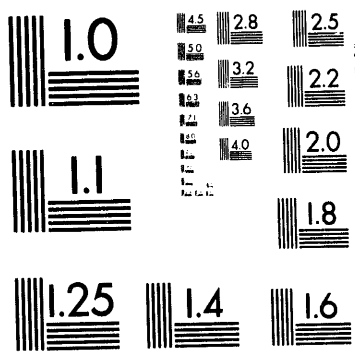
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1 of 1

INTERLABORATORY COMPARISON OF THE HORIZONTAL PIPE INSULATION TEST APPARATUS UP TO 350°C*

Thomas E. Whitaker(1), Ronald S. Graves(2), David L. McElroy(3), and David R. Smith(4)

ABSTRACT

The purpose of this interlaboratory comparison was to provide information for the precision and bias section in the ASTM Standard Test Method C 335, "Steady-State Heat Transfer Properties of Horizontal Pipe Insulation." (The text describes the ASTM C 335 test method, the specimens tested and the test protocol.) The apparent thermal conductivity of two rigid calcium silicate pipe insulation specimens was measured by eight laboratories. Each laboratory measured both specimens at four different temperatures. The test mean temperatures ranged from 35 to 390°C. The two standard deviation value for the data ranged from 4.5 to 7.7% and the average value was 6.3%. The statement recommended for the precision and bias statement for Section 13.1.4 of ASTM C 335 is: "Tests performed at seven different laboratories using guarded-end horizontal pipe test apparatus and at one laboratory using an unguarded cylindrical screen test apparatus on two specimens of calcium silicate insulation in the range of mean temperatures from 35 to 390°C did not vary by more than 6.3% (two standard deviations) of the average."

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INTRODUCTION

The American Society for Testing and Materials (ASTM) Committee C 16 on Thermal Insulation recognizes the importance of thermal conductivity (k) measurements. ASTM C 16 establishes and maintains a number of test method standards for absolute-or- comparative, linear-or-radial techniques to measure k of insulations. ASTM C 335 [1] is a standard test method for the measurement of steady-state heat transfer properties of pipe insulations installed on a horizontal test pipe operating at temperatures above ambient. It is an absolute, radial method where direct measurements of the quantities needed to obtain k are made. ASTM Subcommittee C 16.30 on Thermal Measurements has direct responsibility for this standard. Maintaining and developing an accurate and viable Precision and Bias (P/B) statement that describes the capability of a C 335 apparatus is an integral part of this responsibility. The goal of this interlaboratory comparison was to obtain results on a stable material. Calcium silicate was used to add to the P/B statement of C 335. This addition is needed because C 335 is cited in ASTM C 533, the standard for calcium silicate pipe insulation, as a method to measure k.[2]

Table 1 summarizes the existing P/B section of ASTM C 335 that is based on three comparison programs conducted by ASTM Subcommittee C 16.30 to determine the reproducibility of this test method.[3,4] In two studies properties were measured concurrently using several specimens chosen from the same production lot. This choice forces the test error to include both apparatus and material variabilities. In the current interlaboratory comparison, and in the initial study [3], measurements on one specimen or two specimens were compared, so the test error does not include a material variability value. The current study is an additional comparison based on the recommendations in ASTM C 335 (89).

APPARATUS DISCUSSION

Figure 1 shows the cross section of a horizontal pipe insulation test apparatus designed to meet ASTM C 335(89). It consists of the heated test pipe and instrumentation for measuring the pipe and insulation surface temperatures, the average ambient temperature, and the average power dissipated in the test section of the heater. In the guarded-end design, the central cylindrical core heater has cylindrical guard heaters placed at each end of the core heater. This assembly is positioned inside Type 304 stainless steel or Inconel pipe (88.9 mm (3 1/2 inch) outside diameter).

