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In the early 1980s an international round robin was held in which apparent thermal conductivity of specimens of fibrous glass insulation board was measured by users of guarded hot plates (GHPs) and heat-flow meters (HFMs). The round robin was performed over a period of several years by laboratories in Europe, North America, Australia, and the Far East. Participants in this round robin were organized into 12 "loops," 8 for participants with GHPs and 4 for those with HFMs. Each loop included laboratories located in the same region of the world, and sharing the same set of specimens. In an attempt to obtain insight into the accuracy of the measurements, participants were also asked to measure the thermal conductivity of a layer of air. The data submitted in this round robin are exhibited and analyzed. The overall agreement of individual measurements with a least-squares fitted curve, as measured by one standard deviation σ, was σ = 2.4% for GHPs and σ = 2.7% for HFMs. Suggestions are made for conducting future round robins of this type.

Key Words: fibrous glass; guarded hot plate; heat flow meter; thermal conductivity; thermal insulation

1. INTRODUCTION

In October of 1978, under the auspices of the International Organization for Standardization (ISO), members of working group WG 6 of subcommittee SC 1 (Test and Measurement Methods) of ISO technical committee TC 163 (Thermal Insulation) met to organize a round-robin test program. This round robin would involve users of guarded hot plates (GHPs), and, optionally, heat-flow meters (HFMs), measuring apparent thermal conductivity. Those attending this planning meeting represented Canada, France, Germany, Italy, Japan, the United Kingdom, and the U.S.A. The minutes of the meeting record that the purpose for this working group was to:

* determine the current world-wide state of the art in GHP and HFM measurement technology, prior to development of ISO standards;
* create uniformity in [GHP and HFM] test methods for measuring apparent thermal conductivity[1] of thermal insulation specimens;
* create confidence and credibility in international measurements;
* allow each laboratory and each country to evaluate its measurement capabilities;
* provide additional input to the preparation of ISO standardized test methods in the development stages;
* gather statistical information from a world-wide population of users of GHP and HFM equipment and techniques; and
* finally, conduct another round robin following the development of the standards, showing (it is hoped) that precision of measurement has been improved by use of the new standards.

The recorded objectives of the working group were to:

* coordinate sponsorship of the round robin by ISO;
* conduct the round robin with an international scope;
* complete it within two to three years;
* focus on GHPs, but also include optional HFM data;
* measure thermal conductivities of high-density glass-fiber board and of an enclosed air gap.

Operational considerations were:

* participation in the round robin would be voluntary, at no cost to ISO;
* the number of participants would not be limited unless the number became too large to accommodate;
* there would be subsets of test specimens circulating within each country or region;
* participants would undertake measurements with their "standard" procedures (their

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[1]Because heat may often be transported through thermal insulation by both radiative and conductive processes, such a thermal insulation does not have a true thermal conductivity and one should therefore speak of "apparent" conductivity. However, for brevity, in the rest of the text the term "apparent" will be dropped.

national standards, where applicable), using appropriate techniques in accordance with the procedure as they understood it;

* thermal conductivity would be measured at two specified mean temperatures; a third measurement would be performed at a temperature selected by the laboratory; and
* the U.S. National Bureau of Standards (NBS) would supply the needed specimens of fibrous glass board insulation.

The original members of WG 6 were R. Doussain (France), Convenor; C. Shirtliffe (Canada), R. Jenish (Germany), F. DePonte (Italy), T. Otouma (Japan), P. Cornish and I. Williams (UK), and F.J. Powell and R.P. Tye (USA). By April of 1979 NBS (now NIST: the National Institute of Standards and Technology) had organized the round robin with F.J. Powell as Convenor.

2. PARTICIPANTS

Several hundred laboratories around the world were invited to participate in the round robin, with the understanding that participation would be at no cost to ISO. About 80 laboratories indicated interest. These respondents were surveyed to determine the types of equipment they had so that the size(s) of test specimens could be determined to accommodate the needs of all participants. All participants were assured that test results would be held in confidence; the results, when released, would not be linked to the name of the source laboratory.

The participants in the round robin are identified in Table A1 of Appendix 1.

3. ORGANIZATION OF THE ROUND ROBIN

Because of the logistical problems that would have been encountered in distributing round-robin test specimens to a large number of participants around the world, the same set of test specimens was not distributed to all participants. For each participant was able to accommodate only a specific size of specimens.

Instead, the round robin was actually an intercomparison of measurements on samples from the same lot of material. Specimens were distributed among participants in each of 12 small and localized, round-robin groups, called "loops." Logistical problems arose during the circulation of test specimens within some loops, so in some cases additional specimens had to be introduced to allow all participants to perform their measurements. However, the whole program will be called a round robin. The thermal conductivities of the separate loop specimens were not measured. Because all the specimens came from the same lot, it is assumed that their conductivities agree within less than the standard deviation of the global round-robin measurements.

Within each loop the laboratory requiring the largest specimen size was given the loop specimen first. After each laboratory finished, the specimen was circulated to the next laboratory in order of size needed. Each laboratory trimmed the received specimen to the proper size for its own test apparatus, ending with the laboratory needing the smallest specimen.

4. MEASUREMENTS

4.1. Test Specimens

ISO working group WG-6 had selected semi-rigid high-density fibrous glass insulation board with phenolic binder as the test material. The density was approximately 164 $kg \cdot m^{-3}$ (10.2 $lb_m \cdot ft^{-3}$). From a single lot of material, the manufacturer supplied boards 1220 mm (48 in) square and 25.4 mm (1 in) thick to the convenor at NBS, where the test specimens were prepared and distributed to participants. Other portions of this material also became the NBS thermal-conductivity standard reference material SRM 1450b. The actual specimens were distributed in sizes ranging from squares with an edge dimension of 1220 mm down to disks 180 mm in diameter.

As a means of giving some information on the accuracy of measurements by participant, each laboratory was invited to measure also the apparent thermal conductivity of an inexpensive and universally available "standard reference material": air. This "standard" was to be an enclosed air gap using the same apparatus (GHP or HFM) that was used to measure the conductivity of the fibrous glass board.

4.2. Test Procedures

Before measuring the thermal conductivity, each laboratory was to dry its test specimen(s) to constant mass in an oven maintaining a temperature of 103 °C. Then the length, width and thickness were to be measured and combined with the (dry) mass to determine the total "dry" test density. The density of the metered section alone, which would be more representative of the measured conductivity, was not measured. Due to possible inhomogeneities in the specimen (pair), the density of a specimen may have shifted slightly as the specimen was passed on to each following participant and cut down to smaller sizes to accommodate smaller apparatuses.

The dimensions and bulk densities of each specimen were to be reported in SI units on the data-entry form appropriate to each measuring apparatus. Because two specimens were measured in the guarded hot plate apparatus, two values of density were reported for each corresponding laboratory's specimens. Participants measuring the thermal conductivity of the fibrous glass specimens with guarded hot plates were asked to measure the conductivities at mean specimen temperatures of 283 K and 297 K (approximately 10 and 24 °C) and at a third temperature within the range from 273 K to 313 K (0 to 40 °C). As is conventional, the mean temperatures reported are arithmetic means of the hot-side and cool-side temperatures actually used. Thermal conductivity in HFMs was to be measured at 23.9 °C (291 K).

Originally the conductivity of an enclosed air gap 6 mm thick was to be measured at a mean temperature of 23.9 °C (291 K), and with a temperature difference of 28 K. Somehow a thickness value of 25 mm, rather than 6 mm, was introduced into the instructions communicated to the participants.

5. INPUT OF DATA BY PARTICIPANTS

Participants were requested to record their measurements on standard data-entry forms supplied by the convenor. Facsimiles of each data-entry form distributed to participants are given in Appendix 2. The data forms requested the entry (in SI units) of raw data: oven-dried mass (g), specimen dimensions (mm), total specimen density[2] ($kg \cdot m^{-3}$), mean specimen temperature, temperatures of each plate, temperature difference ΔT across the specimen, and ambient temperature (all in kelvins), thickness of specimen as tested (m), ambient relative humidity (%), metering area A (m^2) and power input Q (W) to the metering heater, and emissivities of hot and cold plates. From the raw data the participant was asked to calculate the thermal resistance $R_{th} = A \cdot \Delta T/Q$ ($m^2 \cdot K \cdot W^{-1}$), the thermal conductance $C_{th} = Q/(A \cdot \Delta T) = 1/R_{th}$ ($W \cdot m^{-2} \cdot K^{-1}$), and then the thermal conductivity $k = (Q_{th}/A)/(\Delta T/\Delta X) = C_{th} \cdot \Delta X$ ($W \cdot m^{-1} \cdot K^{-1}$). The steps in the calculations just outlined here requested the participants to follow a logical order from the raw data to a final calculation of thermal conductivity.

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[2]This "total" density, total mass divided by total specimen area, is not necessarily equal to the density of the central metered area. Also, the specimens within a regional loop were sent to laboratories in order of decreasing size of measurement apparatus, and so total densities of the specimens may have varied as the specimens were reduced in size.

To analyze the round-robin data, we used spreadsheet templates for recording the data in formats very similar to those originally used by the participants to submit their data. Minor changes were made in the formats for ease of data entry and analysis by computer, but all the original data were faithfully preserved. The purpose of this part of the analysis was to allow the data to be regrouped for various useful comparisons, as desired.

6. ANALYSIS OF RETURNED DATA

Several important factors were assessed while entering the returned data into the spreadsheet templates for analysis. First, each data sheet was carefully examined for internal consistency among the reported values. Calculated values, such as density, thermal resistance, and thermal conductivity, derived from the data submitted by each participant, were checked for accuracy by recalculation. In this stage several types of questionable data were found.

A few data were obviously in error, but it was apparent in most cases that simple errors in transcription had probably occurred. We assumed that this was the source of the discrepancy, and corrected such data. For example,

(a) a temperature difference was in error as listed on the data form, but the thermal conductivity had been correctly computed from the correct value of difference between the warm- and cool-side temperatures. In this case, because the correct temperature difference had obviously been used, the correct (not that originally listed) temperature difference was used in reporting the data here. This correction of submitted data more faithfully reflected the intent (and results) of the participant.

(b) in a very few cases an improper (but easily detectable) conversion of temperature difference was made from degrees Celsius to kelvins. That is, a temperature difference of, say, 25 °C, had been converted by the participant to 298.1 K, an error that was corrected by using the correct value of 25 °C. (In this case the participant had used 25 °C to compute the thermal resistance, thermal conductance, and thermal conductivity.) This error was also corrected to reflect the true results.

Two serious types of error occurred when (a) the values of thermal resistance, conductance, and conductivity were internally inconsistent, or (b) the raw data were incomplete (lacking the value of heater power used, for example). In the latter case no test of internal consistency could be performed. In these two cases the values of thermal resistance, conductance, and conductivity were listed as submitted by the participant. Only small benefits of the doubt were given to the submitted data.

6.1. Outliers

If the purpose of a given set of conductivity measurements were to determine the thermal properties of a material, then it would be proper to test for the presence of outliers according to accepted statistical guidelines. However, the purpose of this set of measurements is not to establish the thermal properties of fibrous glass board, but rather to compare the results of measurements by different laboratories around the world so that each laboratory can evaluate its measurement apparatus and technique. Thus the concept of "outliers" has no application to this present case. No "outliers" have been excluded from presentation in this work, except as explained next.

In one particular case detailed later, a least-squares curve was fitted to measurements of thermal conductivity versus temperature by the GHP apparatus so that HFM data could be evaluated by comparison. For this special case alone, three deviant points were treated temporarily as outliers and so were excluded from the curve fit determining the dependence of conductivity on temperature as indicated by GHP measurements.

