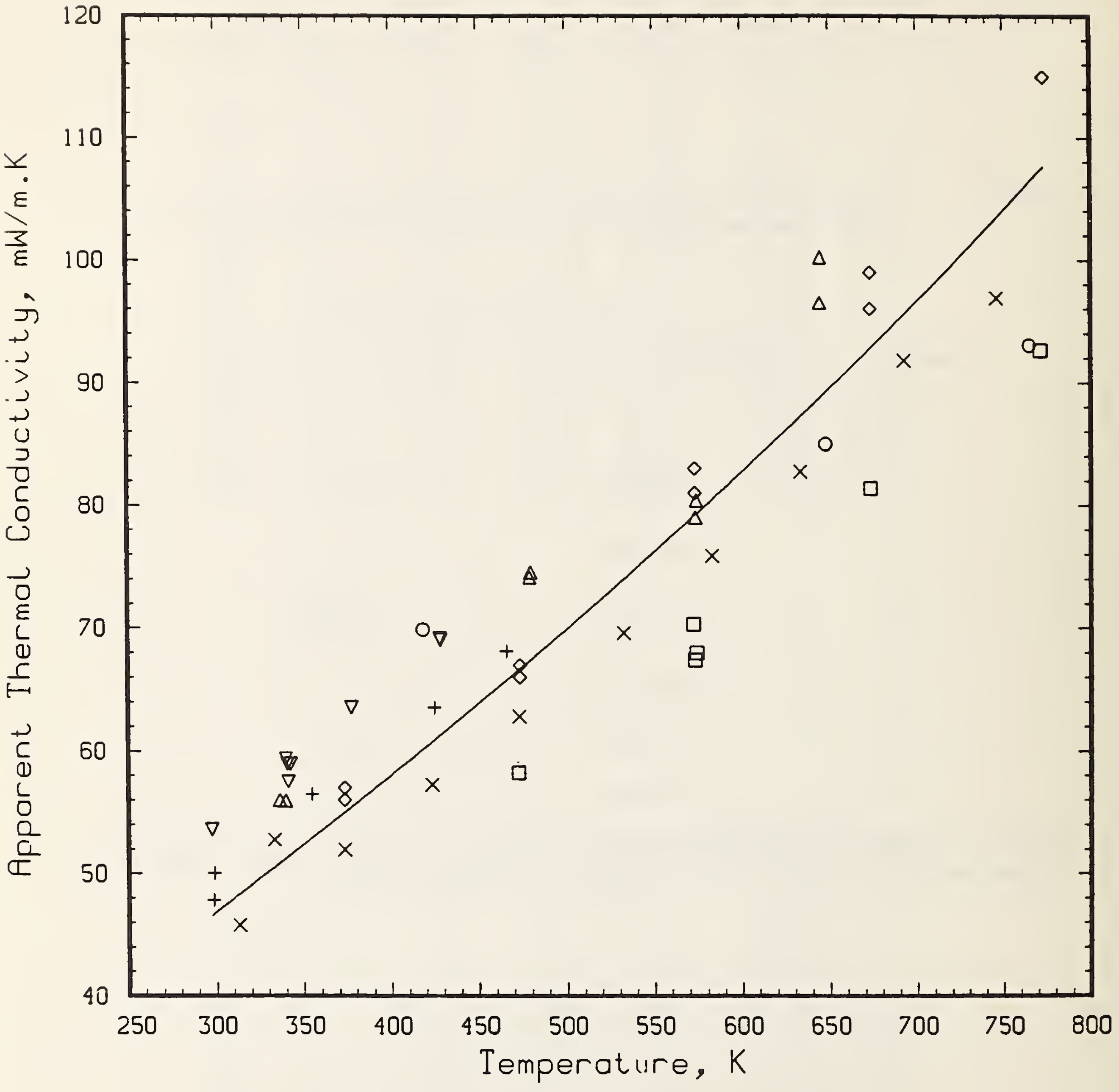

Figure 1. Thermal conductivity of round-robin specimens of fibrous alumina-silica; test densities range from 218 to 247 kg/m³. The solid curve is calculated from eq (2).