Table 2 lists the total lengths, the active metered lengths and the guard lengths for seven guarded-end apparatuses and one unguarded tester. The total apparatus lengths ranged from 0.9 to 2.1 m (36 to 84 in.) with lengths of metered areas from 0.4 m (18 in.) to 0.9 m (36 in.). The specimen insulation to be tested is fitted around the stainless steel or Inconel pipe. The pipe has cylindrical grooves cut at the ends of the active length to minimize heat exchange between the main test section and the guarded sections. The pipe and the insulation specimen are fitted with thermocouples to determine the steady-state temperature differential across the specimen. The guarded-end apparatus uses separately heated pipe sections at each end of the test section to minimize axial heat flow in the apparatus. The guard section length is sufficient to limit the combined axial heat flow at each end of both the apparatus and the specimen to less than 1% of the test section measured heat flow.[1] The thermal conductivity is calculated from:

$$k = (P \cdot \ln r2/r1)/(2 \cdot \pi \cdot (T1 - T2) \cdot L), \quad (1)$$

where P is the meter length power, W,

r2 is the outer radius of circular insulation, m,

r1 is the inner radius of circular insulation, m,

L is the length of the meter heater, m,

T2 is the temperature of insulation outer surface, K,

T1 is the temperature of insulation inside surface, K.

The guarded-end, horizontal pipe test apparatus is an absolute technique because no calibration specimen is used with the apparatus and because k is obtained from direct measurement of the quantities in Eq. 1.

One participant in this interlaboratory comparison used an electrically-heated, cylindrical Nichrome screen rather than an internally heated pipe.[5] Table 2 lists the total length and the metered length for this unguarded cylindrical screen heater that was 88.9 mm outside diameter, instrumented with Type S (Pt-10% Rh versus Pt) thermocouples, and had an estimated fractional error of 1.3% for the quantities in Eq. 1. The text of ASTM C 335 notes this design is pertinent to the standard, and its inclusion in this interlaboratory comparison provides an opportunity to validate this note. Each participant was asked to complete the equipment survey form. These forms showed all seven participants using guarded-end apparatuses used Type K thermocouples. The estimated measurement uncertainties of their apparatuses ranged from 2 to 5%.

DESCRIPTION OF SPECIMENS AND TEST PROTOCOL

The Chairman of the C 16.30 Task Group 3.1 C 335(89) Pipe Insulation Test Methods, (T. E. Whitaker, who was a participant in the 1992 Interlaboratory Comparison) carefully selected Specimens A1/A2 and B1/B2 from a commercially-produced calcium silicate pipe insulation [6]. The four individual pieces were halves of pipe insulation cylinders that were 0.91 m (36 in.) long and for use on 3 inch nominal pipe size. The actual specimen inside diameter was near 88.9 mm (3.5 in.) and the wall thickness was near 41.5 mm (1.6 in.). The four individual pieces were selected on the basis of density, nominally 145 kg/m^3 (9.1 lb/ft^3), to produce two matched specimens. Each participant was asked to submit as-tested specimen dimensions (length, wall thickness, and circumference), mass, and density. Table 3 lists the as-tested density values for Specimens A1/A2 and B1/B2, which had average values of 145.3 and 150.2 kg/m^3 (9.07 and 9.38 lb/ft^3) respectively. Specimen B1/B2 is about 3.4% more dense than Specimen A1/A2.

The as-tested density values given in Table 3 were obtained by the participants when Specimens A1/A2 and B1/B2 were at their facilities. The specimens were "circulated concurrently in opposite directions" to a list of the participants. For example, an alphabetical listing of the eight participants would have started testing of Specimen A1/A2 at the California Bureau of Home Furnishings and ended testing of it at Pabco, while concurrently Specimen B1/B2 would have started at Pabco and ended at the California Bureau of Home Furnishings.

Prior to any thermal testing by the participants, Specimens A1/A2 and B1/B2 were conditioned in the Pabco C 335 apparatus with the hot cylindrical surface at 650°C (1200°F) for 24 hours. The k-values for the post-conditioned state for Specimens A1/A2 and B1/B2 (Test k-1) were determined at Pabco. In addition, three tests were conducted at Pabco after the participants had completed all thermal tests. These data sets were fitted by the method of least-squares to

$$k = A + B \cdot Tm + C \cdot Tm^2 \qquad (2)$$

where Tm is the mean test temperature. The 100°C values of k predicted by these fits are given in Table 4. The predicted k-values agree to 2.2%, and this result gives the reproducibility of the mean values from the C 335 apparatus at Pabco at 100°C.