In summary, because the purpose of this exercise was to perform an interlaboratory comparison, and not to determine the thermal properties of a material, all data submitted have been used in the round-robin intercomparison. Submitted values were changed only when the error was easily and obviously identifiable, based on common sense, and justified by the internal consistency of related data. If there was any doubt about the source of error in a questionable value, it was left unchanged and reported as submitted.

7. PRESENTATION OF DATA

Sets of data are first presented for the complete population, and then identified according to three individual major groupings. The first grouping, "Asia," actually includes participants in Africa, Asia, and Australia, but these laboratories are grouped together under one title for convenience, and reflecting their participation in a common loop. The second group is Europe, and the third is North America.

7.1 Thermal Conductivity of Fibrous Glass Board

7.1.1 Measurements with Guarded Hot Plates

Characteristics of the GHP apparatuses used by participants are described in table 7.1 (North America, loops 1 and 2), table 7.2 (Africa, Asia, and Australia; loops 4 and 5), and table 7.3 (Europe, loops 7, 8, 10, and 11).

Measurement data for GHPs for all participants are tabulated in table 7.4 (Africa, Asia, and Australia), table 7.5 (Europe), and table 7.6 (North America). The data sets have been sorted in order of increasing thermal conductivity (first datum in the set of three) to conceal the identity of the submitting laboratory. The data are grouped in sets of three, one measurement for each of three different temperatures (283 K, 297 K, and approximately 310 K). Some participants did not submit a complete set of three measurements. Values in parentheses were not reported but were computed from the other data and listed here if the calculated values were consistent with other submitted data. Values that appear to be in error and that could not be self-consistently recalculated were used as submitted.

The complete GHP data set for thermal conductivity as a function of temperature is plotted in figure 7.1. The solid curve is a least-squares fit to all the data; however, in performing the fit, the three highest data points (asterisks) were excluded. The function fitted was of the form

$$\lambda = A_0 + A_1 \cdot D + A_2 \cdot T + A_3 \cdot T^3 , \qquad (1)$$

where λ is thermal conductivity in $mW \cdot m^{-1} \cdot K^{-1}$, D is density in $kg \cdot m^{-3}$, and T is mean specimen temperature in K. The physical justification of this representation is that the conductivities of both the gas and solid vary approximately linearly with temperature, but the solid fibers in low-density insulation should also contribute a term to the conductivity directly proportional to the density; finally, any radiative transport should contribute the term in T^3. The least-squares values found for the coefficients in eq (1) were:

$$A_0 = 9.578 \ mW \cdot m^{-1} \cdot K^{-1} ,$$
$$A_1 = 0.0265 \ mW \cdot m^{2} \cdot kg^{-1} \cdot K^{-1} ,$$
$$A_2 = 0.0457 \ mW \cdot m^{-1} \cdot K^{-2} ,$$
$$A_3 = 2.552 \times 10^{-7} \ mW \cdot m^{-1} \cdot K^{-4} .$$

Table 7.1. Characteristics of guarded hot plate apparatuses and specimens for North American participants (loops 1 and 2). In column 7, "H" denotes a horizontal direction for heat flow, and "V" denotes a vertical direction. "NR" = "not reported."

Labora-tory	Speci-men	L (oven-dried) (mm)	W (oven-dried) (mm)	Plate size (edge) (mm)	Density ($kg \cdot m^{-3}$)	Heat flow dir.	Ambient temper-ature (K)	Ambient relative humidity (%)
1-1	1 ANA	1245	1243	1219	156	H	295.4	28
	4 ANA	1243	1243		158		295.4	28
1-2	1 ANA		[a]1016	[a]1016	164.57	V	308.65	40
	4 ANA						297.05	
1-3	1 ANA		[a]1020	406	158.39	V	294.11	33
	4 ANA		[a]1018				294.11	30
1-4	1 ANA	610	610	610	156	H	302.6	NR
	4 ANA						297.2	NR
1-6a	1 ANA	610	609	610	155.1	V	NR	NR
	4 ANA	610	609		154.1			
1-6b	20-1	610	610	610	125.18	V	NR	NR
	20-2				130.12			
2-1	5ANA	312	311	305	182.5	V	300.5	28.0
	7ANA	310	310		154.0		300.5	25.0
2-2	5ANA	305	305	305	168	V	297.15	40
	7ANA						292.15	
2-7	8-1	432	432	[a]406.4	166	V	283	<30
	8-2						297	<30
2-8	7-1	457.2	457.2	457	164.8	H	296.5	--
	7-2				172.5		283.1	--
2-11	17-1	581	581	610	151	H	282.88	20
	17-2						295.87	20

[a]diameter

Table 7.2. Characteristics of guarded hot plate apparatuses and specimens for "Asian" participants (loops 4 and 5). In column 7, "H" denotes a horizontal direction for heat flow, and "V" denotes a vertical direction. "NR" = "not reported."

Laboratory	Specimen	L (oven-dried) (mm)	W (oven-dried) (mm)	Plate size (edge) (mm)	Density ($kg \cdot m^{-3}$)	Heat flow dir.	Ambient temperature (K)	Ambient relative humidity (%)
4-1	6A-AA	614.0	613.5	605	164.56	NR	308	26
	8A-AA	616.5	613.5				297	33
4-2	6A-AA	320	320	318	167.6	H	304.0	62
	8A-AA						304.5	69
4-3	6A-AA	320	320	305	147.8	V	298.0	71
	8A-AA						295.5	73
4-4	6A-AA	308.4	306.3	300	168	H	271.7	45
	8A-AA	308.0	308.4				281.2	65
4-5	6AAA	[a]200.9		[a]203	167.5	V	301	<5
	8AAA	[a]200.0					314	<5
4-6	6AAA	NR	NR	[a]200	168.5	H	288	63
	8AAA						288	54
4-8	6AAA	306	309	300	167	H	297	51
	8AAA	308	308				294	54
5-4	9A-AA	311.5	311	305	167.2	H	291.2	30
	18A-A							
5-6	9A-AA	311	311	210	167	H	296	30
	18A-A							

[a]diameter

Table 7.3. Characteristics of guarded hot plate apparatuses and specimens for European participants (loops 7 and 8). In column 7, "H" denotes a horizontal direction for heat flow, and "V" denotes a vertical direction. "NR" = "not reported."

Laboratory	Specimen	L (oven-dried) (mm)	W (oven-dried) (mm)	Plate size (edge) (mm)	Density ($kg \cdot m^{-3}$)	Heat flow dir.	Ambient temperature (K)	Ambient relative humidity (%)
7-2	17AE	502	505.2	500	152.7	V	293.5	60
	20AE	502	505.2		162.6		293.5	
7-4	17AE	500	500	500	159.7	NR	296	50
	20AE						296	
7-6	11-1	305	305	305	172	V	293.4	40
	11-2						293.4	
7-7	19-1	304.8	304.0	305	157	V	293.4	37
	19-2	305.4	305.7		159		295.3	45
7-9	5-1	305	305	305	148	V	293	40
	5-2				177			
7-11a	6-1	[a]450		370	150.0	V	290	NR
	6-2				147.8		290	
7-11b	6-1	[a]450		450 (D)	150.0	V	301	NR
	6-2				147.8		298	
7-13	3-1	600	600	610	170	V	293	65
	3-2						293	65
7-14	17AE	613.2	614.8	610	153.86	V	293	55
	20AE	613.3	616.5					
8-1	11AE	1003	1003	1000	174	V	286.8	40
	15AE						287.1	
8-2	11AE	805	805	800	165.4	V	296.05	35
	15AE				173.1		283.15	30
8-5	11AE	602	601	600	170.0	V	284.9	28
	15AE	602	601		168.6		285.0	30

[a]diameter

Table 7.3. (cont.) European, loops 10 and 11.

Laboratory	Specimen	L (oven-dried) (mm)	W (oven-dried) (mm)	Plate size (edge) (mm)	Density (kg·m^{-3})	Heat flow dir.	Ambient temperature (K)	Ambient relative humidity (%)
10-1a	21?	855	855	850	161	V	293	NR
	25?						293	NR
10-1b	21?	802	800	800	161	V	293	NR
	25?						293	NR
10-3	21	803	802	800	165.0	V	"Trm"	NR
	25	801	801		162.0		"Trm" (293?)	NR
10-5	1	770	770	770	160.5	NR	294.60	40
	2				158.7		294.60	40
11-1	24:AE	500	500	500	168	V	283.15	17
	27:AE						296.15	17
11-2	24:AE	501	499.75	500	170	V	283.17	17
	27:AE						296.19	11
11-3	24:AE	502.2	500.2	500	175.77	V	286.35	26
	27:AE	501.8	502.4		161.48		291.85	25
11-4	24:AE	NR	NR	246	168.3	V	NR	60
	27:AE	NR	NR				NR	70
11-6	24:AE	300.5	300.4	300	171	V	293	68
	27:AE						294	68
11-7a	24:AE	250	250	250	178.8	V	296.35	47
	27:AE							
11-7b	24:AE	249	249	250	161.3	V	273.12	48
	27:AE						296.81	
11-8	9-1	[a]203.8		203 (D)	171.0	V	296	52
	9-2	[a]204.5						

[a]diameter
(Values in parentheses were not reported, but were computed from the given data)

Table 7.4 Thermal conductivity data (GHP) for Africa, Asia and Australia.

Test run:	Temp. diff. (K)	Thick-ness (mm)	Power (W)	Metering area (m^2)	Rth ($K \cdot m^2 \cdot W^{-1}$)	Cth ($W \cdot m^{-2} \cdot K^{-1}$)	Kth ($mW \cdot m^{-1} \cdot K^{-1}$)	Tmean (K)	Mean Density ($kg \cdot m^{-3}$)
1	30.1	25.4	0.722	0.01	0.834	1.198	30.3	283.3	167
2	31.3	25.3	0.782		0.800	1.249	31.6	297.5	167
3	33.8		0.879		0.769	1.300	32.9	308.3	167
1	28.8	25.4	[a]35.00 (3.25)	0.0929	0.823	1.215	30.9	298	164.56
2	29.1	25.4	[a]38.24 (3.544)		0.763	1.311	33.3	313	164.56
1	38.0	25.4	1.9263	0.04	0.791	1.264	32.1	283.0	167.6
2	30.0		1.6478		0.729	1.371	34.8	296.0	167.6
3	31.0		1.8063		0.686	1.457	37.0	304.0	167.6
1	20.6	24.8	0.86	0.03223	0.772	1.29533679	32.15	284.2	167.2
2	28.3		1.225		0.745	1.34228188	33.36	297.0	167.2
3	27.7		1.236		0.723	1.38312586	34.36	307.0	167.2
1	20.6	24.8	0.86	0.03223	0.772	1.29533679	32.15	284.2	167.2
2	28.3		1.225		0.745	1.34228188	33.36	297.0	167.2
3	27.7		1.236		0.723	1.38312586	34.36	307.0	167.2
1	36.0	25.38	0.3859	0.0084	0.782	1.279	32.47	283.2	167.5
2	36.0	25.38	0.4021		0.751	1.332	33.81	296.2	167.5
3	36.0		0.4181		0.722	1.384	35.13	309.2	167.5
1	28.2	24.9	(0.303)	0.0081	0.7582	1.319	32.8	283.0	168.5
2	28.1		(0.313)		0.7298	1.370	34.1	296.2	168.5
3	28.0		(0.325)		0.7018	1.425	35.5	308.9	168.5
1	29.7	25.5	1.75	0.0225	0.764	1.31	33.4	288.0	168.0
2	27.2	25.4	1.65		0.742	1.35	34.4	296.8	168.0
3	27.6		1.75		0.710	1.41	35.9	310.9	168.0
1	18.0	24.8	0.4023	0.01628	0.7283	1.373	34.1	301.2	167
2	20.0		0.4511		0.7217	1.386	34.4	303.7	167
3	20.5		0.4773		0.6991	1.430	35.5	313.1	167
1	28	25.4	1.0625	0.0231	(0.6088)	(1.643)	41.73	283	147.8
2	28		1.1405		(0.5671)	(1.763)	44.79	296	147.8
3	28		1.368		(0.4728)	(2.115)	53.71	313	147.8

[a]Value as submitted

Table 7.5. Thermal conductivity data (GHP) reported by European participants.