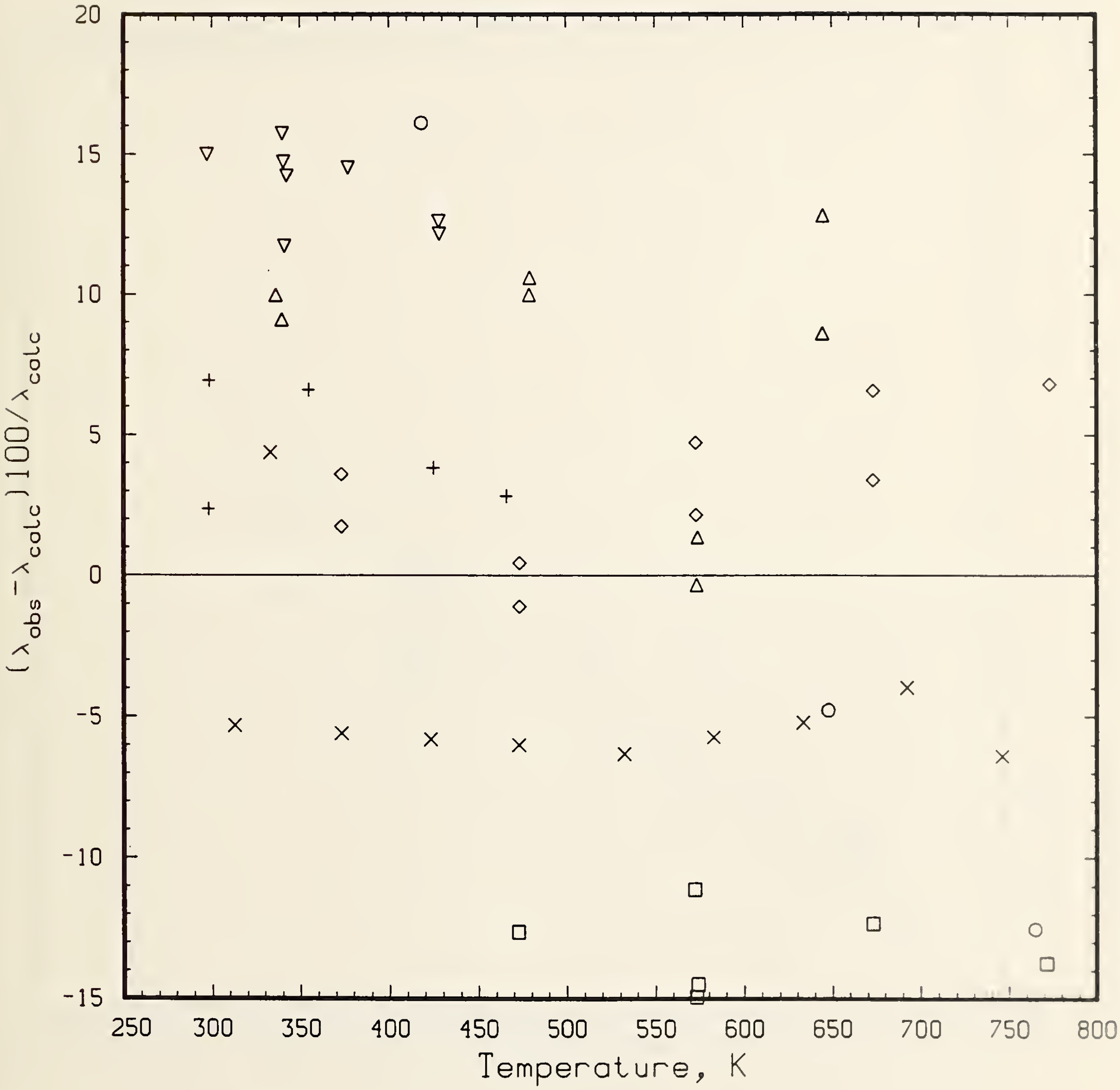

Figure 2. Deviations of thermal conductivity round-robin test results from values calculated with eq(2) for fibrous alumina-silica.

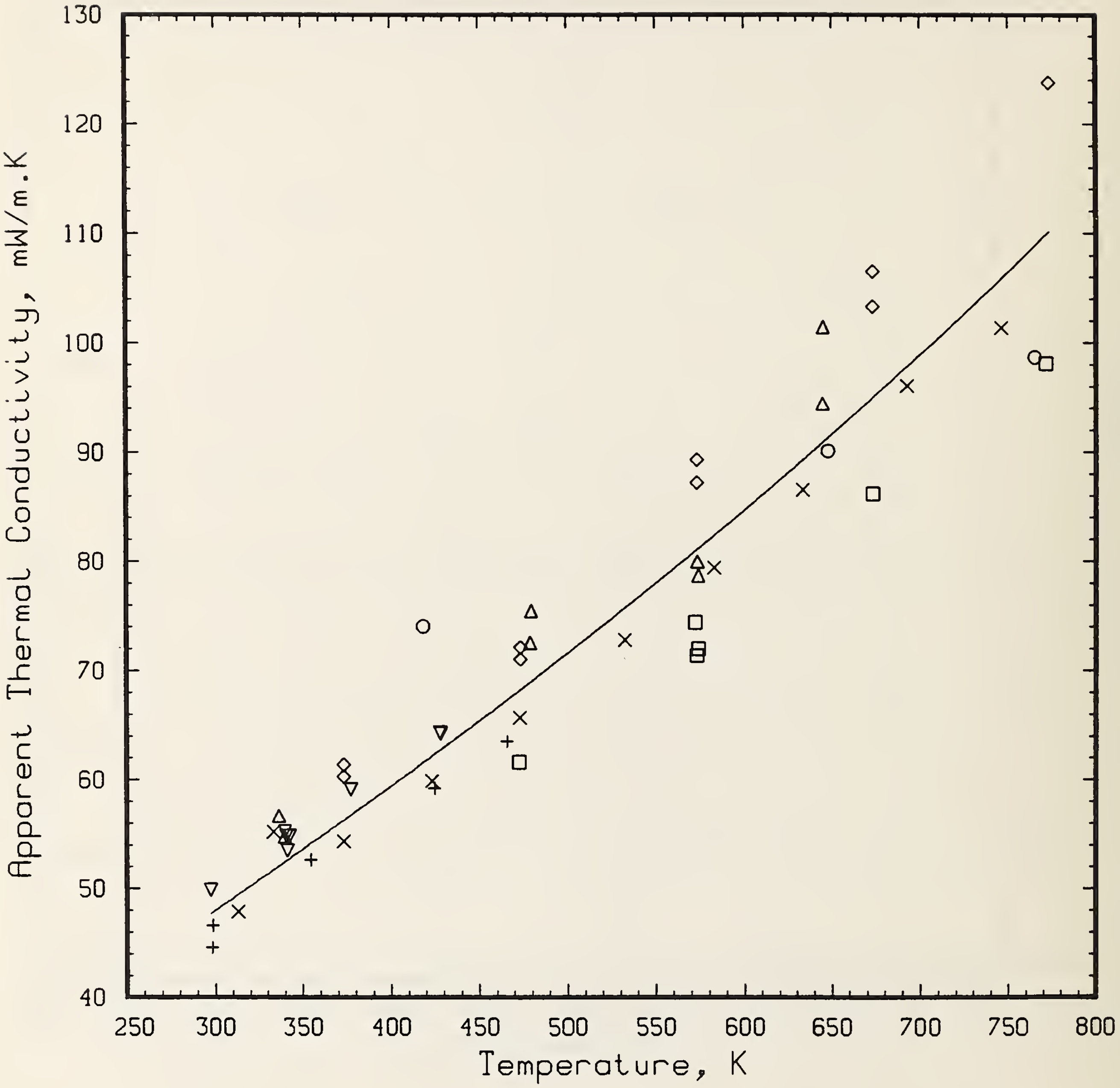

Figure 3. Thermal conductivity round-robin test results, corrected for deviation of apparent thermal conductivity from mean thermal conductivity, 49.9 mW/m.K, for fibrous alumina-silica; test densities range from 218 to 247 kg/m³. The solid curve is calculated from eq (3).