RESULTS BY PARTICIPANTS AND ANALYSIS

Specimens A1/A2 and B1/B2 were circulated to the participants with a test data form. The form identified the participant, laboratory, specimen dimensions and density and had space for data from four tests with a hot surface temperature below 650°C (1200°F). The requested data included duration of test, average and range of the pipe temperature and the cold surface temperature, the main heater power, and the apparent conductivity.

Each participant submitted four data points on Specimen A1/A2 and four data points on Specimen B1/B2. Table 5 contains the 64 individual data points submitted for Specimens A1/A2 and B1/B2 by the eight participants. The data sets provided by the participants were converted to SI units and these were checked for consistency by calculating the geometry factor from $k \cdot (T_2 - T_1)/P$. This revealed two of 64 data were in error and these were corrected. The tests used hot temperatures ranging from 50 to 700°C (120 to 1290°F) and cold temperatures from 20 to 90°C (68 to 194°F) to yield mean temperatures from 36 to 390°C (97 to 734°F) with k-values from 43 to 76 mW/m·K (0.30 to 0.52 Btu·in./h·ft^2·°F.

The 32 individual k-values for Specimen A1/A2 and 32 values for Specimen B1/B2 are plotted versus the test mean temperature in Figure 2 and Figure 3, respectively. The 32 data points in Table 5 (Specimen A1/A2) were least-square fitted using equations listed in Table 6. The r-squared values given in Table 6 for these equations do not indicate any significant difference in the quality of the fits. Thus, Eq. 3 in Table 6 (Tm quadratic) was used to fit each of the data sets listed in Table 5 for Specimens A1/A2 and B1/B2. This procedure yielded the coefficients given in Table 7 for each data set. The individual data sets have r-squared values that exceed 0.99. These coefficients were used to calculate the k-values at 50°C increments from 50 to 350°C that are given in Table 8 and plotted in Figs. 4 and 5. For each specimen the eight points calculated at each temperature were used to compute an average k and the two standard deviation value for these eight points. Two standard deviations ranged from 2.1 to 5.5 mW/m·K (0.015 to 0.038 Btu·in./h·ft^2·°F). The two standard deviation value expressed as a percentage ranges from 4.5 to 7.7% and has an average of 6.3%.

The measured k increases with temperature and has a k that is 1.5 to 1.6 times that of gaseous nitrogen (conduction only).[7] The calcium silicate samples are about 10% of the theoretical density of calcium silicate, which is 2905 kg/m^3, which suggests that radiative, solid, and gaseous conduction components are acting in parallel with additive thermal conductivity components:

$$k\ (\text{total}) = k\ (\text{radiation}) + k\ (\text{gas}) + k\ (\text{solid}) \qquad (3)$$

$$= aT^3 + F \cdot k\ (N_2) + (1 - F)\ k\ (\text{solid})$$

where F is the fraction of theoretical density. Table 9 shows one set of values for these components that account for the magnitude and temperature dependence of k (total) to ±1 mW/m*K.

CONCLUSIONS AND RECOMMENDED P/B STATEMENT

Eight laboratories measured the thermal conductivity of two specimens of calcium silicate insulation in the 1992 Interlaboratory Comparison for ASTM C 335. Each laboratory reported four data points in the range 35 to 390°C on each specimen. The two standard deviation value for the data set was 6.3%.

The statement recommended for the precision and bias statement for Section 13.1.4 of ASTM C 335 is: "Tests performed at seven different laboratories using guarded-end, horizontal pipe test apparatus and at one laboratory using an unguarded cylindrical screen test apparatus on two specimens of calcium silicate insulation in the range of mean temperatures from 35 to 390°C did not vary by more than 6.3% (two standard deviations) of the average."

