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Optimizing the decay range in room acoustics measurements using maximum-length-sequence techniques

NRCC-38845

Bradley, J.S.

April 1996

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Report on Inter-Laboratory Comparison of Guarded Hot Plate Measurements

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INTRODUCTION

THE GUARDED HOT-PLATE apparatus is the primary standard for the measurement of thermal conductivities of thermally insulating materials. Standard test procedures using the guarded hot plate are prescribed by ASTM and ISO. In principle, the values of thermal conductivities determined using a well-designed apparatus could be accurate to between 0.5% and 1%, but experience shows that the design, construction and operation of

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a guarded hot plate apparatus are very challenging tasks and it is not always possible to attain the highest theoretical accuracy. For example, the ISO Standard Document No. 8302:1991(E) quotes the following limit values:

- Expected guarded hot plate method accuracy (at room temperature)—2%
- Expected guarded hot plate method accuracy (full temperature range**)—5%

The work reported here was undertaken to compare the results obtained using four guarded hot plate apparatuses that differ in design and modes of operation and to establish agreement between three standard laboratories, one each from the United Kingdom, France and two from Canada. The Division of Quantum metrology of the National Physical Laboratory, Teddington, has the British National Standard. The Centre for Research and Development of Isover St. Gobain (CRIR), Rantigny, France, maintains an ISO Standard. The National Standard of Canada is maintained at the Institute for Research in Construction, Ottawa, Canada.

WORK PLAN

The work plan included the following steps:

1. From stocks of 25 mm and 75 mm thick glass fiber insulation of well-characterised bulk density, thickness and thermal resistance, select matched pairs of test specimens of dimensions 600 mm × 600 mm.
2. Each of the participating laboratories should test the same matched pairs on their apparatus to determine the apparent thermal conductivity of the insulation as a function of temperature in the range 0°C to 40°C.

TEST SPECIMENS

Three pairs of test specimens were included in the work. Two pairs were selected from NPL and one pair from IRC. All the pairs had well-characterised thermal conductivities and physical characteristics, as listed in Table 1.

The NPL Specimens

The two pairs of NPL specimens were made out of four slabs with coding LA4, LA5, LA6 and LA8. The physical characteristics of the slabs, as shown

**Although the standard uses the phrase "full temperature range," it does not specify what this range should be.

Table 1. The physical properties of individual slabs used to make three pairs of test specimens. The thermal resistances were determined using a heat flow meter apparatus at a mean specimen temperature of 24°C.

Specimen Code	Thickness mm	Bulk Density $kg \cdot m^{-3}$	Thermal Resistance $m^2 \cdot K \cdot W^{-1}$
	Specimen Pair NPL1		
LA4	74.64	53.5	2.37
LA6	74.48	52.3	2.36
	Specimen Pair NPL2		
LA5	74.62	44.3	2.31
LA8	74.48	44.2	2.30
	Specimen Pair IRC1		
364-146-A	26.09	53.2	0.822
364-146-B	26.09	53.4	0.818

in Table 1, were determined at IRC. The properties of LA4 and LA6 match well, as do those of LA5 and LA8. Hence, the two pairs of specimens were matched for thermal conductivity measurements as:

- Specimen pair 1, referred to as NPL1, consists of LA4 and LA6
- Specimen pair 2, referred to as NPL2, consists of LA5 and LA8

The IRC Specimens

One pair of slabs from IRC, coded as 364-146-A and B, formed yet another pair of test specimens, referred to as IRC1. The properties of these slabs are given in Table 1.

TEST APPARATUS

All the apparatuses used in this work are guarded hot plates and they are all based on the same principle. All hot plates have a square geometry, however, as summarised below, there are some differences in the details of design and methods of operation.