Test run:	Temp. diff. (K)	Thick-ness (mm)	Power (W)	Metering area (m^2)	Rth ($K \cdot m^2 \cdot W^{-1}$)	Cth ($W \cdot m^{-2} \cdot K^{-1}$)	Kth ($mW \cdot m^{-1} \cdot K^{-1}$)	Tmean (K)	Mean Density ($kg \cdot m^{-3}$)
1	9.42	25.5	0.1193	0.01056	0.8333	1.2000	30.6	300.13	178.8
2	10.16		0.1295		0.8279	1.2078	30.8	296.18	178.8
3	9.89		0.1277		0.8173	1.2235	31.2	297.60	178.8
1	9.40	25.4	0.1215	0.01056	0.8167	1.2244	31.10	273.12	161.3
3	9.49		0.1235		0.8115	1.2323	31.30	296.82	161.3
2	9.37		0.1235		0.8013	1.2480	31.70	296.81	161.3
3	28.4	25.4	8.740	0.25	0.805	1.242	31.6	274.35	169.2
2	28.2		9.023		0.781	1.280	32.5	283.25	169.2
1	27.9		9.422		0.750	1.333	33.8	296.20	169.2
3	29.57	25.5	4.580	(0.0625)	(0.8070)	(1.239)	31.6	283.46	168.3
2	31.14		5.180		(0.7514)	(1.331)	33.9	298.13	168.3
1	32.43		5.812		(0.6975)	(1.434)	36.6	309.89	168.3
1	29.15	25.4	6.908	0.1898	0.8010	1.2484	31.71	287.75	158.56
2	33.93		8.295		0.7763	1.2882	32.72	297.15	158.56
3	27.65		7.018		0.7477	1.3374	33.97	304.50	158.56
1	29.5	25.7	6.991	0.0948	0.800	1.251	31.8	283.4	169.3
2	30.4	25.2	7.340		0.785	1.275	32.4	290.3	169.3
3	31.4		7.774		0.765	1.307	33.3	296.4	169.3
3	32.36	25.43	5.845	0.07211	0.7935	1.2524	31.85	284.44	148.9
2	30.70		5.766		0.7679	1.3022	33.12	297.55	148.9
1	29.98		5.732		0.7544	1.3256	33.71	303.25	148.9
3	31.70	25.43	2.131	0.02657	0.7905	1.2651	32.17	283.55	148.9
2	30.51		2.131		0.7608	1.3144	33.43	297.29	148.9
1	29.95		2.140		0.7437	1.3447	34.19	302.93	148.9
1	28.1	25.5	46.74	0.6561	0.789	1.27	32.2	281.2	174
3	27.9		48.14		0.761	1.32	33.4	289.1	174
2	28.7		49.97		0.754	1.33	33.7	294.3	174
3	28.0	25.63	2.913	0.04129	0.793	1.260	32.3	283.0	158
2	28.2		3.064		0.761	1.315	33.7	296.3	158
1	28.0		3.167		0.730	1.371	35.1	309.2	158
1	26.80	25.7	6.10	0.09	(0.791)	(1.264)	32.5	282.6	161
2	28.30		6.72		(0.758)	(1.319)	33.9	296.3	161
3	27.20		6.71		(0.730)	(1.370)	35.3	310.2	161
1	29.1	25.7	(2.954)	0.04	0.788	1.268	32.6	282.75	162
2	28.2		(2.950)		0.765	1.307	33.6	292.75	162
3	26.9		(2.952)		0.734	1.362	35.5	303.15	162

(Values in parentheses were not reported, but were computed from the given data)

Table 7.5. (cont.) European GHP data.

Test run:	Temp. diff. (K)	Thick-ness (mm)	Power (W)	Metering area (m²)	Rth (K·m²·W⁻¹)	Cth (W·m⁻²·K⁻¹)	Kth (mW·m⁻¹·K⁻¹)	Tmean (K)	Mean Density (kg·m⁻³)
1	11.90	25.4	4.0	0.25	(0.744		[a]32.6 (34.2)	285.3	163.5
2	10.90	25.5	4.0		(0.681		[a]33.6 (37.3)	294.4	163.5
3	10.40		4.0		(0.650		[a]34.9 (39.1)	304	163.5
3	26.24	25.7	16.59	0.25	0.791	1.264	32.7	286.94	159.6
2	28.97	26.0	18.91		0.766	1.305	33.7	295.48	159.6
1	28.17		19.01		0.741	1.349	34.9	304.91	159.6
1	28.5	25.4	2.315	0.063	0.776	1.288	32.71	283.0	157.6
2	28.4		2.369		0.755	1.324	33.64	296.4	157.6
3	28.5		2.467		0.726	1.376	34.94	313.3	157.6
1	28.37	25.7	2.995	0.040	0.784	1.276	32.8	282.02	172
2	33.00		3.629		0.751	1.331	34.2	296.65	172
3	31.96		3.618		0.730	1.370	35.2	307.29	172
1	30.21	25.42	5.002	0.064	0.773	1.293	32.87	283.17	170
2	29.62		5.096		0.744	1.344	34.16	296.19	170
3	30.24		5.398		0.717	1.394	35.46	309.17	170
1	27.96	25.62	4.565	0.063	0.777	1.285	32.99	283.11	168
2	27.80		4.754		0.742	1.346	34.55	296.16	168
3	28.01		4.981		0.714	1.400	35.93	308.26	168
1	[b]27.146	25.4	4.442	0.062	0.763	1.309	33.2	[b]282.567	168.62
2	[b]28.134		4.764		0.738	1.354	34.4	[b]296.038	168.62
3	[b]30.475		5.326		0.715	1.398	35.5	303.18	168.62
1	29.40	25.7	19.4	0.25	(0.758		33.3	285.75	162
2	28.40		19.5		(0.728		34.7	297.95	162
3	27.70		19.5		(0.710		35.7	309.70	162
1	27.65	25.4	4.553	0.062	0.759		33.5	283.7	159.7
2	26.55		4.561		0.728		34.9	297.7	159.7
3	21.2		3.778		0.701		36.2	308.6	159.7
1	8	25.4		0.1	0.74	1.35	34.3	296	170
2	30		(4.02)		0.75	1.33	34	313	170
1	30.30	25.4	1.842	0.022	0.740	1.351	35.0	283.0	171
2	28.80		1.915		0.677	1.477	37.5	296.2	171
3	29.60		1.939		0.686	1.460	37.0	303.4	171
1	29.23	25.4	0.683	0.008	0.694	1.441	36.6	281.64	171.0
2	28.29		0.696		0.660	1.516	38.5	296.71	171.0
3	27.79		0.697		0.636	1.572	39.3	306.86	171.0

[a]Value as submitted
[b]Unrealistic precision

Table 7.6. Thermal conductivity data (GHP) reported by North American participants.

Test run:	Temp. diff. (K)	Thick-ness (mm)	Power (W)	Metering area (m^2)	Rth ($K{\cdot}m^2{\cdot}W^{-1}$)	Cth ($W{\cdot}m^{-2}{\cdot}K^{-1}$)	Kth ($mW{\cdot}m^{-1}{\cdot}K^{-1}$)	Tmean (K)	Mean Density ($kg{\cdot}m^{-3}$)
3	[a]22.544	25.4	9.216	0.1662	0.8154	1.2264	31.15056		158.39
2	[a]26.400		11.362		0.7725	1.2945	32.8803	[a]297.422	158.39
1	[a]27.262		12.285		[b]0.7014 (0.7376)	1.3512	34.32048	[a]311.316	158.39
1	(28.17)	25.6	3.264	0.09266	0.7996	1.251	32.04	283.18	151
2	(28.04)		3.370		0.7709	1.297	33.24	296.19	151
3	(28.11)		3.568		0.7300	1.370	35.10	313.45	151
3	27.73	25.4	8.966	0.1299	0.8041	1.244	32.10	283.08	161.4
2	27.80	25.4	9.419		0.7665	1.305	33.64	297.00	161.4
1	27.81		9.865		0.7324	1.365	35.24	310.83	161.4
1	28.0	25.4	2.30	0.0648	0.790	1.27	32.2	283.0	166
2	27.7		2.43		0.740	1.35	34.3	297.1	166
3	26.7		2.54		0.685	1.46	37.1	316.3	166
3	27.78	25.4	11.64	0.165	0.786	1.271	32.3	283.15	156
2	27.78		12.16		0.754	1.328	33.7	297.05	156
1	27.78		12.69		0.722	1.385	35.2	310.93	156
2	38.44	25.65	4.623	0.1898	(1.578)	(0.6336)	32.7	285.0	154.6
1	36.27	25.93	4.489		(1.533)	(0.6521)	33.6	295.7	154.6
3	39.16		5.099		(1.457)	(0.6861)	35.4	312.2	154.6
3	27.78	25.1	2.994	0.0825	0.7645	1.308	32.8	283.15	168
2	27.78		3.117		0.735	1.361	34.2	297.05	168
1	27.78		3.247		0.706	1.417	35.6	310.93	168
1	28.2	25.0	[a]7.9	0.0225	0.766	1.305	32.9	283.0	168.2
2	28.0	25.4	[a]8.2		0.741	1.350	34.0	296.0	168.2
3	28.0		[a]11.3		0.722	1.385	34.9	303.0	168.2
2	28.4	25.48	3.14	0.0852	0.77	1.30	33.0	283.2	168.6
1	29.4		3.30		0.76	1.31	33.5	296.3	168.6
3	29.7		3.44		0.73	1.37	34.8	308.4	168.6
3	21.2	25.4	11.78	0.211	0.759	1.32	33.4	289.7	157
1	22.3		12.60		0.747	1.34	34.0	297.1	157