Results from the 1992 Interlaboratory Comparison:

1.) Show that equivalent results are obtained by the guarded-end and the unguarded screen apparatus.

2.) Show that the apparent thermal conductivity of calcium silicate insulation increase with mean temperature and can be described equally well by either linear or quadratic functions of mean temperature.

3.) Show a 9% range in as-tested density, which seems excessive and suggests examination of the procedure used to determine the density.

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T. E. Whitaker, Pabco, Fruita, CO.

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Table 1. Summary of precision and bias statement in ASTM C 335(89).

Section	Number of Participants	Material and Hot Surface Temperature Range	Number of Specimens	Maximum Test Error (%)
13.1.1	10	Glass Fiber, 60 to 260°C	1	3
13.1.2	3	Reflective, 149 to 480°C	3	7
13.1.3	7	Preformed Mineral Fiber Pipe Insulation, 46 to 670°C	7	10

Table 2. Total lengths, meter lengths, and guard lengths for seven guarded-end C-335 apparatuses and one unguarded cylindrical screen pipe insulation tester.

Total Length		Metered Length		Guard Length	
m	in.	m	in.	m	in.
2.13	84	0.914	36	0.614	24
0.914	36	0.614	24	0.152	6
1.524	60	0.915	36	0.305	12
1.324	52	0.610	24	0.355	14
1.524	60	0.914	36	0.305	12
0.914	36	0.610	24	0.152	6
0.914	36	0.610	24	0.102	4
0.952	37.5	0.457	18	Unguarded	

Table 3. As-tested density for calcium silicate pipe insulation Specimens A1/A2 and B1/B2 in the 1992 Interlaboratory Comparison.

Lab	Specimen A1/A2		Specimen B1/B2	
	kg/m³	lb/ft³	kg/m³	lb/ft³
1	145.5	9.08	147.9	9.23
2	144.8	9.04	149.3	9.32
3	140.3	8.76	152.7	9.53
4	147.4	9.20	152.2	9.50
5	141.4	8.83	144.7	9.03
6	153.2	9.56	158.0	9.86
7	144.3	9.01	146.5	9.14
8	145.8	9.10	150.6	9.40
Average	145.3	9.07	150.2	9.38
Std. Dev. σ	3.7		3.9	
Percent	5.1 (2 σ)		5.2 (2 σ)	

Table 4. Values of k at 100°C predicted by fitting Pabco tests on post-conditioned, and after testing by participants materials.

Test	Specimen A1/A2 (mW/m·K)	Specimen B1/B2 (mW/m·K)
k-1 (100)	47.4	46.0
k-2.1 (100)	47.3	45.8
k-2.2 (100)		46.8
k-2.3 (100)		46.2

Table 5. Test results submitted by eight participants in the 1992 Interlaboratory Comparison on the apparent thermal conductivity of calcium silicate pipe insulation Specimens A1/A2 and B1/B2.

	Specimen A1/A2			Specimen B1/B2		
	T(Hot)	T(Cold)	k	T(Hot)	T(Cold)	k
Lab	°C	°C	mW/m·K	°C	°C	mW/m·K
1	155.0	32.2	46.4	142.6	33.0	46.4
	257.2	39.4	50.8	260.5	42.8	50.8
	365.0	49.4	56.1	368.9	53.2	56.1
	481.7	61.7	61.0	479.8	59.8	61.0
2	120.6	30.3	45.1*	102.1	29.1	45.1
	302.6	44.7	52.8	252.2	41.9	51.5
	477.7	60.5	60.6	403.7	55.8	58.6
	583.5	70.3	65.5	544.1	70.2	65.0
3	169.7	35.4	49.9	176.0	36.4	47.8
	315.3	50.5	58.3	317.1	49.9	55.4
	452.2	64.3	66.2	461.6	63.0	62.3
	548.7	74.8	71.7	590.3	74.0	69.5
4	179.1	31.8	48.5	53.1*	20.4	43.1*
	331.6	38.8	58.4	273.5	37.6	53.9
	470.5	50.7	64.9	486.3	53.0	67.9
	578.7	58.2	71.7	588.8	61.5	71.0
5	115.3*	28.2	47.3	110.0	27.5	47.8
	259.1	42.8	51.1	220.8	36.9	50.4
	318.1	51.9	54.6	435.5	56.1	61.0
	651.3*	82.1	73.7*	699.5*	83.0	75.6*
6	176.5	37.2	48.3	179.3	39.0	49.6
	315.9	50.1	55.5	313.3	53.0	56.0
	460.6	65.3	63.6	454.7	58.1	62.6
	595.2	74.3	69.5	595.0	84.3	72.4
7	175.0	39.0	50.4	158.8	38.0	50.5
	335.3	54.5	57.6	330.4	56.3	58.6
	455.0	63.9	63.0	451.1	69.6	64.5
	603.5	80.2	70.7	613.4	89.2	73.3
8	182.3	37.9	48.2	186.7	39.1	46.9
	312.1	49.8	54.2	309.1	48.9	51.9
	390.4	57.3	58.1	401.7	57.3	56.4
	489.4	66.9	63.6	501.2	67.2	62.2