The NPL 610 mm Guarded Hot Plate/Heat Flow Meter Apparatus

The apparatus has been designed to measure the thermal conductivity of single specimens from 30 mm to 300 mm thick in the temperature range 10°C to 30°C, and to operate either in the primary mode as a conventional guarded hot plate, or in a secondary mode using a heat flow meter. A 250 mm square heat flow meter is embedded in the central area of a 610 mm square by 5 mm thick "paxolin" sheet which is bolted to the lower surface of the cold plate assembly. It can be used either to check that linear heat flow has been established in thick specimens when measurements are carried out using the apparatus as a guarded hot plate or to measure the mean heat flux through the specimen when the apparatus is operated as a heat flow meter. Specially designed copper-plated printed circuit boards have been developed as heating elements for the main heater plate, the auxiliary guard and the cold plate of the apparatus to provide the uniform heating necessary to produce large isothermal surfaces. The metering area is ≈ 300 mm $\times$ 300 mm. A linear temperature gradient edge-guard consisting of four thin stainless steel sheets is located parallel to and 25 mm from the specimen edges. One end of each sheet is clamped to the cold plate and the other is controlled at the temperature of the hot plate to produce a linear temperature gradient matching that of the specimen. This additional guard ensures that there is no heat-flux across the boundaries of the specimen. The height of the cold plate assembly above the main hot plate is adjusted by a motor driven mechanism in which the plates are kept parallel by rollers bearing on a long chrome-plated cylinder. Specimen thickness is derived from the output of a linear voltage displacement transducer. A line diagram of the apparatus is given in Figure 1.

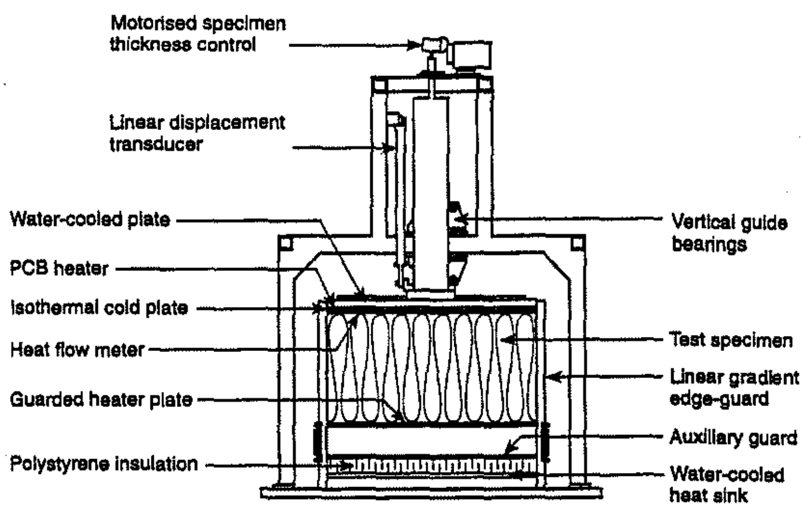

FIGURE 1. Schematic drawing of the 610 mm guarded hot plate/heat flow meter apparatus at the National Physical Laboratory, United Kingdom.

The CRIR (Isover Saint-Gobain) Guarded Hot Plate Apparatus

The CRIR guarded hot plate apparatus is a "one-specimen" apparatus that functions in a bi-guarded, horizontal configuration. Plate dimensions are 610 mm × 610 mm with a metering area of 250 mm × 250 mm. The metering area is surrounded by two guards, and the plate assembly rests in a temperature and humidity controlled atmosphere. The imbalances between the metering area and the first guard and between the first and the second guard are controlled using thermopiles with 100 and 200 thermocouple junctions, respectively.

The IRC Guarded Hot Plate Apparatus

There are two apparatuses at IRC, one of which conforms to ASTM Standard C 177. The 610 mm × 610 mm hot plate has one auxiliary guard. The metering area is 300 mm × 300 mm, and is operated in the two-sided mode in the vertical configuration. This apparatus is referred to as IRC OLD apparatus. The hot plate of the second apparatus, referred to as IRC NEW apparatus, is identical to that of the CRIR apparatus in design. However, the metering area and the guards are held together using foamed-in-place polyurethane insulation to avoid any thermal bridging due to physical connections with lower thermal resistance. The apparatus is designed for use in the one-sided as well as two-sided modes, in either a vertical configuration or a horizontal configuration. The measurements reported here were performed in the two-sided mode in the vertical configuration.

RESULTS ON THE SPECIMEN NPL1

The test results on the thermal conductivity of NPL1 reported from the three participating laboratories are listed in Table 2 and plotted in Figure 2.

RESULTS ON THE SPECIMEN NPL2

The test results on the thermal conductivity of NPL2 reported from the three participating laboratories are listed in Table 3 and plotted in Figure 3.

RESULTS ON THE SPECIMEN IRC1

The rest results on the thermal conductivity of IRC1 reported from the three participating laboratories are listed in Table 4 and plotted in Figure 4.