[a]Unrealistic precision
[b]Value as submitted

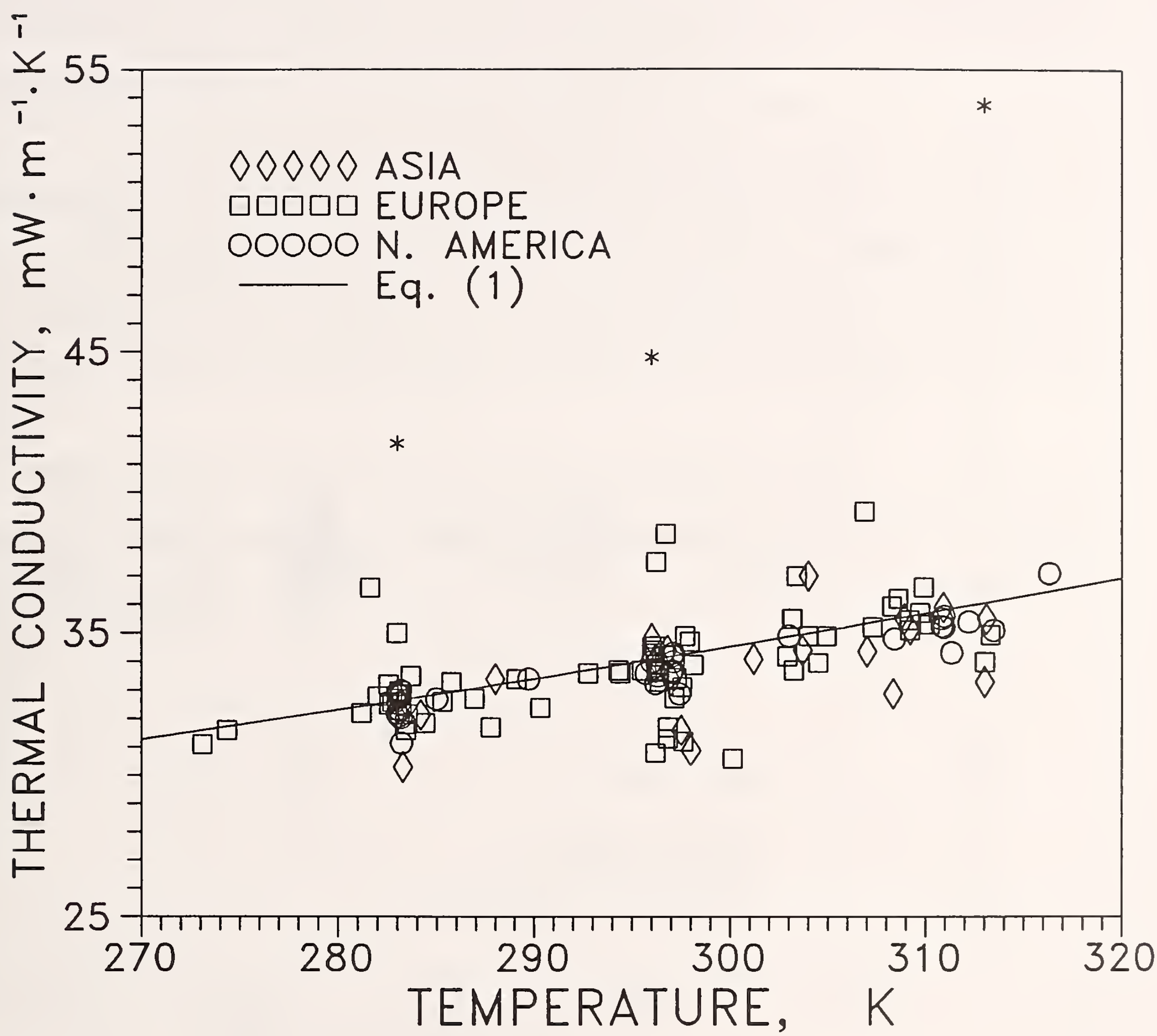

Figure 7.1 Measurements with guarded hot plates (GHPs) of thermal conductivity of fibrous glass board specimens as a function of temperature, for all participants (ASIA: Asia, Africa and Australia; Europe, and North America). The solid curve is eq (1), a least-squares fit to all the data except the three highest-conductivity data points (asterisks).

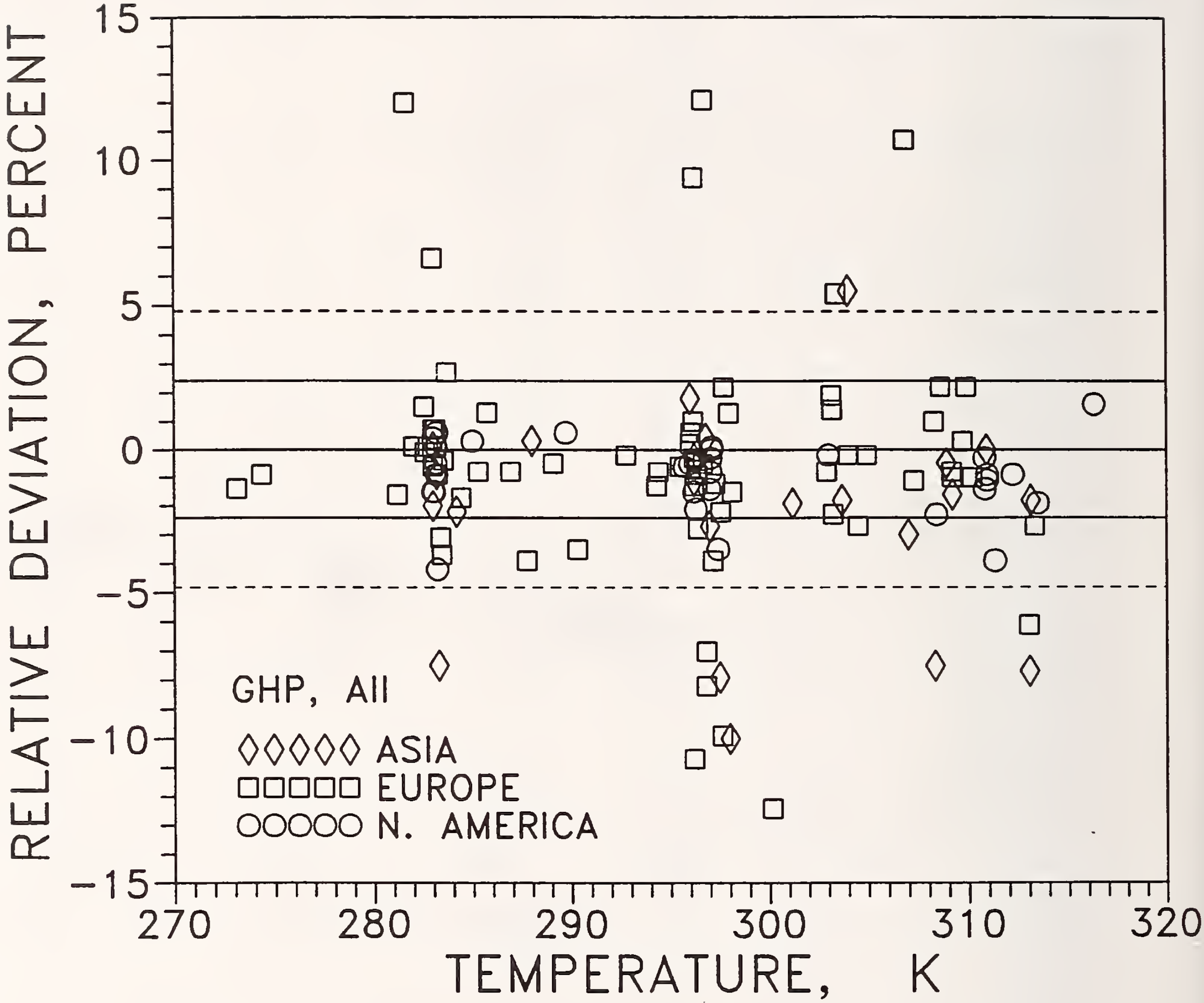

Figure 7.2 Deviations of GHP data in figure 1 from the fitted curve, eq (1), for all participants. The mean density of each individual specimen pair was used in eq (1) to compute each deviation. To allow precise examination of deviations, the deviations for the three highest-conductivity points (asterisks in figure 7.1) are not shown here.

The deviations of the GHP data from the fitted curve in figure 7.1 are plotted in figure 7.2. In order to show the value of each deviation more precisely, the data showing the three largest deviations (data represented by asterisks in figure 7.1) are not included in figure 7.2. The relative standard deviation of the data from the fitted curve is 2.4%. In figure 7.2, the two parallel solid lines, one above, and one below the central zero-deviation line, are separated from the central line by one standard deviation (2.4%).

Statistically, lines lying above and below the central zero-deviation line and separated from it by two standard deviations ($\pm$4.8%, or about 1.65 conductivity units at 300 K) should include about 95% of the data in the complete set, if the data are normally distributed. The two parallel dashed lines in figure 7.2 are separated from the central line by two standard deviations (4.8%). Clearly the data are not normally distributed about the fitted curve, as there are about 22 data points (19 of which are shown in figure 7.2) that deviate from the fitted curve by more than 5%, out of a total population of 124 points.

The same conductivity data for GHPs, separated into three geographical groupings ("Asia," Europe, and North America) are plotted in figures 7.3 through 7.5. In figures 7.3, 7.4, and 7.5 the solid curve is a plot of eq (1) using $D = 164\ kg \cdot m^{-3}$, which is the mean value of density for all the specimens represented by this data.

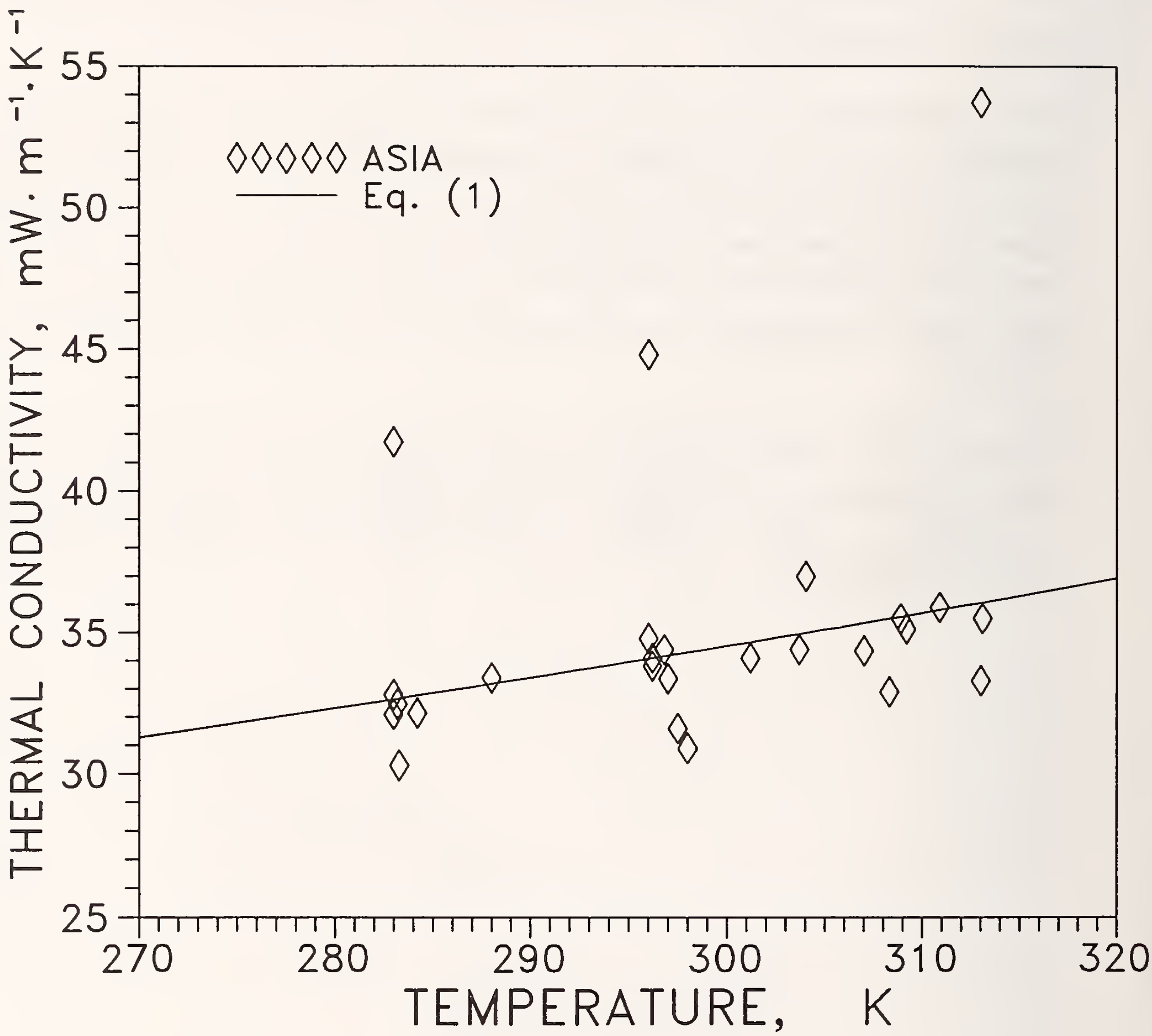

Figure 7.3 Measurements with guarded hot plates (GHPs) of thermal conductivity of fibrous glass board specimens as a function of temperature, for participants in the "Asian" (Asia, Africa and Australia) measurement loops. The solid curve is eq (1), a least-squares fit to all the data except the 3 highest-conductivity data points (asterisks in figure 7.1).