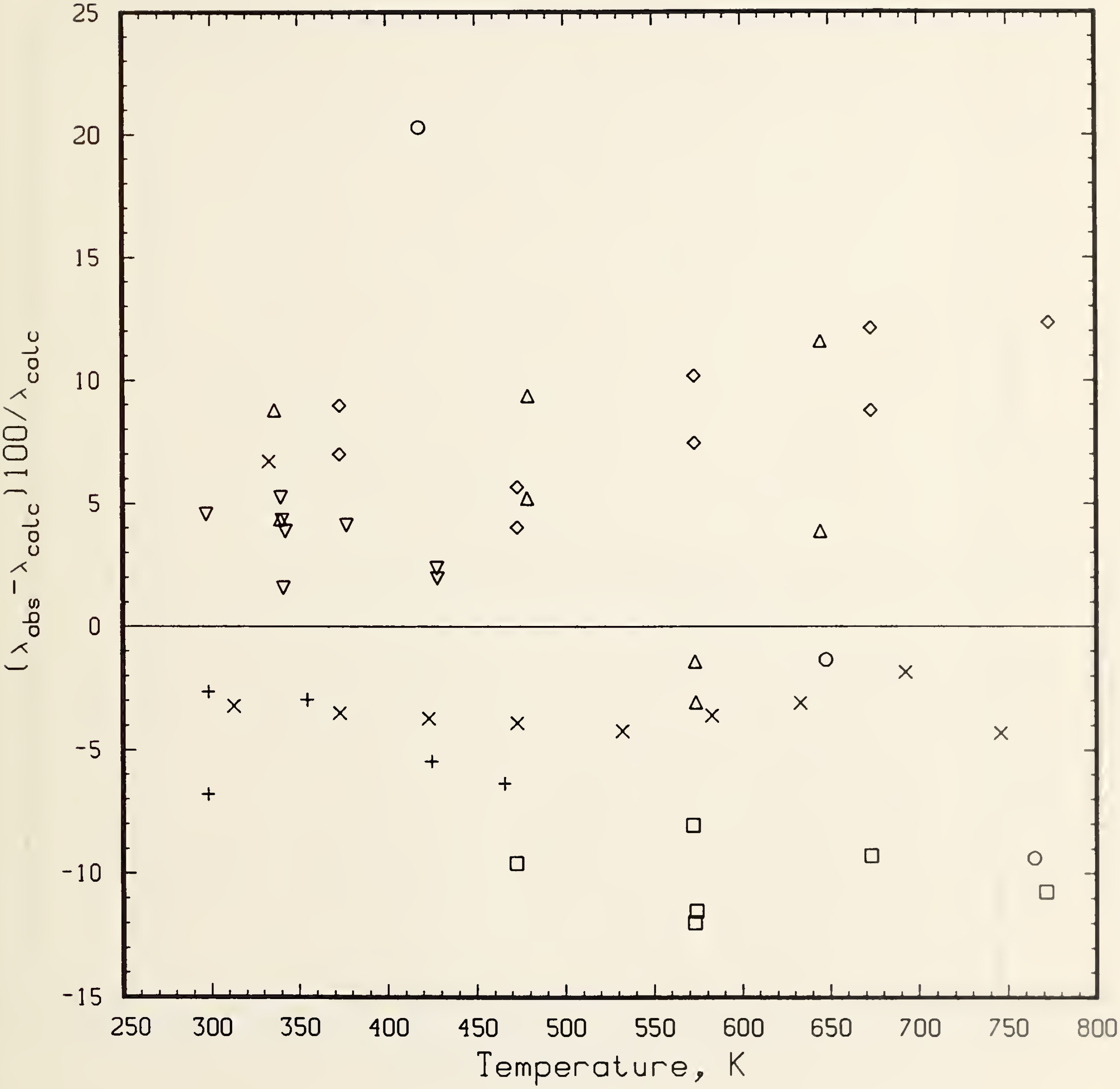

Figure 4. Deviations of corrected thermal conductivity round-robin test results from values calculated with eq (3) for fibrous alumina-silica.

