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NEW MEASUREMENTS ON THERMAL CONDUCTIVITY REFERENCE MATERIALS

R. W. POWELL* and R. P. TYE†

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Abstract—In order to provide further information on the thermal and electrical conductivities of materials that have been suggested for use as thermal conductivity reference materials, new data are presented for copper (three samples), lead, iron (six samples), tungsten (two samples), Inconel 702 and 18/8 stainless steel (nine samples). The thermal comparator method is suggested as a means whereby standard reference samples may be readily intercompared. This method seems likely to be particularly appropriate for materials having a large phonon component of thermal conductivity.

1. INTRODUCTION

IN MANY branches of scientific measurement, reference materials, having accurately known properties, serve three important functions:

(i) as a standard when comparative methods are employed;
(ii) as a reference material on which to check the performance of newly installed equipment associated with an accepted method;
(iii) as a reference material for use when assessing the possibilities of a newly developed method.

The measurement of thermal conductivity is one in which a lot of care needs to be taken in order to avoid insidious errors that can arise from the presence of unsuspected heat transfers and inaccuracies of temperature measurement. It therefore tends to be a time-consuming measurement requiring expert technical knowledge. These factors have led to the frequent adoption of thermal conductivity reference materials under category (i) and make (ii) and (iii) more essential. Experience also indicates that the thermal conductivity of a reference material should not differ too widely from that of the test material. Hence, materials of accurately known thermal conductivities are required covering a wide range of values. The above-mentioned uncertainties naturally hold for all determinations and it is only in recent years that generally accepted values are being suggested for a few materials [1], and the need for the complete characterization of these materials is being appreciated. Further information is required in many instances and the present paper contains the results of several unpublished sets of measurements made at the National Physical Laboratory on some materials that have already been employed as reference standards and on others likely to be of value for this purpose.

These new thermal conductivity measurements have been made by the longitudinal heat flow method [2], although often they have been limited to the lower temperature range of 50–350°C.

Electrical resistivity measurements, made by the usual comparative potential drop method, have also been included to give values for the Lorenz function.

Finally, a simple method is proposed for the intercomparison of a set of thermal conductivity reference samples.

* Present address: Thermophysical Properties Research Center, Purdue University, West Lafayette, Indiana, U.S.A.
† Present address: Dynatech Corporation, 17 Tudor Street, Cambridge, Massachusetts, U.S.A.

2. NEW MEASUREMENTS

(i) Copper

Three sets of measurements have been made on samples of high purity copper.

The first was a Johnson, Matthey & Co. spectrographically standardized rod, 7 mm in diameter and 15-cm long, Laboratory No. 4351, stated to be oxygen free and of a high degree of purity. The approximate estimates of foreign elements present were stated to be silver 0·0005 per cent, nickel <0·0003 per cent and lead <0·0004 per cent. This sample was first heat treated to 900°C and electrical resistivity measurements made as the sample was heated to this temperature and cooled. These values showed no noticeable change due to the treatment.

The other two were samples of "pure copper". One was a rod 1 cm in diameter and approximately 10-cm long that had been tested on behalf of Queen Mary College, London, the other was a rod 1·27-cm dia. and 10-cm long that was tested for the former Ministry of Supply. No further details were supplied, nor were these samples given any heat treatment prior to the test.

Table 1 contains the results for these three samples as read from smooth curves drawn to fit the experimental data.

In order to facilitate comparison with earlier

Table 1. Thermal conductivity, λ, W cm^{-1} C^{-1}, electrical resistivity, ρ, Ω cm and Lorenz function, $L = \lambda\rho/T$, V^2 K^{-2} of copper

Temperature		J.M. & Co., Sample 1			Q.M.C., Sample 2			M.S., Sample 3		
°C	°K	λ	$10^6\,\rho$	$10^8\,L$	λ	$10^6\,\rho$	$10^8\,L$	λ	$10^6\,\rho$	$10^8\,L$
20	293	—	1·75	—	—	1·78	—	—	1·73	—
50	323	$3{\cdot}97_5$	1·93	$2{\cdot}37_5$	3·89	1·95	2·35	4·06	1·93	2·42
100	373	3·94	2·25	2·39	3·89	2·28	2·37	3·99	2·27	2·42
200	473	$3{\cdot}87_5$	2·93	2·40	—	—	—	3·87	2·97	2·43
300	573	—	3·60	—	—	—	—	3·75	3·68	2·41
400	673	—	4·33	—	—	—	—	3·65	4·43	2·40
500	773	—	5·08	—	—	—	—	3·60	5·17	2·41
600	873	—	5·88	—	—	—	—	3·55	5·95	2·42
900	1173	—	8·30	—	—	—	—	—	—	—