*Low or high values

Table 6. Equations used to fit data sets for Specimens A1/A2 and B1/B2.

Equation for k	r-squared
1. $A + BTm + C\frac{Th^3 - Tc^3}{(Th - Tc)/3}$	0.944
2. $A + BTm$	0.942
3. $A + BTm + CTm^2$	0.944
4. $A + BTm + C(Th^2 - Tc^2)*Tm/2$	0.943

Table 7. Coefficients of a quadratic fit to the participants data sets for Specimens A1/A2 and B1/B2.

Lab	Specimen A1/A2 Coefficients			Specimen B1/B2 Coefficients		
	A	B*E+2	C*E+5	A	B*E+2	C*E+5
1	38.14	8.94	-1.86	40.87	5.64	6.86
2	39.52	7.29	1.98	40.03	7.59	1.82
3	39.05	10.63	-0.47	38.23	8.97	1.24
4	35.57	12.99	-5.51	39.03	10.37	-0.88
5	44.85	2.13	15.66	43.86	4.47	9.38
6	36.81	11.07	-3.83	42.92	5.05	10.62
7	42.71	6.77	4.13	42.81	7.47	3.40
8	40.25	6.41	7.10	41.01	3.73	13.04

Table 8. Smoothed k-values at 50°C increments from 50 to 350°C.

Specimen A1/A2:

Lab	50	100	150	200	250	300	350
1	42.56	46.89	51.13	55.28	59.34	63.30	67.17
2	43.22	47.01	50.90	54.89	58.98	63.17	67.46
3	44.35	49.62	54.88	60.11	65.32	70.50	75.66
4	41.93	48.01	53.81	59.34	64.60	69.58	74.28
5	46.31	48.55	51.57	55.38	59.97	65.34	71.50
6	42.26	47.51	52.57	57.44	62.12	66.60	70.90
7	46.21	49.90	53.81	57.91	62.23	66.75	71.48
8	43.64	47.37	51.47	55.91	60.72	65.87	71.39
Avg.	43.81	48.11	52.52	57.03	61.66	66.38	71.23
Two SD	3.18	2.16	2.78	3.70	4.41	4.93	5.47
(%)	7.25	4.48	5.29	6.49	7.15	7.42	7.68

Specimen B1/B2:

Lab	50	100	150	200	250	300	350
1	43.86	47.20	50.88	54.90	59.26	63.97	69.02
2	43.88	47.81	51.83	55.95	60.15	64.45	68.84
3	42.75	47.33	51.96	56.67	61.43	66.25	71.14
4	44.19	49.31	54.38	59.41	64.40	69.34	74.24
5	46.33	49.27	52.68	56.56	60.91	65.72	71.00
6	45.71	49.03	52.88	57.26	62.18	67.62	73.59
7	46.63	50.62	54.78	59.11	63.61	68.28	73.12
8	43.20	46.04	49.54	53.68	58.48	63.93	70.03
Avg.	44.57	48.33	52.37	56.69	61.30	66.19	71.37
Two SD	2.73	2.77	3.23	3.63	3.83	3.85	3.88
(%)	6.14	5.74	6.17	6.41	6.24	5.81	5.44

Table 9. Heat transfer components (mW/m·K) of calcium silicate insulation.