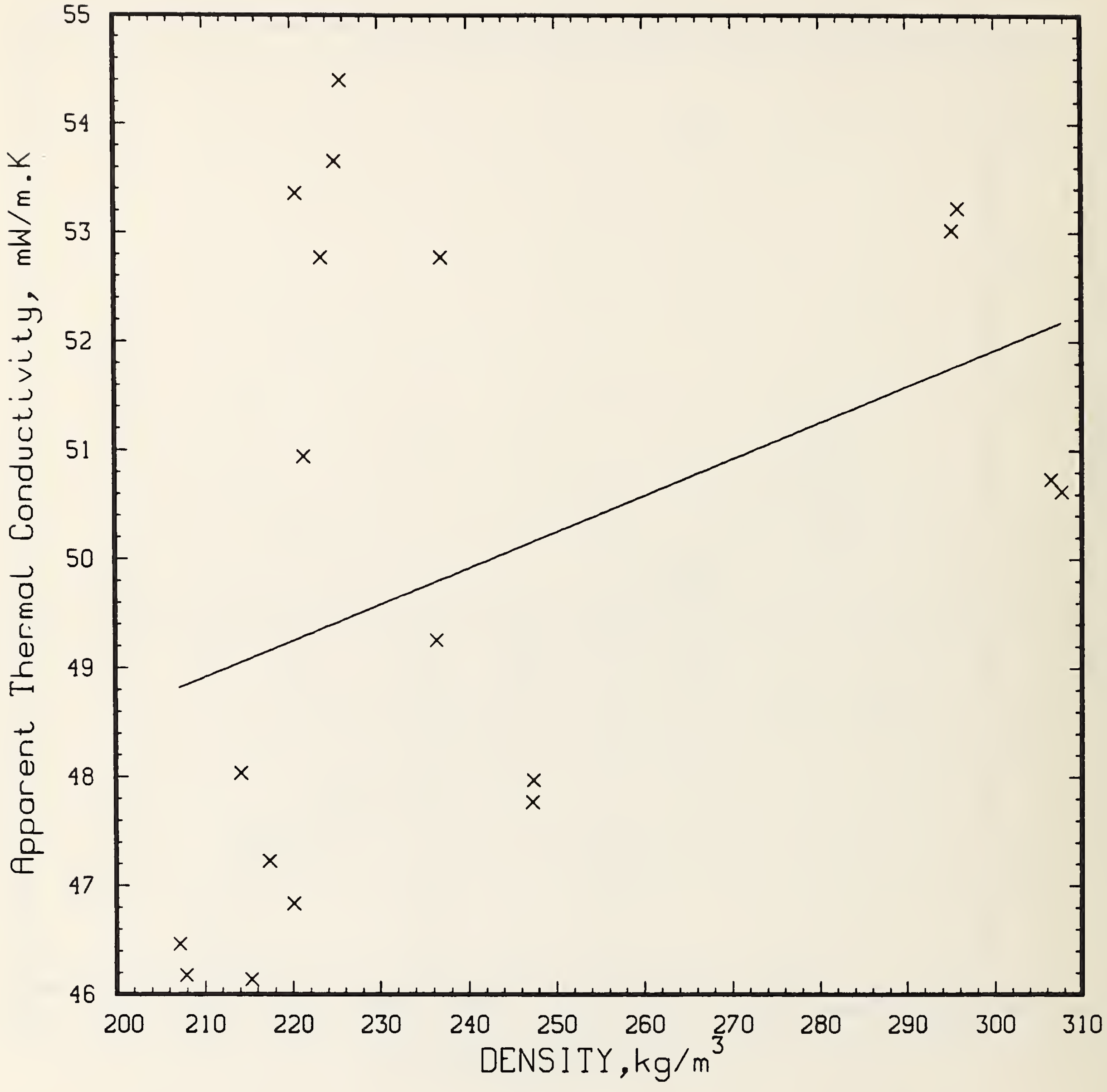

Figure 5. Thermal conductivity of round-robin specimens of fibrous alumina-silica as measured by NBS at a mean temperature of 333 K. The solid curve is calculated from eq (4).

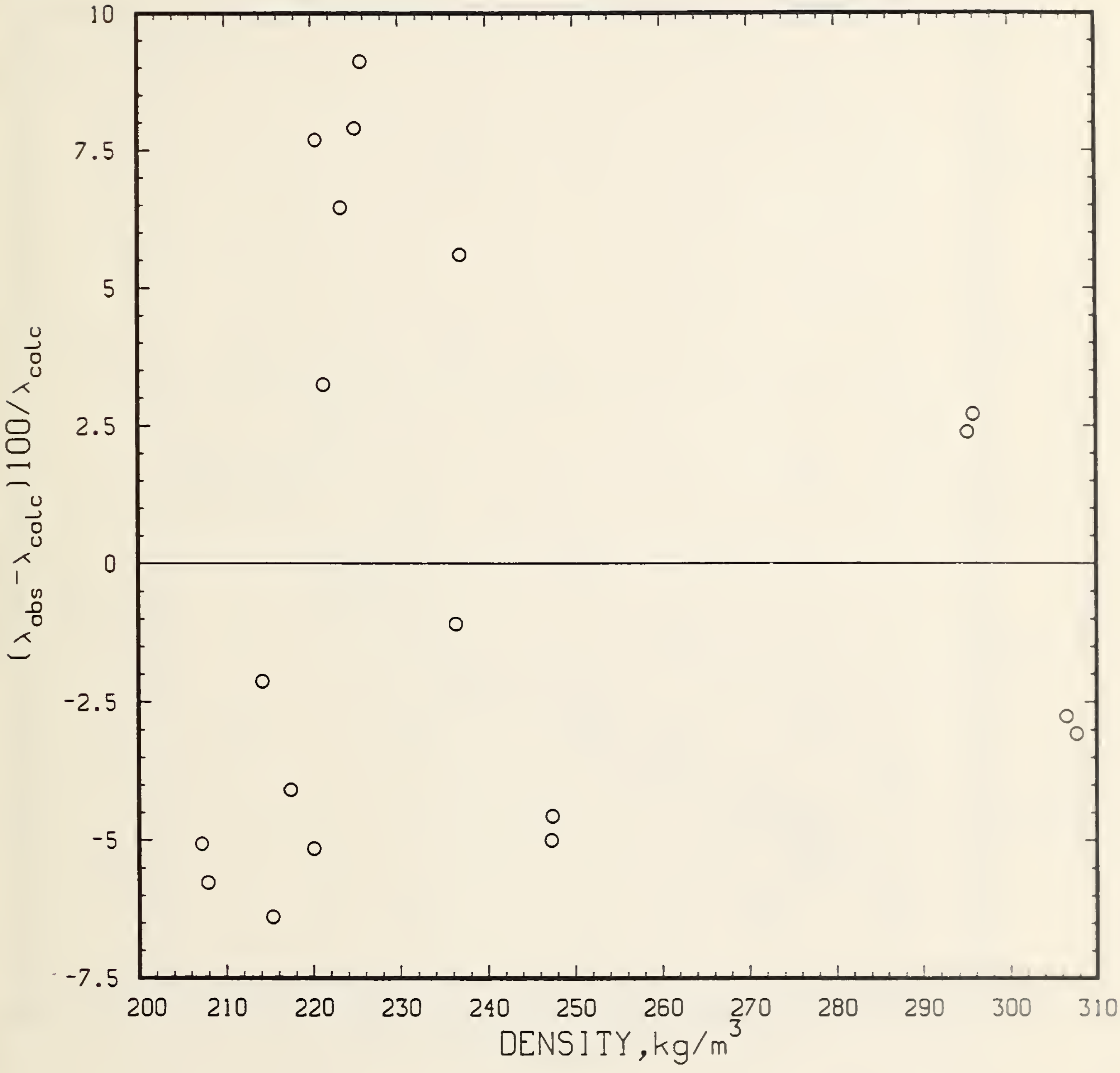

Figure 6. Deviations of thermal conductivity of round-robin specimens of fibrous alumina-silica from values calculated with eq (4).