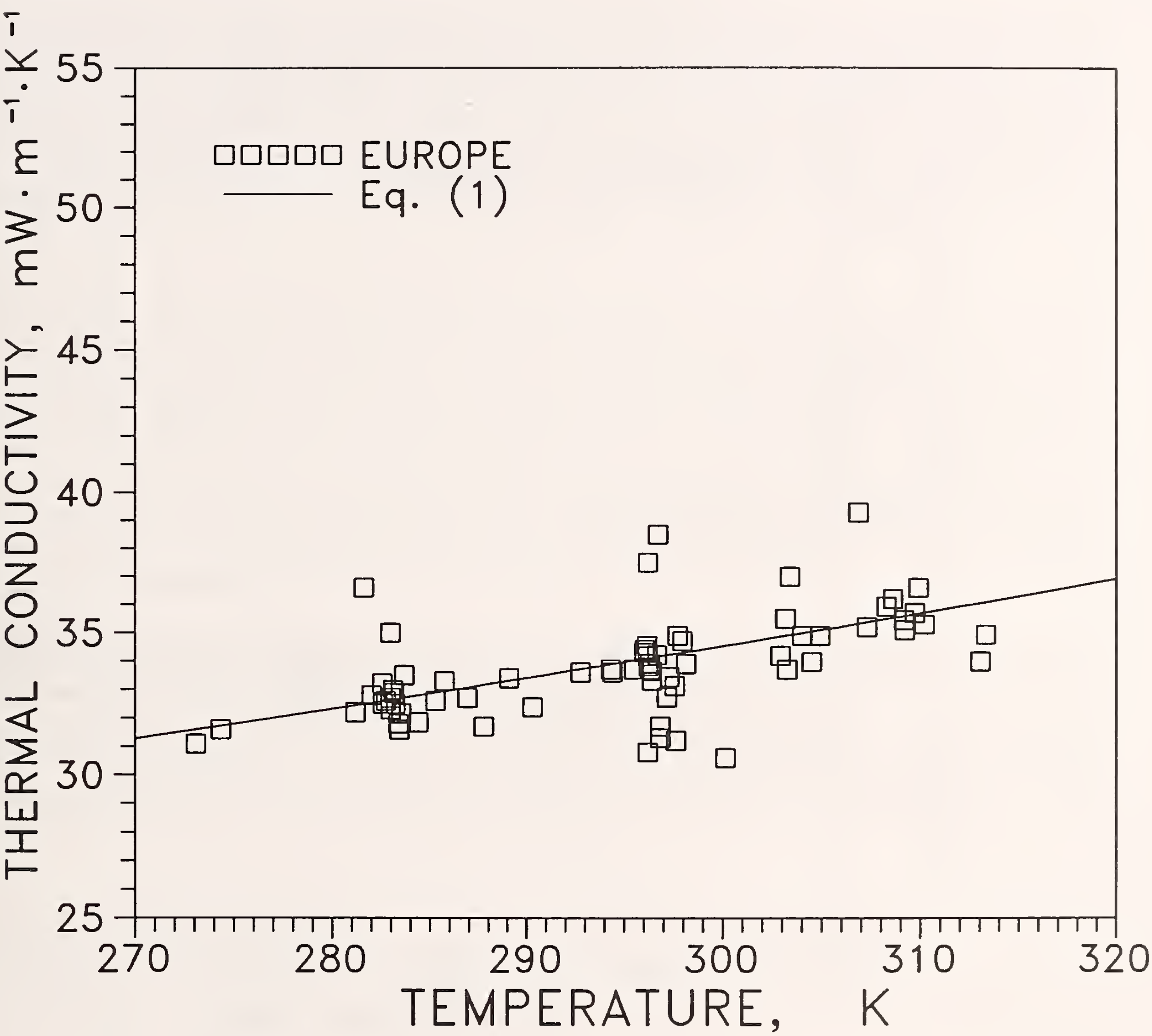

Figure 7.4 Measurements with guarded hot plates (GHPs) of thermal conductivity of fibrous glass board specimens as a function of temperature, for participants in the European measurement loops. The solid curve is eq (1), a least-squares fit to the data.

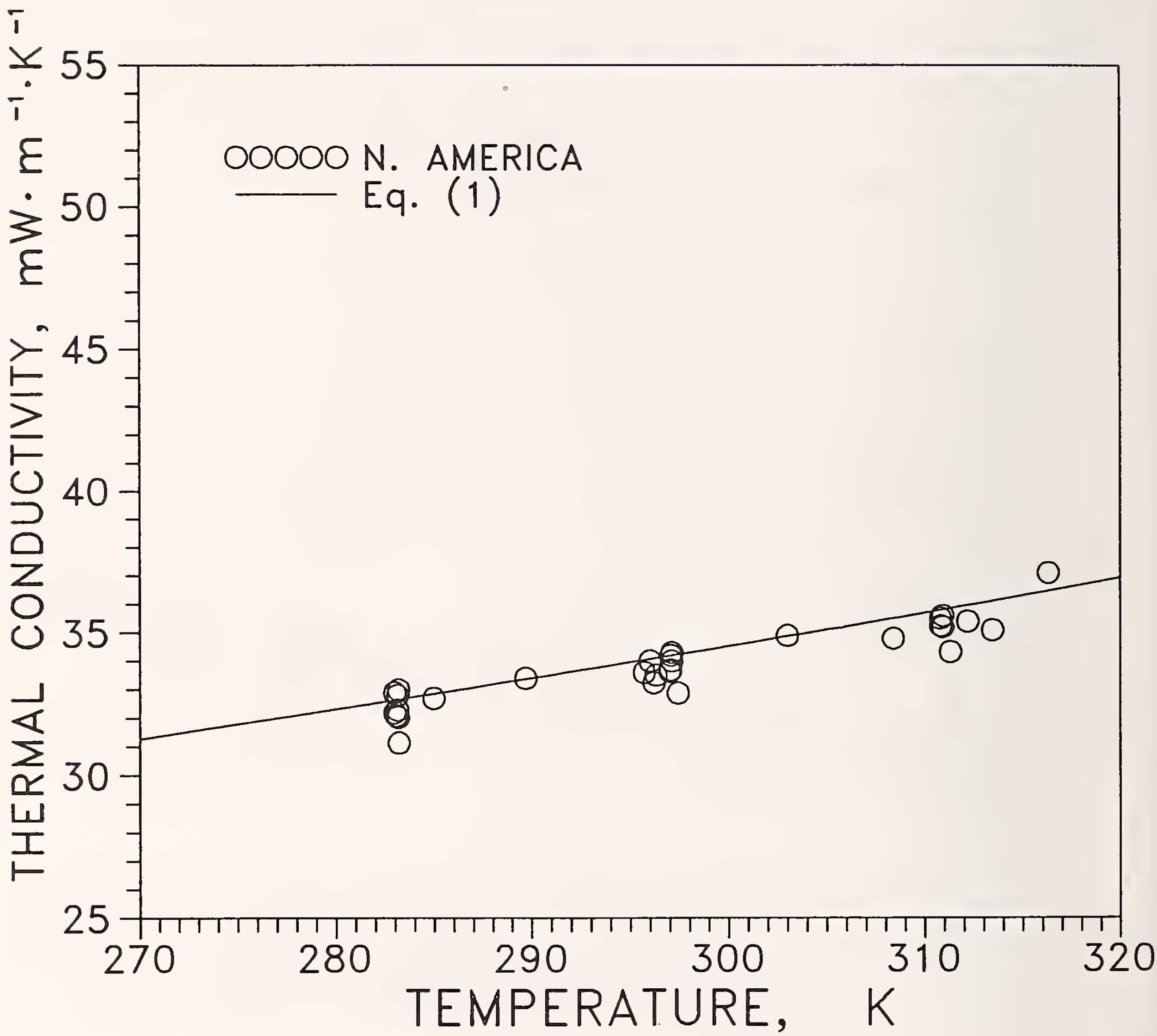

Figure 7.5 Measurements with guarded hot plates (GHPs) of thermal conductivity of fibrous glass board specimens as a function of temperature, for participants in the "North American" (U.S.A. and Canada) measurement loops. The solid curve is eq (1), a least-squares fit to the data.

7.1.2 Measurements with Heat Flow Meters

Characteristics of the HFM apparatuses used by participants are described in table 7.7 (North America, loop 3), table 7.8 (Africa, Asia, and Australia, loop 6) and table 7.9 (Europe, loops 9 and 12).

The HFM measurement data are tabulated in table 7.10 (Africa, Asia, and Australia), table 7.11 (Europe) and table 7.12 (North America). The data sets have been sorted in order of increasing thermal conductivity (first datum in the set of three) to conceal the identity of the submitting laboratory. Values in parentheses were not reported but were computed from the other data submitted by the participant and listed here if the calculated values were consistent with all other submitted data. Values that appear to be in error and that could not be self-consistently recalculated were used as submitted.

Figure 7.6 shows the complete data set for HFMs as a function of specimen density for all participants. The solid curve is the least-squares fit to all the GHP data, eq (1), and calculated for an assumed mean specimen temperature of 297 K. The mean specimen temperature for the five "Asian" participants' data displayed here was 297.4 K; that for the 15 European participants' data was 297.9 K; and that for the 21 North American participants' data was 297.6 K. The global mean specimen temperature for all 41 participants was 297.7 K. Plots of eq (1) (dashed lines) for mean specimen temperatures of 295 K and 300 K are almost equally separated from the mean temperature of measurement, 297.7 K. These are shown for comparison, to illustrate the effect of mean specimen temperature on the submitted data.

Figure 7.7 plots deviations of HFM data in figure 7.6 from the fitted curve, eq (1), for all participants. The mean density of each individual specimen pair was used in eq (1) to compute each deviation. The standard deviation from the curve for the "Asia" data is 2.7% (for all 26 data points; the mean deviation for 23 points left after excluding the three highest conductivity points for "Asia" is −1.9%); the standard deviation for the European data is −0.6%; and that for North American data is −1.0%.

Table 7.7. Characteristics of heat flow meter apparatuses and specimens: for loop 3 (North America [U.S.A. and Canada]). In column 5, "V" denotes a vertical direction for heat flow; Vdn, downward heat flow; Vup, upward heat flow. "NR" = "not reported." Specimens grouped together without spacing were measured by the same participant.