T, K	(1-F)* k (solid)	0.9 k (N_2)	k(rad)* $0.5E\text{-}7T^3$	k (pred.)	k (avg.)	Diff.
323	18	24.5	1.7	44.2	44.2	0.0
423	18	30.2	3.8	52.0	52.5	0.5
523	18	36.1	7.2	61.3	61.5	0.2
623	18	41.9	12.1	72.0	71.3	0.7

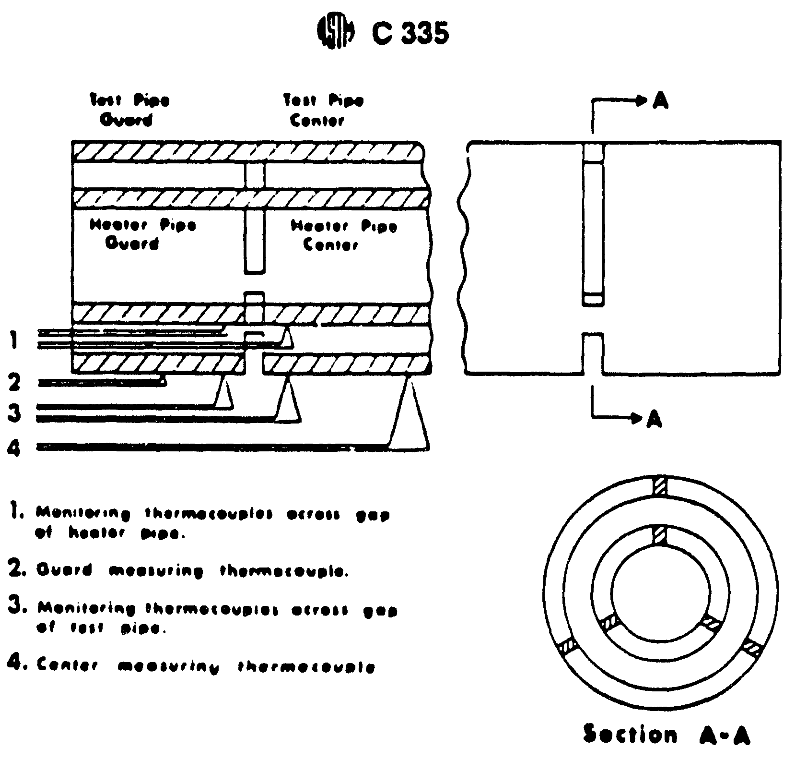

Figure 1. Cross section of a horizontal, guarded-end C 335 pipe insulation test apparatus.