Table 2. Comparison of data for copper at 50°C with those of earlier workers

Author		Year	Ref.	λ	$10^6 \times \rho$	$10^8 \times L$
Jaeger and Diessselhorst		1900	3	3·824	1·964	2·33
Lees		1908	4	[3·78]	[1·97]	[2·31]
Meissner	(1)	1915	5	3·875	1.888	2·26
Meissner	(2)	1915	5	3·805	1·93	2·28
Schofield		1925	6	[3·79]	1·97	[2·31]
Kannuluik and Laby		1928	7	[4·05]	[1·915]	[2·40]
Smith and Palmer		1935	8	3·93	1·895	2·31
Mikryukov		1956	9	[4·03]	[1·93]	[2·41]
Powell and Tye	(1)	1966	Present Work	$3{\cdot}97_5$	1·93	2·375
Powell and Tye	(2)	1966	Present Work	3·89	1·95	2·35
Powell and Tye	(3)	1966	Present Work	4·06	1·93	2·42

Bracketed values involve extrapolation.

data, the measurements reported by authors who have made determinations of both thermal and electrical conductivity are given in Table 2 at a mean temperature of 50°C. A certain amount of extrapolation has been necessary in some instances.

The thermal conductivities of two of the present samples are higher than most and agree well with the two highest values of Kannuluik and Laby [7] and Mikryukov [9]. The values for L also tend to increase with increase in thermal conductivity and purity. This group of higher thermal conductivity values seems the most probable for high purity copper.

Table 3. Thermal conductivity, λ, W cm^{-1} C^{-1}, *electrical resistivity, ρ,* μΩ cm, *and Lorenz function L,* V^2, K^{-2} *of lead*

Temperature		λ	ρ	$L \times 10^8$
°C	°K			
0	273	—	19·3	—
50	323	0·360	23·4	2·61
100	373	0·356	27·5	$2{\cdot}62_5$
150	423	0·351	31·8	2·64
200	473	$0{\cdot}343_5$	36·3	2·64
250	523	0·335	40·8	2·62
300	573	[0·326]	45·7	[2·60]
327·3	600·5 (solid)	[0·316]	[49·2]	[2·59]
327·3	600·5 (liquid)	[0·155]	[94·0]	[2·43]

Bracketed values are extrapolated.

(ii) *Lead*

The lead sample was a Johnson Matthey & Co. spectrographically standardized sample, of Laboratory No. 5873, and of diameter 7 mm and length 15 cm. It was estimated to have a purity greater than 99·995 per cent lead, with estimated impurities of cadmium 0·001 per cent, copper and silver each 0·0005 per cent and bismuth 0·0003 per cent.

The results read from smooth curves for this sample are given in Table 3.

The thermal conductivity experimental points are plotted in Fig. 1, together with the data of