Specimen	L (oven-dried) (mm)	W (oven-dried) (mm)	Plate size (edge) (mm)	Heat flow direc-tion	Ambient temp. (K)	Ambient relative humidity (%)
14 ANA	1218	1218	1016	V	295	28
14 ANA	914	914	914	V	295	28
14 ANA	914	914	914	NR	NR	NR
14 ANA	914	914	NR	NR	295.9	50
14 ANA	610	610	NR	NR	NR	NR
14 ANA	610	610	NR	V	294.66	30
14 ANA	610	610	1016	V	294	22
7-3	305	305	305	Vdn	296.0	52
7-4	610	610	NR	V	296.0	52
8-1	432	432	381	NR	297	30
8-2	432	432				
1 ANA	NR	NR	610	NR	NR	NR
4 ANA	NR	NR		NR	NR	NR
20-1	NR	NR	610	NR	NR	NR
20-2	NR	NR		NR	NR	NR
3 AAA	610	610	610	Vup	294	22

Table 7.8 Characteristics of heat flow meter apparatuses and specimens: for loop 6 (Africa, Asia, and Australia). In column 5, "V" denotes a vertical direction for heat flow; Vdn, downward heat flow; Vup, upward heat flow.

Specimen	L (oven-dried) (mm)	W (mm)	Plate size (edge) (mm)	Heat flow direction	Ambient temp. (K)	Ambient relative humidity (%)
3A-AA	301	301	300	Vdn	295	64
3A-AA	311.5	311	300	Vdn	291.2	30
3A-AA	265	265	265	Vup	291	69.5
3AAA	308	308	NR	Vdn	NR	NR
10 AE	1000	1000	1000	Vup	296	50

Table 7.9. Characteristics of heat flow meter apparatuses and specimens: for loops 9 and 12 (Europe). In column 5, "V" denotes a vertical direction for heat flow; Vdn, downward heat flow; Vup, upward heat flow. "NR" = "not reported." Specimens grouped together without spacing were measured by the same participant.

Specimen	L (oven-dried) (mm)	W (mm)	Plate size (edge) (mm)	Heat flow direc-tion	Ambient temp. (K)	Ambient relative humidity (%)
12 AE	705	705	700	Vdn	297.55	35
12 AE	610	610	610	Vup	294	22
NA	400	400	400	Vdn	297	NR
5-1	305	305	305	Vup	293	40
10 A-1	300	300	305	V	293.5	NR
16 AE	610	610	610	NR	294	22
24 AE 27 AE	NR	NR	NR	NR	NR	NR
16 AE	500	500	500	Vdn	296.15	22
16 AE	500	500	500	Vdn	303.2	20-30
16 AE	306.5	305.5	305	Vdn	296.15	53
16 AE	NR	NR	#250	V	292.2	54
17 AE	500	500	NR	NR	296	50
20 AE	500	500		NR	296	50

Table 7.10. HFM data for participants in Africa, Asia, and Australia.

Temp. diff. (K)	Thick-ness (mm)	Power (W)	Metering area (m^2)	Rth ($K \cdot m^2 \cdot W^{-1}$)	Cth ($W \cdot m^{-2} \cdot K^{-1}$)	Kth ($mW \cdot m^{-1} \cdot K^{-1}$)	Tmean (K)	Mean density ($kg \cdot m^{-3}$)
27.8	25.4	35.5	0.04	0.782	1.278	32.5	297.1	159
31.41	25.4	41.05 (W/m^2)	0.209	0.765	1.307	33.2	296.82	164.7
31.02	25.0	41.56 (W/m^2)	0.0121	0.7463	1.3399	33.49	297.34	155.37
53.18	25.4	NR	0.0144	0.729	1.370	34.80	298.6	165.1
29.3	25	-0.423	0.0103	0.73	(1.370)	35.0	297.0	165.0

(Values in parentheses were not originally reported, but were computed from the data submitted)

Table 7.11. HFM data for European participants.

Temp. diff. (K)	Thick-ness (mm)	Power (W)	Metering area (m^2)	Rth ($K \cdot m^2 \cdot W^{-1}$)	Cth ($W \cdot m^{-2} \cdot K^{-1}$)	Kth ($mW \cdot m^{-1} \cdot K^{-1}$)	Tmean (K)	Mean density ($kg \cdot m^{-3}$)
(28)	25	35.3 (W/m^2)	0.008	0.79	1.26	31.5	297	141.9
27.26	50.23	17.45 (W/m^2)	0.04	1.562	0.640	32.2	296.5	172
27.8	25.8	2.36	0.0645	0.777	1.29	32.9	297.0	163
6.4	25.4	[a]3	0.008	0.765	1.31	33.2	298.2	169
27.8	25.9	2.32	0.0645	0.764	1.31	33.5	297.1	178
28.03	25.4	1.842	0.0576	0.754	1.327	33.7	297.05	181.6
27.2	25.9	(0.2865)	0.008	0.760	1.317	34.1	297.6	148
12.2	25.4	2.08	0.0625	0.733	(1.364)	34.6	299.5	155
11.6	25.4	[a]2	0.0625	0.725	1.37931	35.0	299.1	164.4
NR	25.64	NR	NR	NR	NR	34.76	297.05	NR
8.86	25.52	(0.494)	0.04	0.717	1.395	35.6	296.78	166.1
9.7	25.5	(3.404)	0.25	0.712	1.404	35.8	303.2	167.8
28.06	25.4	39.77 (W/m^2)	0.01	0.706	1.417	36	296.93	167.6

[a]Value as submitted
(Values in parentheses were not originally reported, but were computed from the data submitted)

Table 7.12. HFM data for North American participants.

Temp. diff. (K)	Thick-ness (mm)	Power (W)	Metering area (m^2)	Rth ($K \cdot m^2 \cdot W^{-1}$)	Cth ($W \cdot m^{-2} \cdot K^{-1}$)	Kth ($mW \cdot m^{-1} \cdot K^{-1}$)	Tmean (K)	Mean density ($kg \cdot m^{-3}$)
24.02	25.86	(1.947)	(0.0645)	-0.796	(1.257)	32.5	297.06	125.18
-27.8	25.4	(3.325)	0.0929	(0.777)	(1.29)	32.7	297.0	163
24.12	25.90	(1.976)	(0.0645)	(0.787)	(1.270)	32.9	297.16	130.12
28.66	25.4	2.43	0.0645	0.762	1.31	33.0	297.3	158
27.1	26.1	(2.31)	0.0645	0.775	1.29	33.3	296.7	157
23.96	25.86	(2.002)	(0.0645)	(0.772)	(1.295)	33.5	297.05	155.1
21.9	25.4	(6.05)	0.209	0.756	1.32	33.6	297.0	165
24.02	25.90	(2.010)	(0.0645)	(0.771)	(1.297)	33.6	297.15	154.1
22.2	25.4	(6.05)	0.209	0.756	1.32	33.6	297.1	165
21.7	25.4	(6.02)	0.209	0.753	1.33	33.7	297.0	165
22	25.6	(2.70)	NR	(0.759)	(1.32)	33.8	297.3	(162)
27.8	25.4	2.377	0.0645	0.75	1.33	33.8	297.1	162.6
27.8	25.4	(2.39)	0.0645	(0.750)	(1.33)	33.9	297.0	160
27.6	25.4	0.380	0.0103	0.75	1.34	33.9	297.1	157.1
22.2	25.4	29.8 (W/m^2)	0.0413	0.745	1.34	34.1	297	166.0
22.200	25.4	-1.936	0.0645	(0.739)	1.352	34.35	296.888	159.83

(Values in parentheses were not originally reported, but were computed from the data submitted)

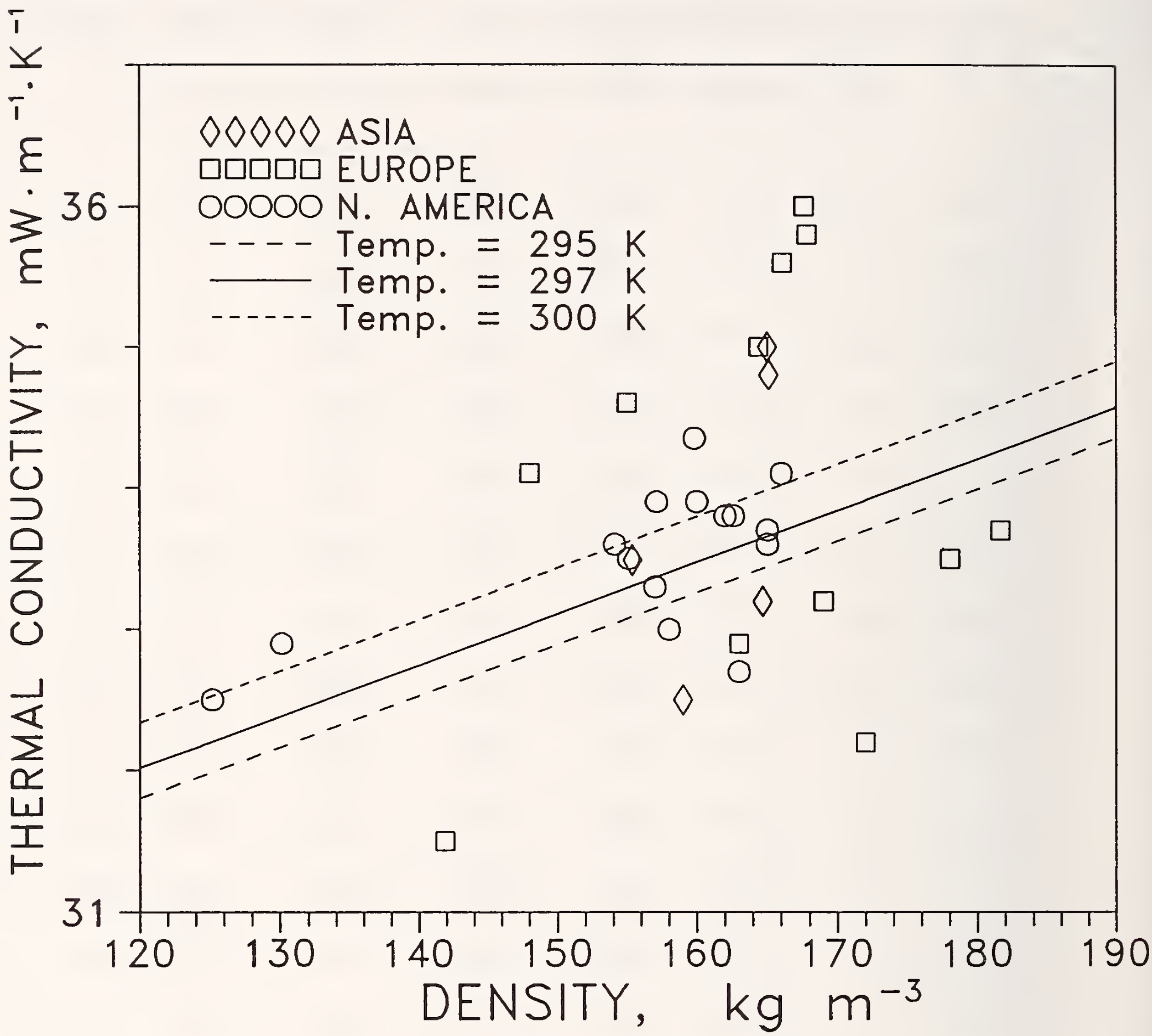

Figure 7.6 Measurements with heat flow meters (HFMs) of thermal conductivity of fibrous glass board specimens as a function of temperature, for all participants (Asia, Africa and Australia; Europe, and North America). The solid curve is eq (1), a least-squares fit, calculated for an assumed mean specimen temperature of 297 K. The mean specimen temperature for the five Asian participants' data displayed here was 297.4 K; that for the 15 European participants' data was 297.9 K; that for the 21 North American participants' data was 297.6 K. Plots of eq (1) for mean specimen temperatures of 295 K and 300 K are shown for comparison, to illustrate the effect of mean specimen temperature.