DISCUSSION

The results presented in Tables 2, 3 and 4 and plotted in Figures 2, 3 and

Table 2. Experimental results on the thermal conductivity of NPL1 at various temperatures; the data referred to as "fitted" are those calculated from a linear equation generated using all the available data.

Temperature	Thermal Conductivity $W \cdot m^{-1} \cdot K^{-1}$					
°C	NPL	CRIR	IRC-OLD	IRC-NEW	Fitted	% Deviation
8.85	0.03025				0.03012	+0.5
8.86	0.03020				0.03012	+0.3
23.45	0.03218				0.03206	+0.4
23.49	0.03201				0.03207	−0.2
30.54	0.03302				0.03300	+0.1
36.84	0.03378				0.03384	−0.2
36.85	0.03400				0.03385	+0.5
1.5		0.0290			0.02914	−0.5
2.0		0.0292			0.02920	0.0
4.7		0.0295			0.02956	−0.2
9.5		0.0302			0.03020	0.0
9.5		0.0303			0.03020	+0.3
24.0		0.0325			0.03213	+1.1
24.0		0.0318			0.03213	−1.0
29.3		0.0328			0.03284	−0.1
29.3		0.0329			0.03284	−0.2
39.6		0.0344			0.03421	+0.6
40.2		0.0344			0.03429	+0.3
9.98			0.03036		0.03027	+0.3
23.71			0.03209		0.03209	0.0
40.08			0.03424		0.03428	−0.1
11.34				0.03040	0.03045	−0.2
15.95				0.03103	0.03106	−0.1
21.02				0.03172	0.03174	−0.1
26.04				0.03226	0.03241	−0.5
30.77				0.03283	0.03304	−0.6
35.97				0.03348	0.03373	−0.7

Note: NPL and CRIR values measured at 75 mm nominal thickness for each specimen of the pair.

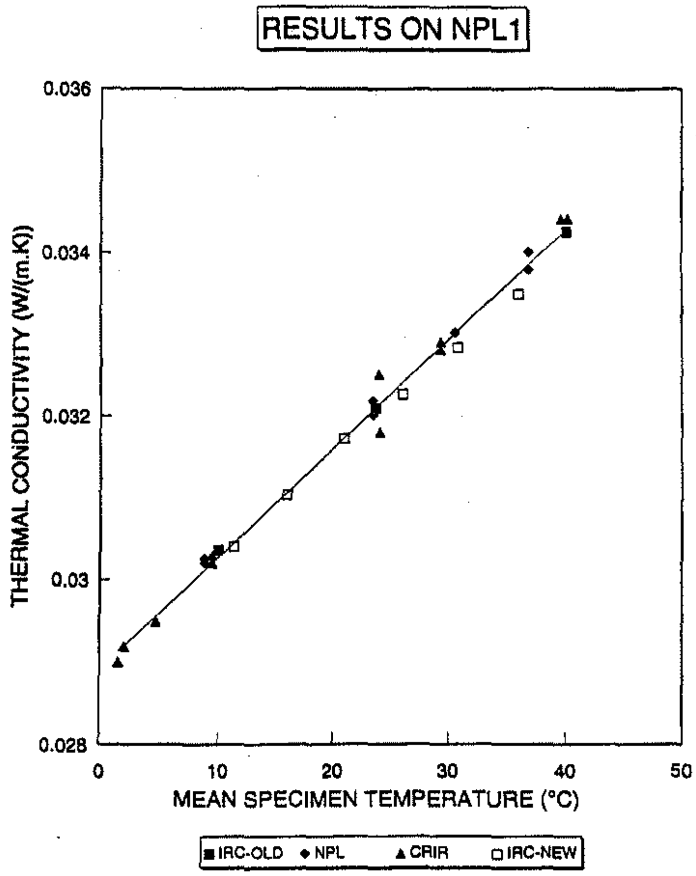

FIGURE 2. Experimental data, listed in Table 2, from four different guarded hot plate apparatuses; the solid line is the best fit obtained from a linear regression that included all the experimental data.

Table 3. Experimental results on the thermal conductivity of NPL2 at various temperatures; the data referred to as "fitted" are those calculated from a linear equation generated using all the available data.