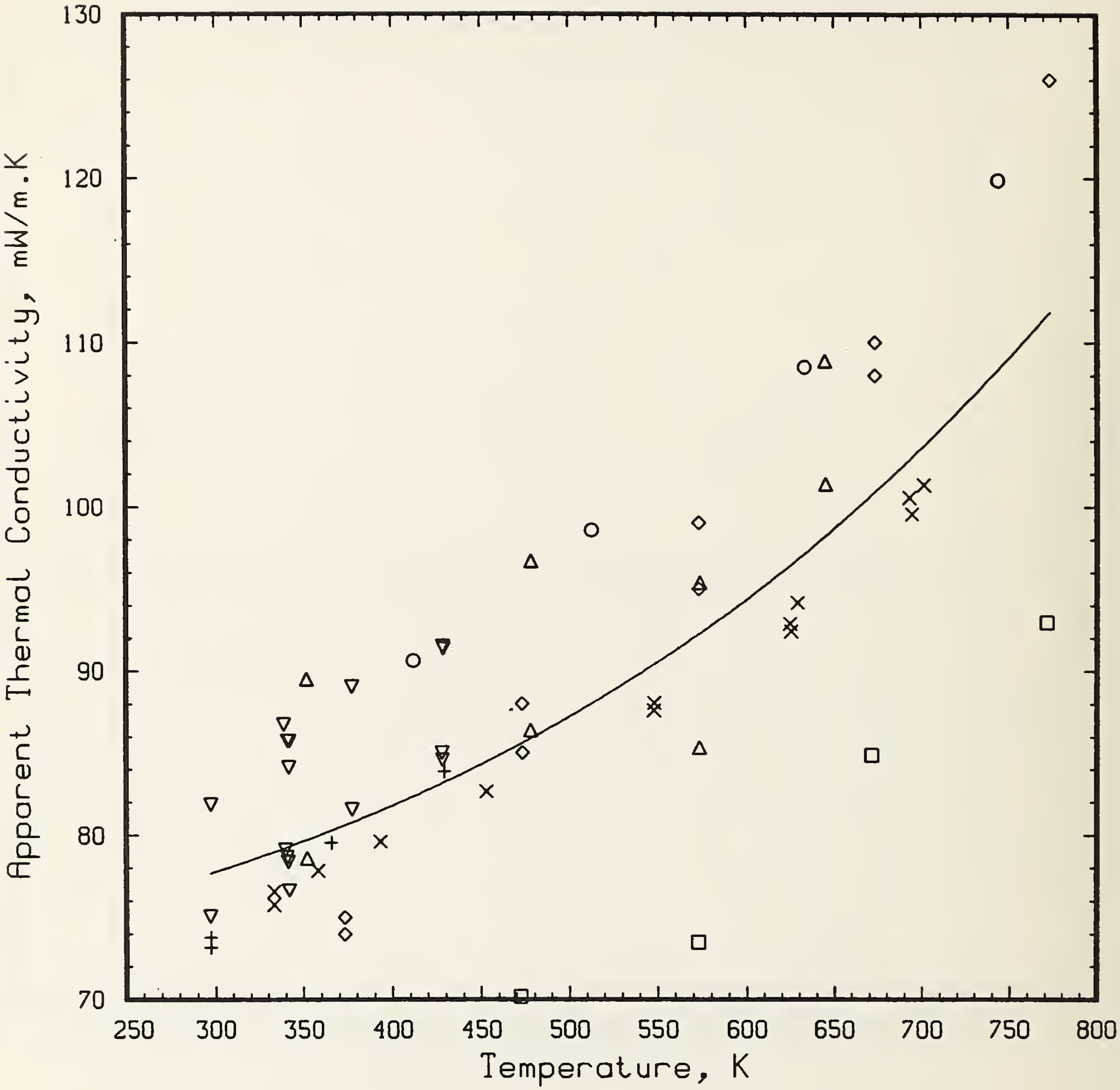

Figure 7. Thermal conductivity of round-robin specimens of calcium silicate; test densities range from 320 to 450 kg/m^3. The solid curve is calculated from eq (6).