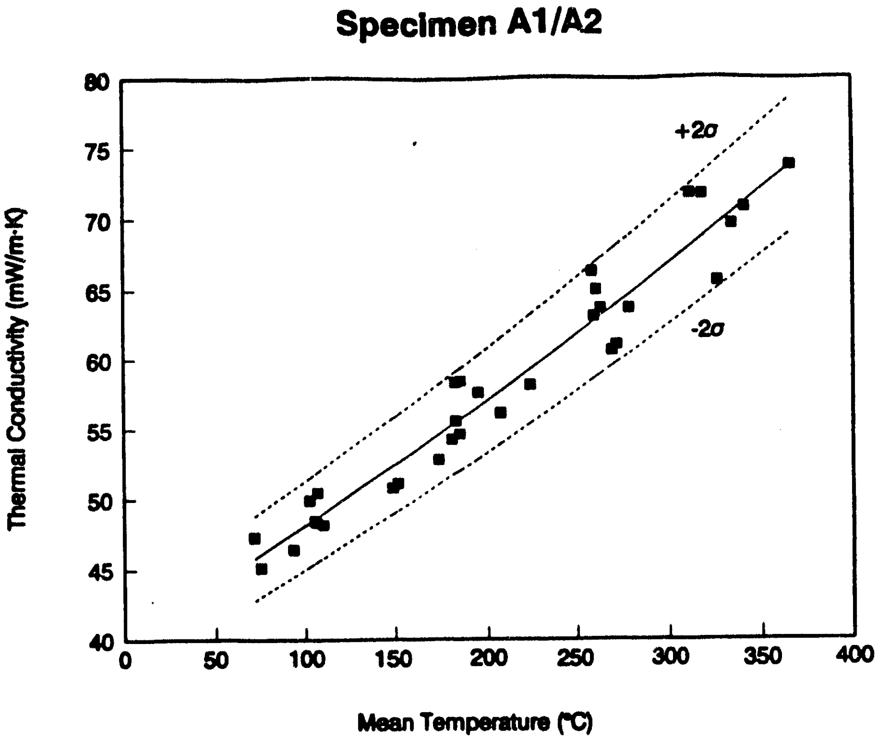

Figure 2. Thermal conductivity results supplied by participants as a function of a mean temperature for Specimen A1/A2.

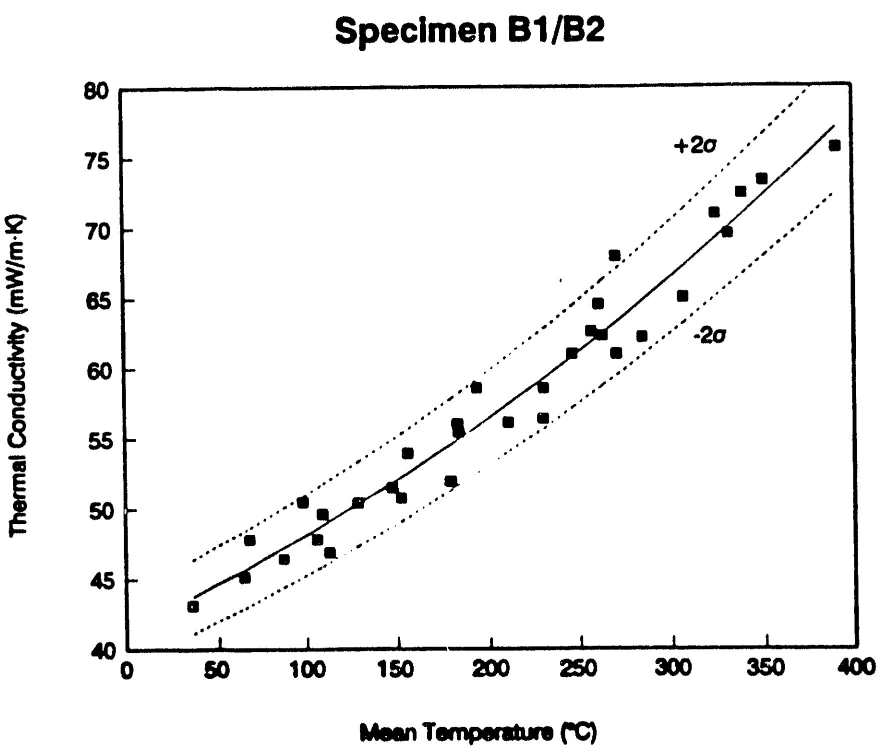

Figure 3. Thermal conductivity results supplied by participants as a function of mean temperature for Specimen B1/B2.