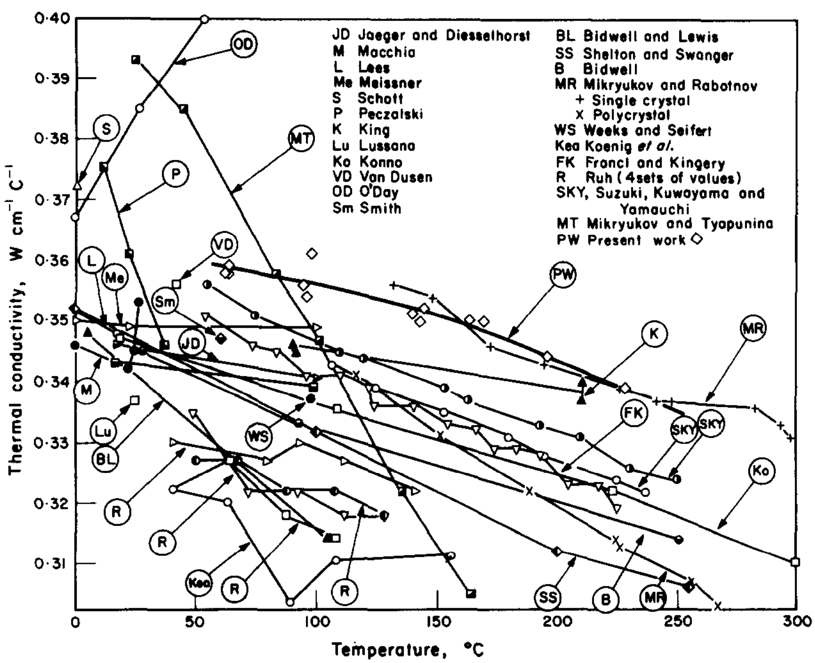

FIG. 1. Thermal conductivity of lead.

other workers from about room temperature upwards. This figure serves to convey some idea of the broad band which is covered by these experimental values. The workers concerned can be identified by the ringed letters and the accompanying legend. References to some have already been given; the others have references [10–28].

Probably good to 13 per cent, our values are about the highest obtained for lead. Only the values by Mikryukov and Rabotnov [22] for a single crystal specimen of lead are at all comparable. The electrical resistivities of the sample used by these workers are also in fairly good agreement with the present values, being some 1 per cent lower at about 130°C and some 3 per cent greater at nearer 300°C. Thus, their Lorenz functions show a steady increase from $2{\cdot}60 \times 10^{-8}\ V^2\ K^{-2}$ at 405°K to $2{\cdot}73 \times 10^{-8}\ V^2\ K^{-2}$ at 570° K whereas those of the present work remain relatively constant at a value of $(2{\cdot}62 \pm 0{\cdot}02)\ 10^{-8}\ V^2\ K^{-2}$.

The thermal conductivity values of Jaeger and Diesselhorst are exceeded in the present work by some 4·5 per cent, those of Shelton and Swanger [20] by about 5·3 per cent and the earlier value of van Dusen [16] by 1·4 per cent.

(iii) *Iron*

The results of new measurements can now be reported for two samples of high purity iron and another sample named "Purefree" Iron, which is of lower purity than Armco iron.

One of the high purity irons, No. 1, had been submitted for test by Tube Investments Limited. This was in the form of a rod of length 15 cm and diameter 1·27 and was stated to be Type 1 as supplied by Metals Research. The other high-purity iron, No. 2, was a rod of similar diameter but rather shorter, which had been machined from one of several disks that had been specially prepared by Metallurgy Division of the National Physical Laboratory. Determinations of the thermal conductivity of this iron have already been made mainly from 650 to 1000°C by means of the stacked-disk–radial-heat-flow method. These results are being reported independently,* but some values are included in Table 5.

The sample of Purefree Iron, No. 6, was

Table 4. Stated analyses of iron samples, weight per cent

	Pure iron sample			Armco iron sample		Purefree iron sample
Element	No. 1	No. 2	No. 3	No. 4	No. 5	No. 6
Carbon	0·0050	0·0014	0·0045	0·0230	0·0200	0·0300
Silicon	<0·0010	0·0053	0·0002	0·0070	0·0040	0·0800
Sulphur	0·0040	0·0035	0·0015	0·0200	0·0230	0·0100
Phosphorus	0·0030	0·0017	0·0010	0·0070	0·0060	0·0150
Nickel	0·0250	0·0055	0·0006		0·0830	
Manganese	0·0010	<0·0010	0·0020	0·0250	0·0300	0·0100
Aluminium		0·0038	trace			
Chromium	0·0070	<0·0010	nil			
Cobalt		0·0020	n.d.			
Vanadium	0·0040		n.d.			
Molybdenum	<0·0100		nil			
Copper	<0·0100		nil		0·0830	
Oxygen	0·0040	0·0008	<0·0005			
Nitrogen	0·0006	0·0007	<0·0010			
Hydrogen	0·000048	0·000016				

* For a short account, see Annual Report National Physical Laboratory, pp. 128–130. H.M.S.O. London (1964).

supplied by Low Moor Best Yorkshire Iron Limited in the form of a rod approximately 20-cm long and 2·54-cm dia. for tests to 800°C.