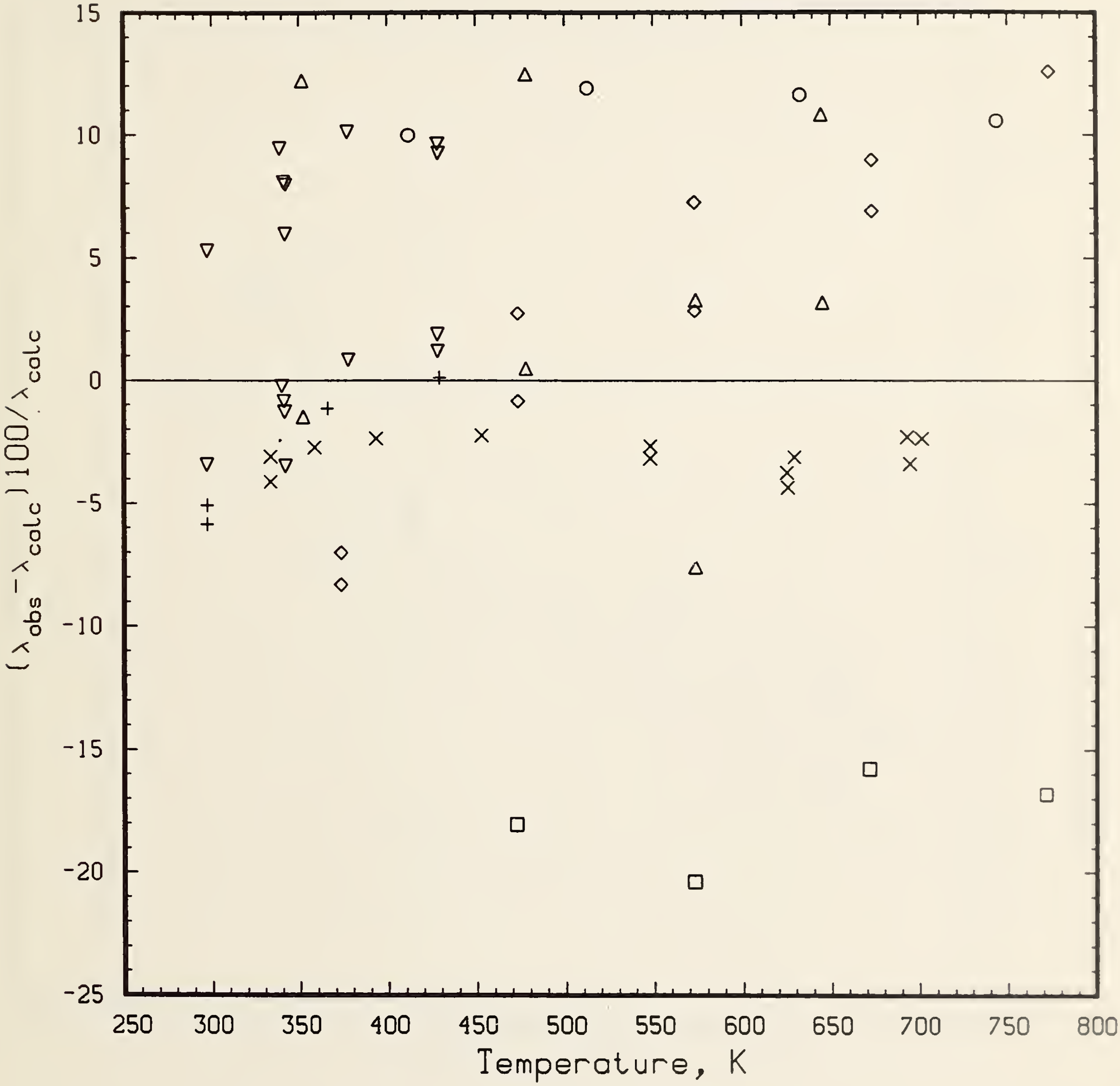

Figure 8. **Deviations of thermal conductivity round-robin test results from values calculated with eq (6) for calcium silicate.**

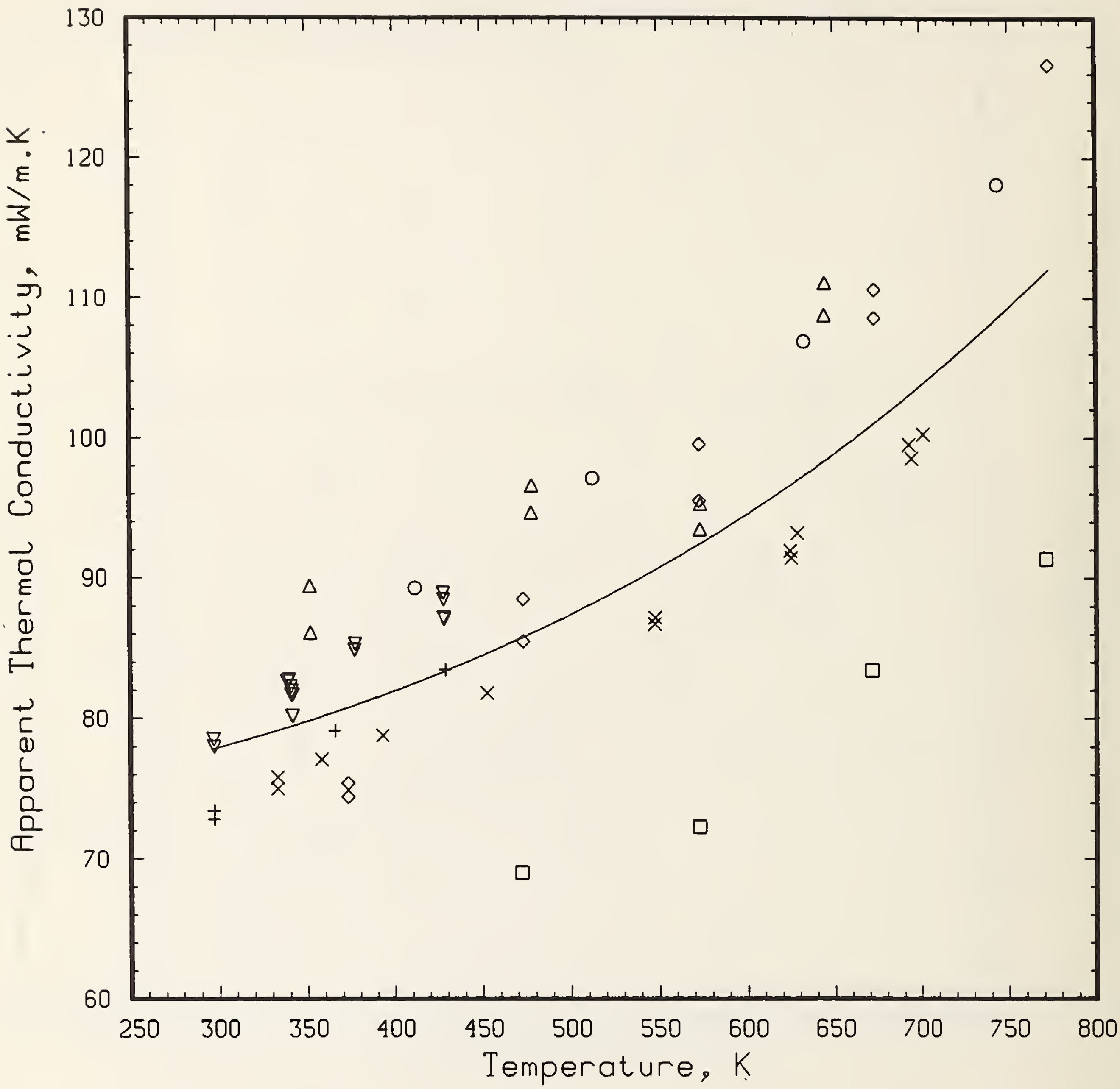

Figure 9. Thermal conductivity round-robin test results, corrected for deviation of apparent thermal conductivity from mean thermal conductivity, 75.0 mW/m.K, for calcium silicate; test densities range from 320 to 450 kg/m^3. The solid curve is calculated from eq (7).