Temperature °C	Thermal Conductivity $W \cdot m^{-1} \cdot K^{-1}$					
	NPL	CRIR	IRC-OLD	IRC-NEW	Fitted	% Deviation
8.79	0.03076				0.03083	−0.2
9.02	0.03099				0.03086	+0.4
23.45	0.03291				0.03293	−0.1
30.76	0.03426				0.03398	+0.8
36.86	0.03478				0.03485	−0.2
37.05	0.03505				0.03488	+0.4
1.8		0.0297			0.02983	+0.5
1.8		0.0300			0.02983	+0.6
9.5		0.0307			0.03093	−0.8
9.5		0.0312			0.03093	+0.9
24.0		0.0334			0.03301	+1.2
24.4		0.0331			0.03306	+0.1
29.3		0.0338			0.03377	+0.1
30.0		0.0339			0.03387	+0.1
39.6		0.0354			0.03524	+0.5
39.6		0.0352			0.03524	−0.1
10.47			0.03098		0.03107	−0.3
24.15			0.03291		0.03303	−0.4
39.80			0.03516		0.03527	−0.3
10.83				0.03114	0.03112	+0.1
15.14				0.03169	0.03174	−0.2
20.04				0.03226	0.03244	−0.6
24.97				0.03297	0.03315	−0.5
29.14				0.03356	0.03374	−0.5
34.13				0.03423	0.03446	−0.7

Note: NPL and CRIR values were measured at 75 mm nominal thickness for each specimen of the pair.

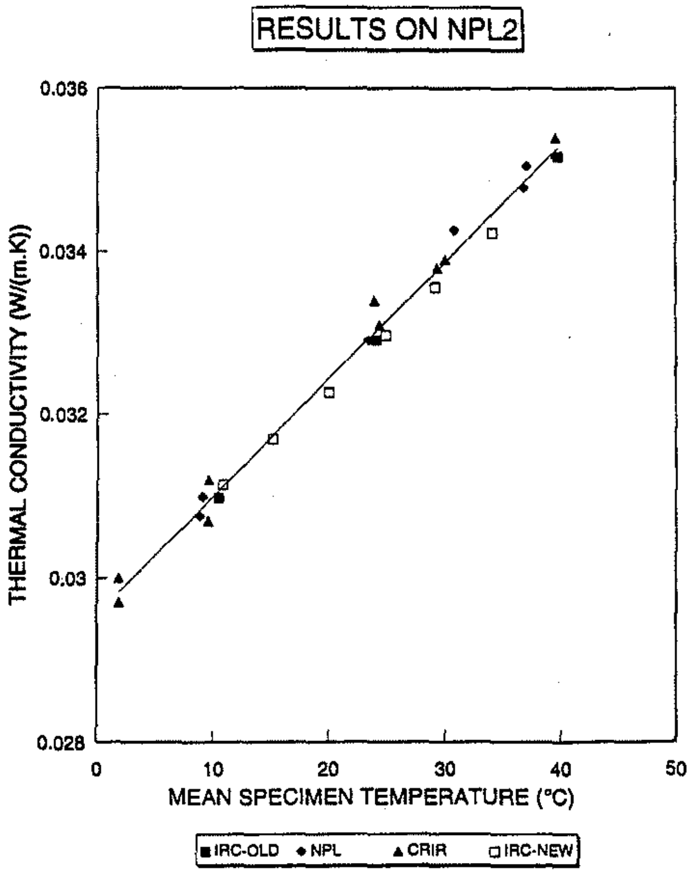

FIGURE 3. Experimental data, listed in Table 3, from four different guarded hot plate apparatuses; the solid line is the best fit obtained from a linear regression that included all the experimental data.

Table 4. Experimental results on the thermal conductivity of IRC1 at various temperatures; the data referred to as "fitted" are those calculated from a linear equation generated using all the available data.

Temperature °C	Thermal Conductivity $W \cdot m^{-1} \cdot K^{-1}$ NPL	CRIR	IRC-OLD	IRC-NEW	Fitted	% Deviation
9.73	0.03091				0.03081	+0.3
12.70	0.03128				0.03118	+0.3
18.68	0.03206				0.03192	+0.4
24.91	0.03290				0.03270	+0.6
27.97	0.03325				0.03308	+0.5
30.50	0.03358				0.03340	+0.5
36.76	0.03442				0.03418	+0.7
37.81	0.03456				0.03431	+0.7
5.0		0.0305			0.03022	+0.9
10.0		0.0311			0.03084	+0.8
24.0		0.0328			0.03259	+0.6
30.0		0.0337			0.03334	+1.1
40.0		0.0348			0.03458	+0.6
7.87			0.0302		0.03057	−1.3
24.36			0.0322		0.03263	−1.5
45.21			0.0351		0.03523	−0.5
14.04				0.0310	0.03134	−1.2
19.00				0.0317	0.03196	−1.0
28.84				0.0328	0.03319	−1.1
34.01				0.0335	0.03384	−1.0
38.99				0.0342	0.03446	−0.8

Note: NPL and CRIR measurements were done on specimens stacked together to form a single test specimen of 52 mm nominal thickness.