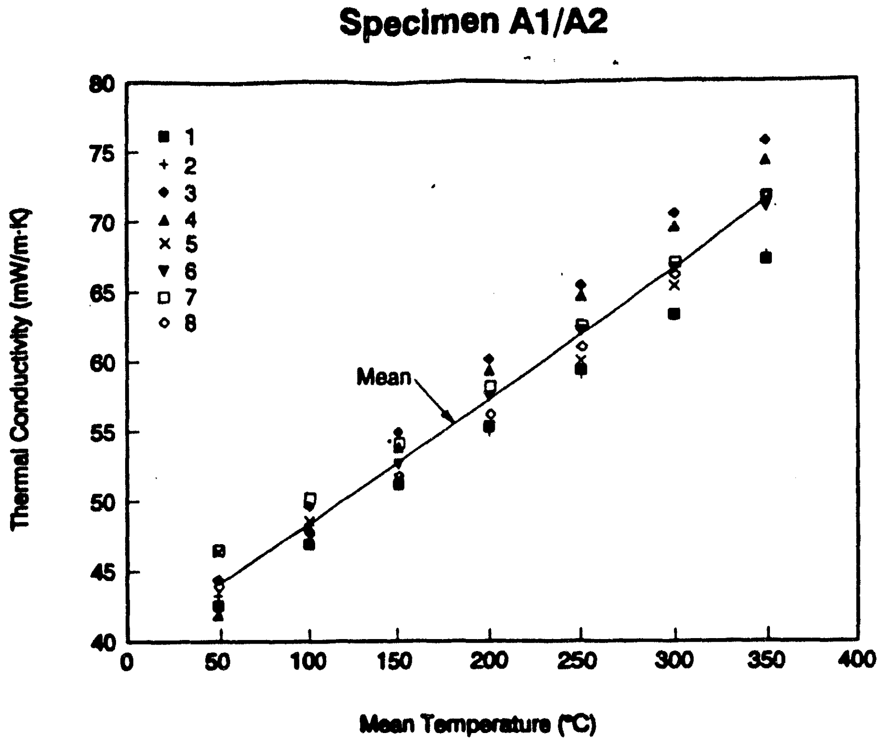

Figure 4. Smoothed thermal conductivity results for Specimen A1/A2 as a function of mean temperature.

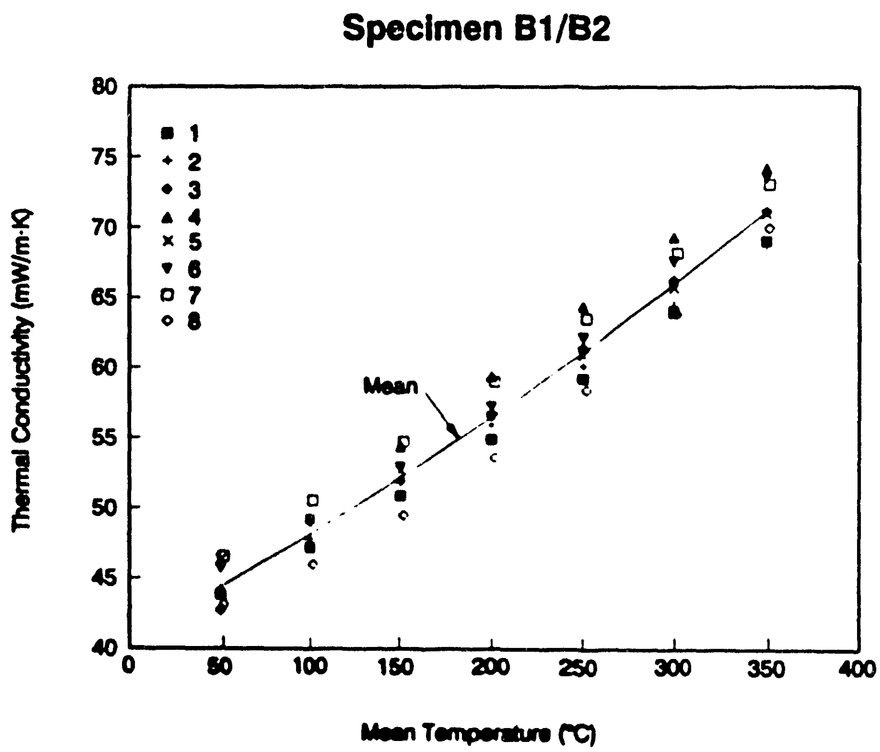

Figure 5. Smoothed thermal conductivity results for Specimen B1/B2 as a function of mean temperature.

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