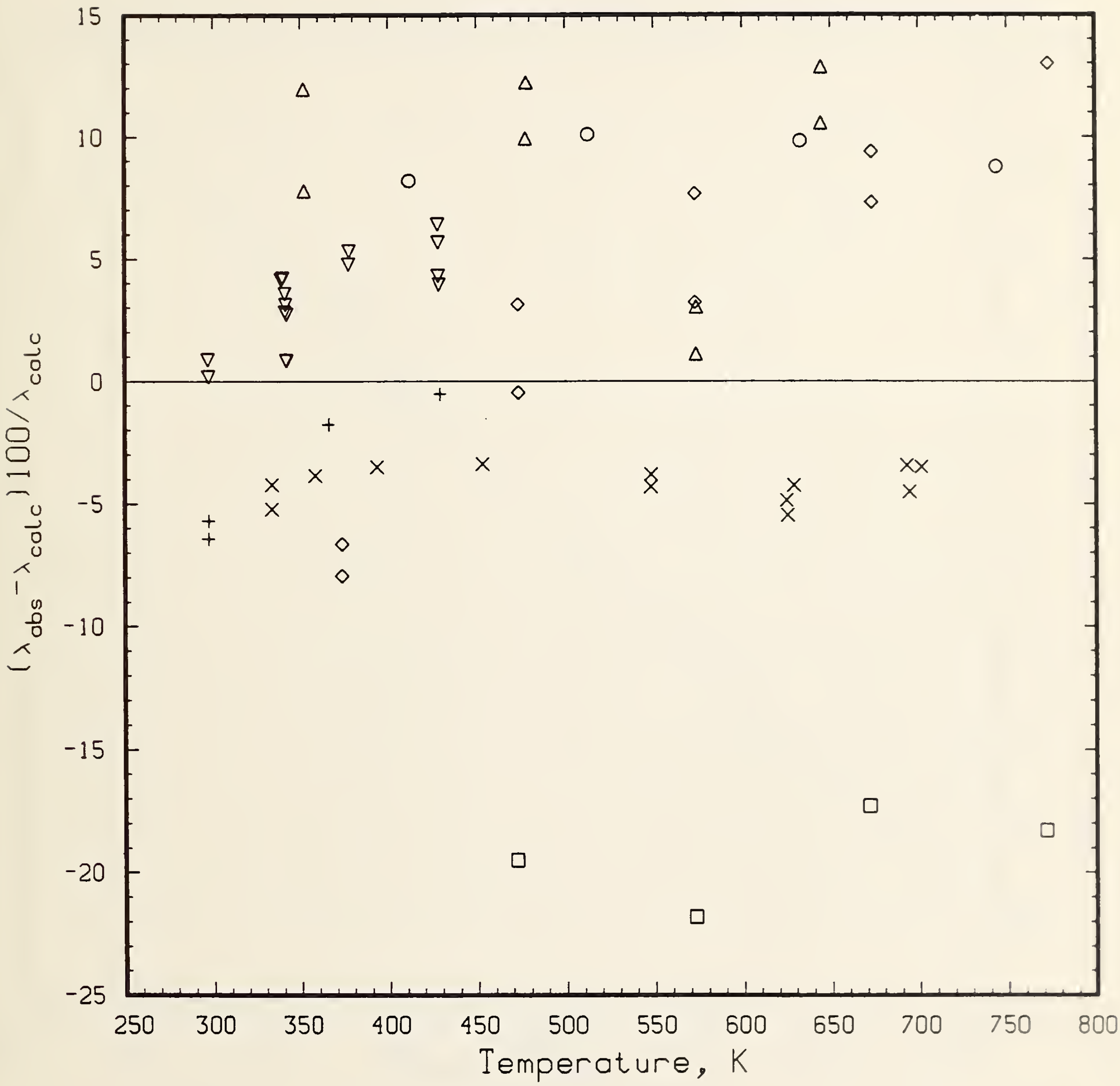

Figure 10. Deviations of corrected thermal conductivity round-robin test results from values calculated with eq (7) for calcium silicate.