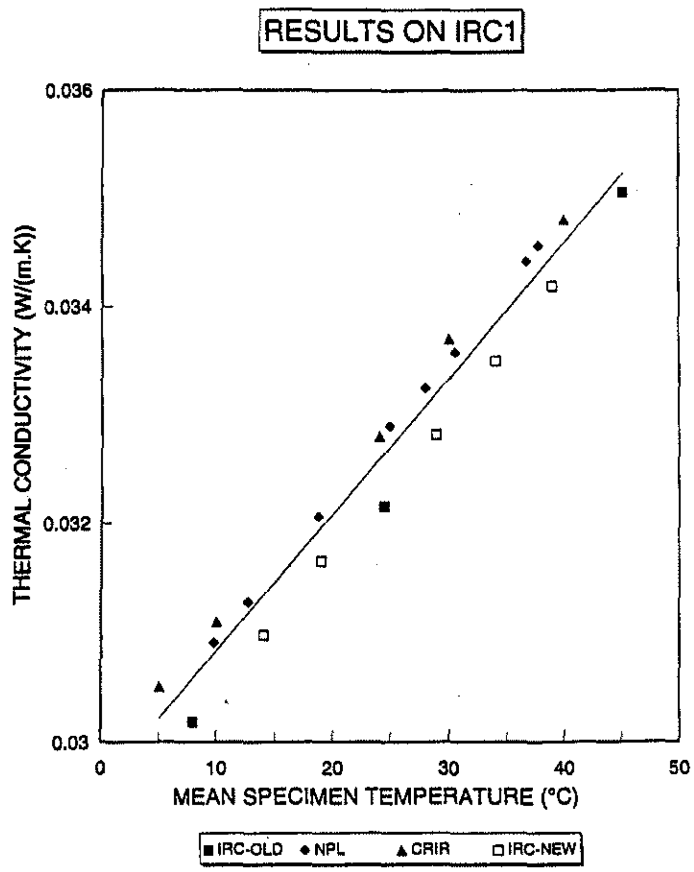

FIGURE 4. Experimental data, listed in Table 4, from four different guarded hot plate apparatuses; the solid line is the best fit obtained from a linear regression that included all the experimental data.

4 are the data obtained from the three participating laboratories. The thermal conductivity measurements were carried out on specimens of slightly different thicknesses depending on the amount of compression applied by each participating laboratory. The largest deviation from the nominal thickness of 25 mm and 75 mm was about 0.5 mm. However, it was not necessary to do a re-analysis of the results because the correction to the thermal conductivity would be quite small. Consider, for example, a 1 mm difference in thickness between the specimens in each apparatus due to varying degree of compression. The effect on thermal conductivity should not be greater than 0.15% based on the available knowledge of the dependence of thermal conductivity of fibrous insulation on temperature and bulk density.

The results listed in Tables 2, 3 and 4 show that the largest deviation of any datum from a least-squares fit is about 1.5%. As mentioned earlier, these least-squares fits were done by using all the available data for each specimen pair. In another series of analyses, the data from each laboratory on each specimen pair were used in separate least-squares analysis. Among all these, the largest deviation between any two laboratories was 2.2% in the full temperature range for the pair IRC1.

CONCLUSION

Three pairs of well-characterised specimens of glass fibre insulation of thicknesses 25 mm and 75 mm were used in the measurements of thermal conductivity in the temperature range 0°C and 40°C at the National Physical Laboratory (UK), CRIR, Isover Saint-Gobain (France) and the Institute for Research in Construction, National Research Council (Canada). The agreement between the three laboratories was within 2.2%, with the largest deviation from the least-squares fit to all the data being less than 1.5%. This is outside the theoretical accuracy of 0.5% to 1% that one would expect from using a primary standard. But, as mentioned in the introduction, the design, construction and operation of guarded hot plates are very challenging tasks and consequently the agreement established between NPL, CRIR and IRC can be considered very satisfactory. The agreement established in this work is much better than what is required by the ISO Standard on guarded hot plates.

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