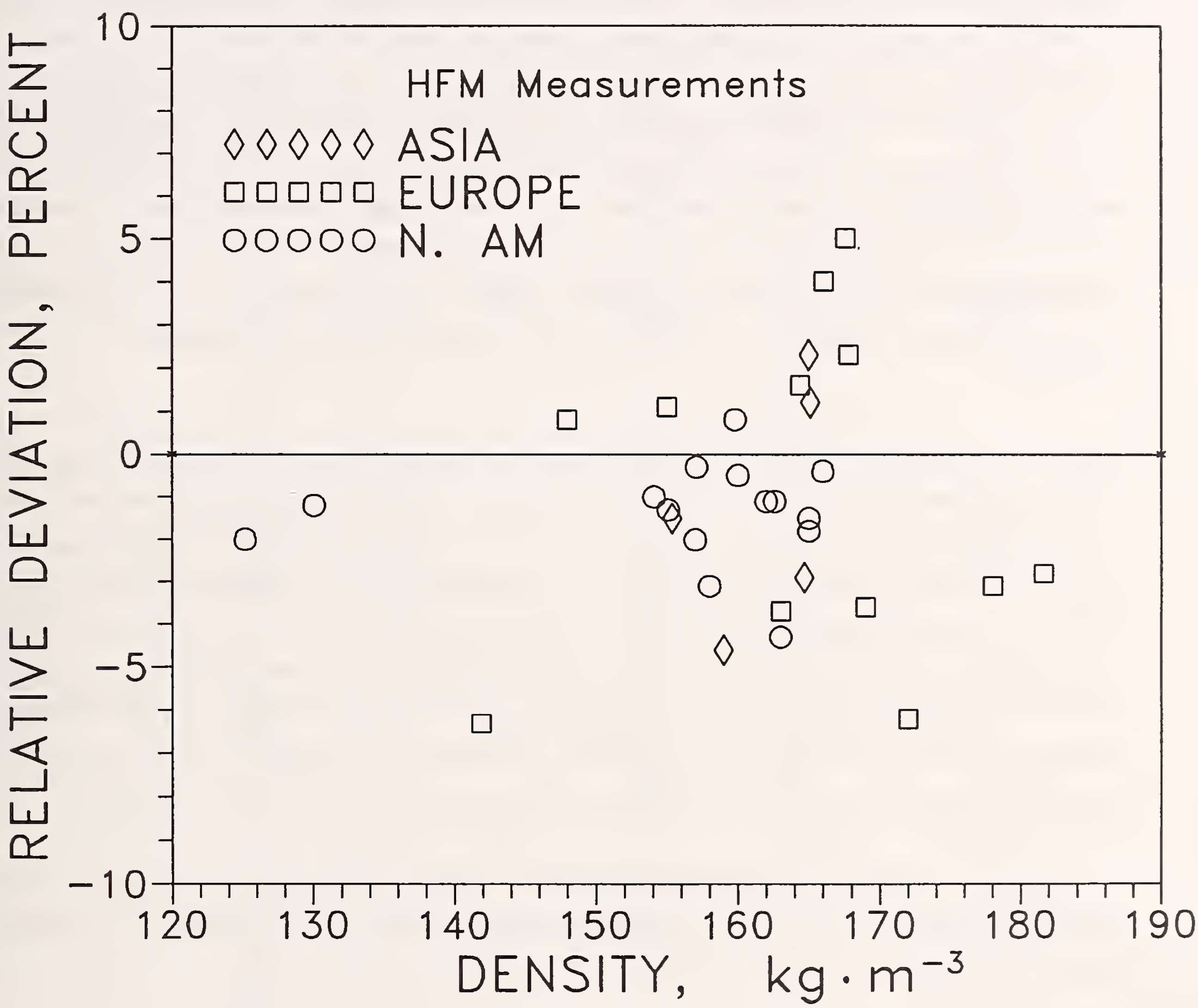

Figure 7.7 Deviations of HFM data in figure 7.6 from the fitted curve, eq (1), for all participants. The mean density of each individual specimen pair was used in eq (1) to compute each deviation.

7.1.3. Thermal Conductivity of a Layer of Air

The second type of specimen to be tested in the round robin was a layer of air approximately 25 mm thick, either on GHP or on HFM apparatuses. Some laboratories did not perform this measurement. The participants were not directed to correct their data for the (appreciable) effects of radiative transfer that could have been present in their apparatuses, between the plates bounding the air layer. No participants indicated that they did so. Thus the measurements here probably include the combined effects of conductive and radiative transfer, and can be compared only qualitatively with accepted values for the thermal conductivity of air. Table 7.13 lists the conductivity data obtained from laboratories that measured the thermal conductivity of the air layer in a GHP apparatus. The data sets have been randomized by sorting in order of increasing thermal conductivity to conceal the identity of the submitting laboratory. Values in parentheses were not reported but were computed from the other data and listed here if the calculated values were consistent with other submitted data. Values that appear to be in error and that could not be self-consistently recalculated were used as submitted.

Table 7.14 lists the data obtained from laboratories that measured the air layer with a HFM apparatus, and have also been randomized, as previously explained. In both tables the data have been sorted in order of increasing thermal conductivity to conceal the identity of the submitting laboratory. The values for the thermal conductivity of the air layer versus temperature as measured on both GHPs and HFMs are plotted in figure 7.8 for comparison. Only one point (lowest open square: 32 $mW{\cdot}m^{-1}{\cdot}K^{-1}$ at 297 K), for a measurement with a GHP, is near the value of the conductivity of air (about 26 $mW{\cdot}m^{-1}{\cdot}K^{-1}$ at 300 K). However, in the absence of information submitted by this participant about whether the total heat transfer was corrected for the effects of radiative transfer, even this point cannot be assumed necessarily to represent a valid measurement of the conductivity of air.

All the measured values obtained with heat flow meters lie far above the value of the thermal conductivity of air at 297 K, and do not represent a measurement of true conductivity. The significance of these data will be discussed in the next section.

Table 7.13. Thermal conductivity of a layer of air as measured with a GHP apparatus for North American (loops 1 and 2), "Asian" (loops 4 and 5), and European (loops 7, 8, 10, and 11) participants. H = horizontal; V = vertical; V_{dn} = vertical, down; NR = not reported.

	Plate emittances top	Plate emittances bottom	Heat flow direction	Tmean (K)	Kth ($mW \cdot m^{-1} \cdot K^{-1}$)	Temp. diff. (K)
NORTH AMERICA:	0.8	0.8	H	297	141.4	27.78
	0.9	0.9	H	297.05	152.8	27.78
	0.89	0.89	V	297	170	27.8
	0.95	0.95	V	297.19	175.9	12.038
	0.86	0.86	H	296.8	180	19.4
	0.9	0.9	H	295	187	22.9
	0.89	0.89	H	296.16	191.3	27.86
	0.96	0.96	V	297	191.8	28.3
ASIA:	0.35	0.35	NR	297	119.6	27.9
	0.8	0.9	H	299.0	123	31.4
	0.41	0.41	V	296.9	127.5	28
	NR	NR	V	297.5	132	28.9
	0.85	0.95	H	306.6	143.4	17.2
	0.8	0.8	H	296.9	148	28
	0.88	0.88	V	297.0	174.5	28.1
EUROPE:	NR	NR	V	297	32	10
	0.15	0.15	V	297	72	28
	0.64	0.64	V	296.6	86.1	9.86
	NR	NR	V	297.7	167	20.8
	NR	NR	NR	297.33	168.33	24.39
	0.9	0.9	V	290.97	168.9	16.20
	0.9	0.9	V	296	170	27.3
	NR	NR	V	297.02	171.5	28.00
	NR	NR	V	297.7	173	26.3
	0.82	0.82	V	297.08	174.0	28.42
	0.9	0.9	V	297	177.5	28.0
	0.92	0.92	V	297.1	178	28.1
	0.9	0.9	V	300.4	181	3.9
	0.95	0.95	V	296.93	184.8	28.08
	0.9	0.9	V_{dn}	296.96	191	28.03
	0.9	0.9	V	296.95	204	23.20

Table 7.14. Thermal conductivity of a layer of air as measured with a HFM apparatus by North American (loop 3), "Asian" (loop 6), and European (loops 9 and 12), participants. H = horizontal; V = vertical; V_{dn} = vertical, down; NR = not reported.

	Plate emittances top	Plate emittances bottom	Heat flow direction	Tmean (K)	Kth ($mW \cdot m^{-1} \cdot K^{-1}$)	Temp. diff. (K)
N. AMERICA:	0.9	0.9	H	297	77.8	22.2
	0.86	0.86	Vdn	297.1	152	27.6
	0.94	0.94	Vup	297.03	184.4	16.74
ASIA:	0.8	0.8	Vdn	301.9	87.78	24.2
	NR	NR	Vdn	297.1	117	27.8
	NR	NR	Vdn	302.2	172	19.5
EUROPE:	NR	NR	Vdn	297.04	142	28.07
	NR	NR	Vdn	294.8	144.3	3.30
	NR	NR	Vdn	297.1	147	27.8
	0.9	0.9	Vdn	297.05	151	37.2
	0.85	0.85	Vdn	297.15	156	27.2
	black	black	Vup	298	205	27.8
	NR	NR	Vup	298.09	207	25.00