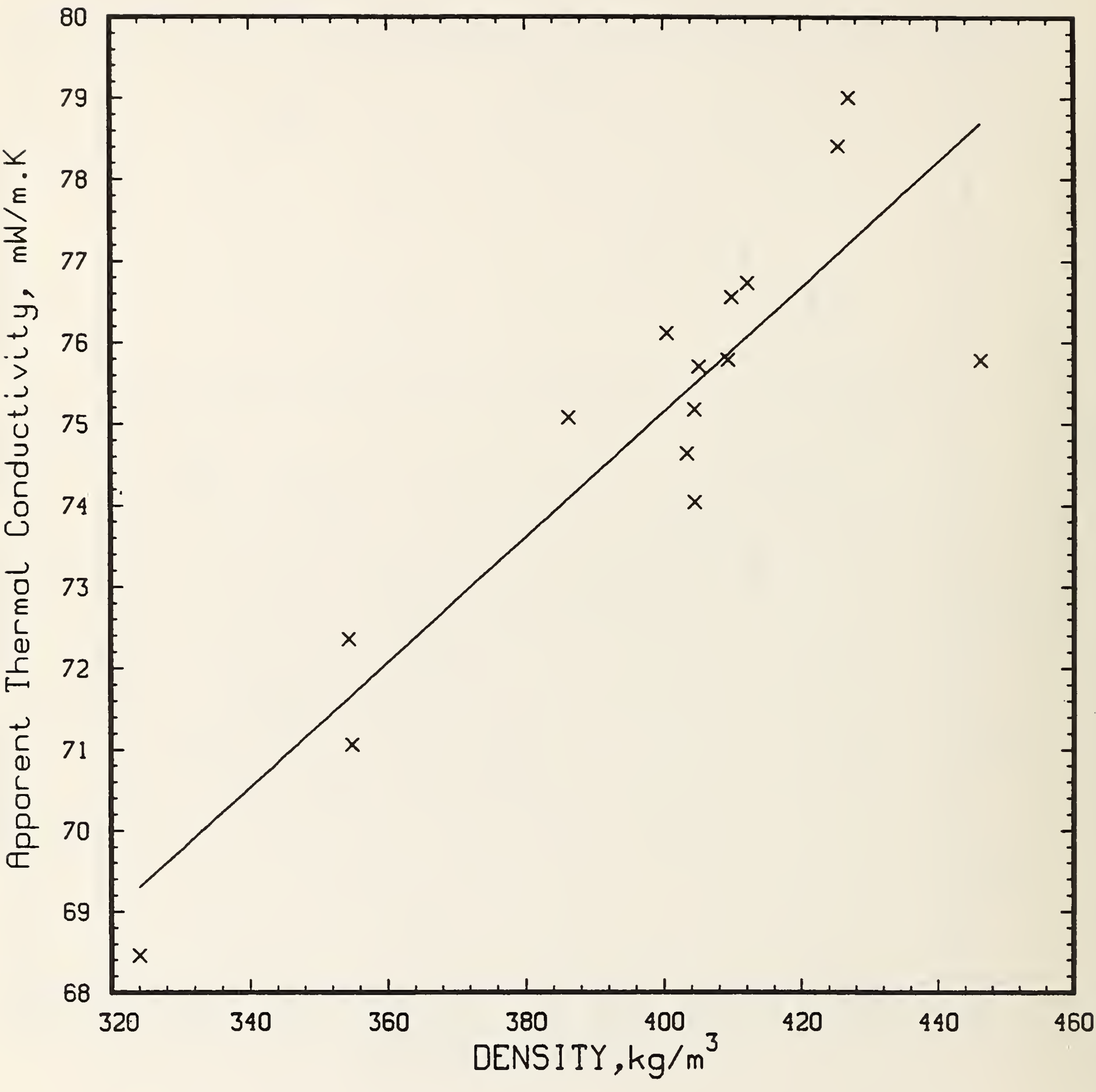

Figure 11. Thermal conductivity of round-robin specimens of calcium silicate as measured by NBS at a mean temperature of 333 K. The solid curve is calculated from eq (8).

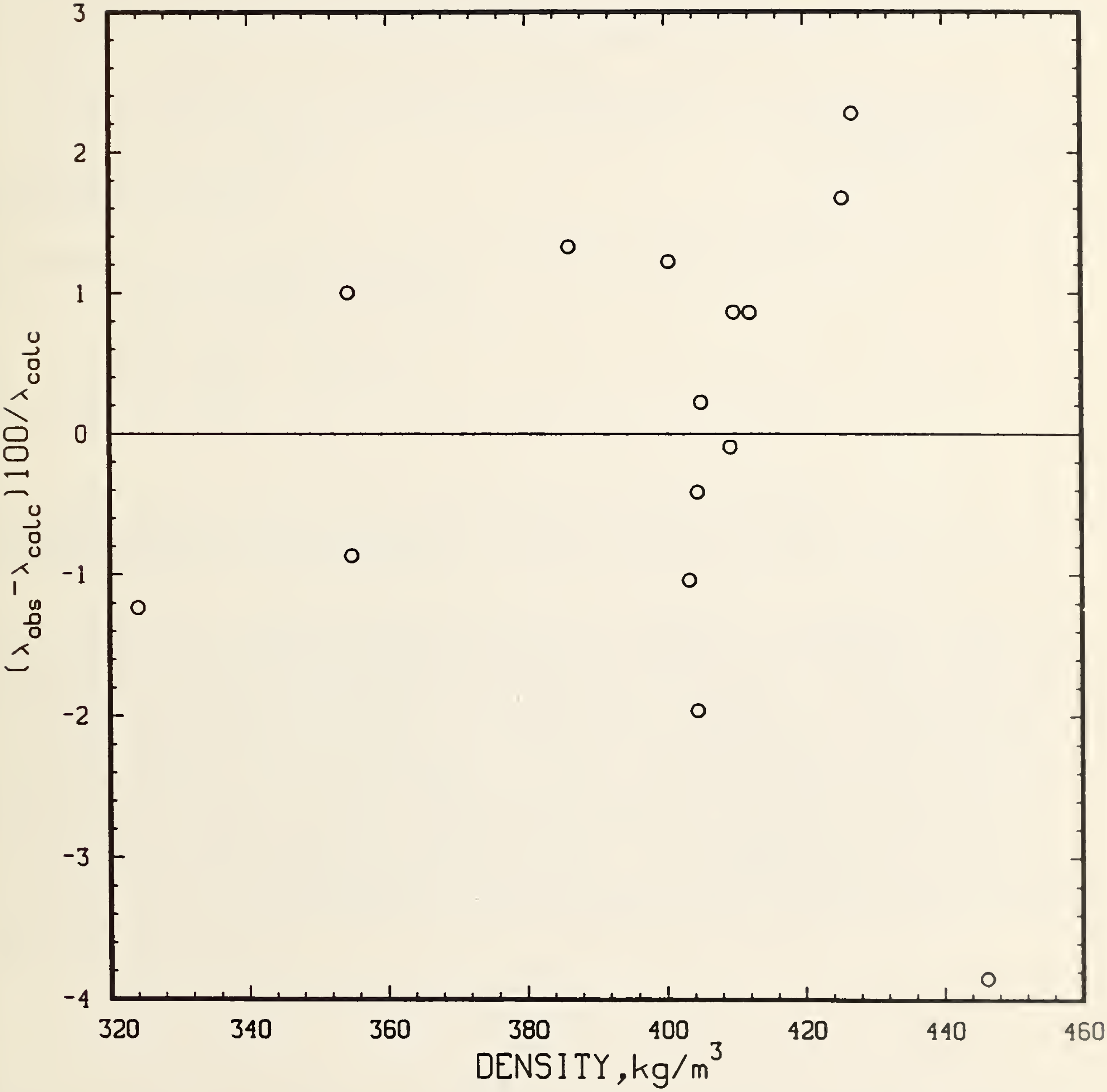

Figure 12. Deviations of thermal conductivity of round-robin specimens from values calculated with eq (8) for calcium silicate.

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5. AUTHOR(S)

Jerome G. Hust and David R. Smith

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☐ 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)*

This report presents the test results and analysis of round-robin measurements of apparent thermal conductivity for two kinds of refractory insulation board using high-temperature guarded-hot-plate apparatus. The round robin was carried out under the sponsorship of the American Society for Testing and Materials (ASTM) Subcommittee C-16.30 on Thermal Measurements. To complete the measurement program in a timely manner the participants chose to measure different specimens, selected, however, from the same production lot. The test results for apparent thermal conductivity illustrate the inter-laboratory reproducibility as well as the temperature and density dependence. The data include the temperature range from 297 to 773 K. The standard deviation is 7.4% for the 48 test results reported by seven participating laboratories for fibrous alumina-silica. The standard deviation is 8.0% for the 58 test results reported for calcium silicate.

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

apparent thermal conductivity; guarded-hot-plate apparatus; high temperature; refractory thermal insulation; round robin

13. AVAILABILITY

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