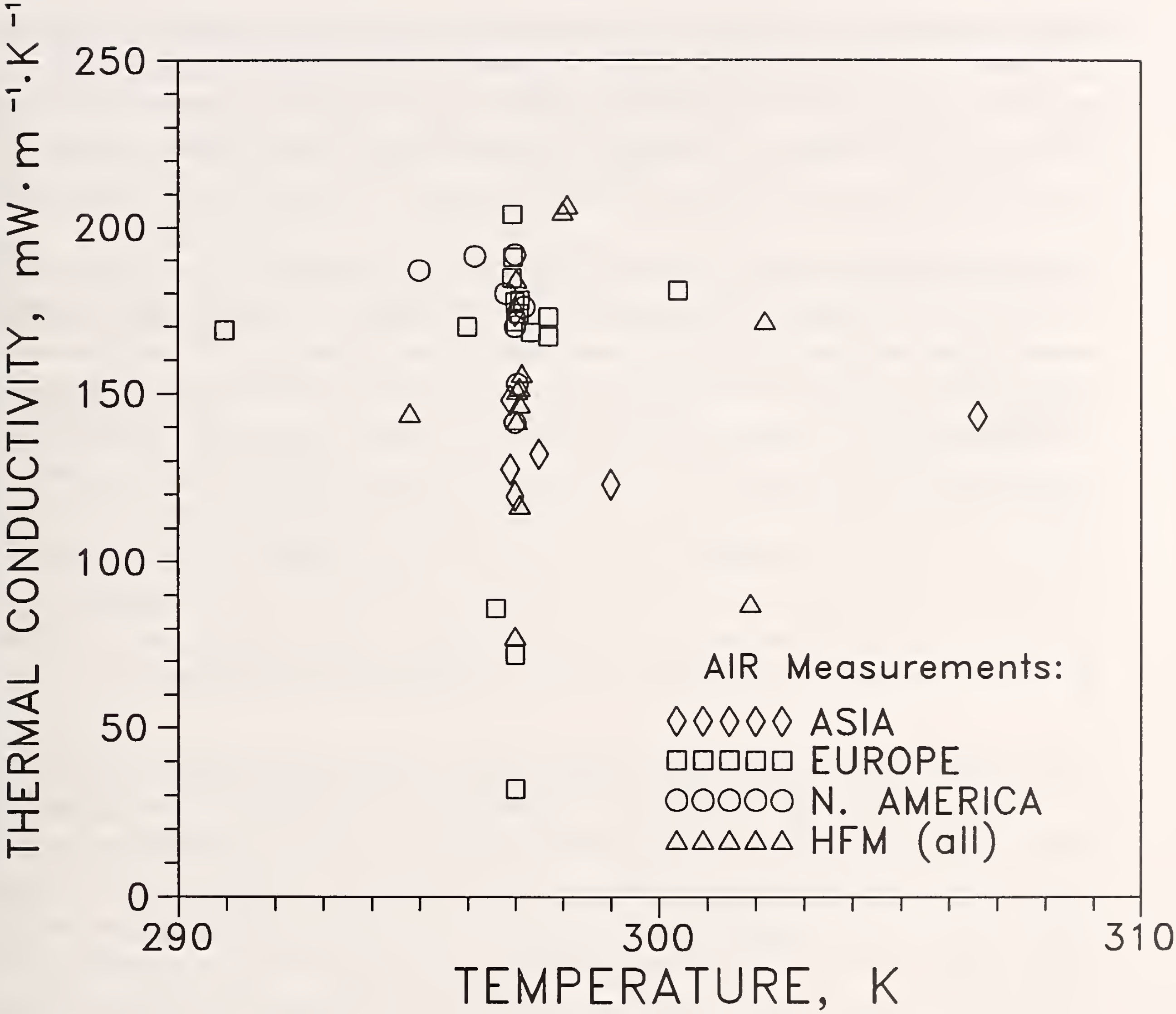

Figure 7.8 Measurements with GHPs and HFMs of the thermal conductivity as a function of temperature of an air layer 25 mm thick, by all participants (GHPs: diamonds, "Asia"; squares, Europe; circles, North America; HFMs: all participants).

8. FUTURE ROUND-ROBIN STUDIES: DISCUSSION AND RECOMMENDATIONS

8.1. Measurement of the Effective Conductivity of a Still Layer of Air

Asking the participants to measure the thermal conductivity of air offers the potential of using the air "specimen" as an in-house "standard reference material" freely and inexpensively accessible to all participants. The air layer would then be available to each laboratory as a permanent and reusable reference material for regular use. However, the very wide scatter in data for the conductivity of air suggests that almost all participants did not understand at all how to perform this measurement.

Measuring the conductivity of air, although not difficult when correctly done, is on the other hand not a trivial exercise. Because of the great difficulty apparently encountered by the participants in measuring the conductivity of air for this round robin, the procedures to be followed (several small thicknesses) in measuring the conductivity of air in any future round-robin program will have to be carefully spelled out in the next round-robin protocol. A paper by Jaouen and Klarsfeld [1] clearly describes a straightforward procedure for obtaining both the plate emittance and thermal conductivity of air in either a GHP or HFM apparatus. Each participant of any future round robin on GHPs or HFMs should at least be provided with a copy of this paper. Better would be to supply each participant with a detailed protocol for this measurement. Because a world-wide distribution of participants could include some located at altitudes as high as 1.5 km or higher, guidance should be given on how to correct for the small, but measurable, effects of atmospheric pressure,

The important feature in performing this measurement is that the conductivities of at least two or three different layers of air of different thicknesses should be measured. To promote stable stratification of the air layer, the flow of heat should be downward only, and the thickness of each layer should be of the order of only a few millimeters, to guard against the occurrence of convective heat transfer. This can be accomplished by the use of a set of two plastic annular rings, each having an annular (radial) width of 4 or 5 mm and an outer diameter equal to that of the usual specimen. If one ring is, say, 3 mm thick and the other, twice as thick (6 mm), then the conductivity of air may be measured at three different thicknesses: 3, 6, and (stacking the two rings together) 9 mm. The exact thicknesses are of course subject to choice, but should be fairly uniformly spaced.

By measuring the heat transfer through the air layers at different thicknesses, one can obtain a line whose slope and intercept contain information from which both the plate emittance and thermal conductivity of air may be readily obtained. The use of at least three different thicknesses allows a line to be fitted by linear least squares, with consequent partial averaging out of the contributions from random experimental errors. This test provides not only a test of the ability to measure the thermal conductivity of a "standard material" (still, nonconvecting) air, but also provides an estimate of the plate emittance in the apparatus.

In retrospect, it seems clear that the choice of a thickness for the air layer of 25 mm, rather than 6 mm, was unfortunate. This thickness is too large to ensure accurate measurements of thermal conductivity of a (fluid) gas. Also, in order to stratify the air layer and minimize the possibility of convective heat transfer, the conductivity should have been measured for only a single layer of air, with the top boundary (hot plate) at a greater temperature than that of the bottom boundary (cold plate). For guarded hot plates this involves operation in a "one-sided" mode, a procedure with which many or most participants may not have been familiar. For both apparatuses care must be taken to set up a thermally stratified, stable (nonconvective) layer of air for measurement.

The data for the air measurements do not prove, but are consistent with, the possibility that (a) convective effects permitted by the large thickness, and (b) effects of unknown but variable plate emittances, had a strong influence on the total heat transfer. The participants did not have the procedure outlined by Jaouen and Klarsfeld [1] available to them. As a result, total heat transfer, not simply thermal conductivity, was the actual physical variable actually measured by both types of apparatus in the round robin.

8.2. Reporting of Data by Participants

The two data sheets sent to participants for submitting their conductivity results were quite detailed. One form asked for information on the preparation of the specimens for the measurements. The second asked for all the experimental data as input. It asked the participant to calculate as output values the heat-flux density and thermal resistance, conductance, and conductivity from the input data. The forms were, in effect, worksheets. The forms for reporting measurements of air were practically identical to those for reporting measurements of fibrous glass board. The only difference was the number of determinations to be made.

Both the input and the output data formed somewhat redundant sets of data. For example, in the set of input data, <u>either</u> the set of both surface temperatures <u>or</u> the set of mean temperature and temperature difference suffice to calculate the output quantities needed. However, asking for <u>both</u> sets of temperature values provided a valuable tool for checking for internal consistency of the input data. Similarly, asking for heat flux, thermal conductance, thermal resistance, and thermal conductivity provided sufficient redundancy for checking for internal consistency of the output data by the author, especially if certain data were not included.

At the cost of additional labor, the redundancy of input and output data allowed, in a few cases, some minor errors to be corrected in both input and output, and the appearance of error, where none really existed, to be avoided. It also revealed, in the case of inconsistent input data, a genuinely erroneous data point that did not truly reflect the experimental input values. However, such an outlier was not rejected from the population of data; the ability to report the values correctly is certainly part of what is (or should be) tested in a round robin. The use of redundancy in the submitted information therefore turned out to be a resource of some significant value in identifying where problems exist.

An interesting problem arose with some laboratories that undertake routine testing of thermal properties regularly. They submitted their round-robin data on the same forms usually used for reporting data to clients. These "in-house" forms did not contain all the information that was asked for on the "official" round-robin forms drawn up by the convenor of the round robin, and this situation prevented any testing for internal consistency. The same defects arose when one report was submitted on raw computer printouts, forcing a search of the output for data that would lead to the requested information.

On a related topic, in some cases the data were not submitted in the (SI) units requested and had to be converted by hand. This leads to the possibility of errors creeping into the output data, where the participant is not the source of the errors.

Submitting reports on unique sizes of paper or in official binders made filing of the whole set of round-robin forms difficult. Whoever analyzes the data handles the report forms many times in entering the data, in double-checking for accuracy, and in going back to answer any questions that may arise. Thus it is wise to emphasize in any round robin that all data should be submitted on the forms supplied to the participants for that purpose, and in the exact units requested.

8.3. Criteria for Measurements

The results show that organizers of any future round robin must ensure that a clear set of criteria are established for conducting the measurements of thermal conductivity. Whether the use of either national or ISO standards are to be left to the choice of the participant, or specified by the planning committee, must be decided upon in advance in order to promote uniformity of measuring conditions among a community of world-wide participants. If only one standard is to be adhered to (or a few uniform, widely accepted standards such as ASTM and/or ISO), care should be taken to ensure that all participants have access to the relevant measurement standards. Participants should then indicate clearly which standard they are using in performing their measurements. For uniformity in submission of data, SI units should again be specified. It should be clearly stated that only data in SI units will be accepted into the round robin.

Deciding on the ambient conditions to be established or permitted is complicated of course by the fact that in any world-wide round robin or intercomparison, ambient conditions can vary widely with geographic location, as well as with seasons of the year. Some participants may have laboratories with carefully controlled ambient conditions, while others may have open-window exposure to local conditions of weather and climate.

In particular, such important parameters as mean temperature of measurement, temperature difference, measured thickness, the range of ambient temperature, pressure and humidity permitted or established in the laboratory during the measurement, and the order in which data points are to be measured, must all be carefully considered. Some conditions (general laboratory ambient) may of necessity have to be left to the participant to decide upon, while other, more critical conditions (such as specimen conditioning for measurement of density and thermal conductivity) may have to be specified as mandatory. Care must be taken in specifying in advance the ambient conditions for measurement of related parameters such as density and thickness.

In this round robin the conditions for measurement of density were carefully specified. However, the period of time allowed to elapse between measurement of density and measurement of thermal conductivity was not specified or even addressed. If a specimen whose density has been measured were then to be permitted to be exposed to the moist air of a humid climate or weather condition for a period of several days or more before having its conductivity measured, the "conductivity specimen" could conceivably be different from the "density specimen," both in density and in conductivity.

8.4. Formal Submission of Data

It is prudent to make it a mandatory requirement that all data from each participant be submitted on the forms supplied by the director of the round robin. As indicated earlier, problems arose in this round robin when data were submitted on report forms other than those provided by the convenor. In every such case the forms either presented irrelevant data or failed to supply some of the requested data, or both. This leaves the analyst with the necessity of converting units and the burden of not making errors that would reflect poorly (and unfairly) on the submitting participant. (When such conversion was required, every effort was made by the analyst to double-check calculations of unit conversions to avoid generating errors.) Such examples complicate the testing of internal consistency or result in incomplete submission of data critical to the round robin.

8.4.1 Statistical Considerations

Repeating measurements after attaining the highest or lowest mean temperature should, if permitted, also be clearly described. In any case it should be made clear what number of conductivity measurements are to be performed by each participant, and that only those submitting this exact number of measurements will have their data accepted into the intercomparison. It is very important to have a uniformly sized set of data from each participant, for uniform statistical weighting of data among the total population of participants. The analyst cannot supply missing data.

In some instances a set of data larger than that requested was submitted. Participants, not convenors and/or analysts, should be the ones deciding which specific set of data is being submitted by the participant as the official entry of a set of data into a round robin. Ultimately, only the participant is fully qualified to make such a decision.

Frank J. Powell (now retired from NBS/NIST) was the convenor of WG 6 and organized this international round robin, coordinated the logistics of getting specimens to the participants, and collected the reports of measurements. He provided much background material to the present author to assist in preparing this report. The Building Environment Division at NIST funded the preparation of this report. Owens-Corning Fiberglas Company, of Toledo, Ohio, USA kindly donated a specially manufactured lot of fibrous glass insulation board used as the round-robin test material.

9. REFERENCES

[1] J.-L. Jaouen and S. Klarsfeld, "Heat Transfer Through a Still Air Layer," in *Thermal Insulation: Materials and Systems: ASTM STP 922*, F. J. Powell and S.L. Matthews, Eds. (American Society for Testing and Materials, Philadelphia, 1987), pp. 283-294.

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