The stated chemical compositions of the above irons are given in Table 4, together with those of another high purity iron, No. 3, [29] and the two Armco irons, Nos. 4 and 5, for which thermal and electrical conductivity values have already been reported. No. 4 was the sample first tested [30, 31] and No. 5 was that submitted by the Battelle Memorial Institute [32] in connection with their round-robin tests.

Figure 2 contains plots of the new experimental results and the smooth curves from the results of the earlier measurements. The complete sets of derived values of λ, ρ, and L for the three high purity irons and the three relatively pure irons investigated at the National Physical Laboratory are given in Table 5. This table also contains corresponding data for a high purity iron and an Armco iron measured by the Oak Ridge National Laboratory [33].

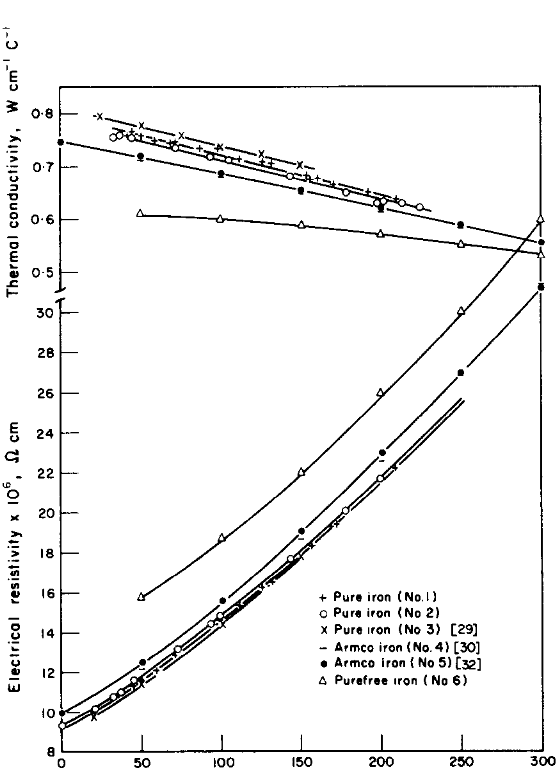

FIG. 2. Thermal conductivity and electrical resistivity data for six iron samples.

Of the irons tested at the N.P.L., sample No. 3 has the highest thermal and electrical conductivity, and this is probably the purest iron. It is seen from Table 4 to contain least silicon, sulphur, phosphorus, nickel and oxygen, but more carbon than sample No. 2. At 50°C, the thermal conductivities of the other high purity irons are lower by 2 per cent (No. 1) and 4 per cent (No. 2), the Armco irons are lower by 7 per cent (No. 5) and 8 per cent (No. 4) and the Purefree iron is lower by 21·5 per cent (No. 6).

With increase in temperature, the thermal conductivities decrease, and show the same tendency to converge that has previously been observed for irons and steels. The Lorenz functions on the other hand agree more closely at any particular temperature, and all increase to a maximum value in the region of 400–600°C. At the lower temperatures there appears to be a little greater spread in the values of the Lorenz function for the less pure Armco iron, as also found by Flynn *et al.* [34], and much higher values for the still more highly alloyed Purefree iron. This last iron has been purposely included as an example of a much less pure iron than the Armco grade so often used. It clearly has a Lorenz function well removed, except possibly at high temperatures, from that of the other samples included in Table 5.

The last column of this table contains the mean value of the Lorenz functions for all of the high-purity and Armco irons. This mean value is seen to depart by less than 2·5 per cent from any of the individual values obtained by these two laboratories. By the use of these values for the Lorenz function it seems that the thermal conductivity of an iron of similar type, high purity or Armco, could be calculated from a knowledge of its electrical resistivity, probably to within ±2 per cent and certainly to within 4 per cent. The mean value of L extrapolated to

Table 5. Thermal conductivity, λ, W cm^{-1}C^{-1}, electricity resistivity, ρ, μΩ cm.

Temperature		Pure iron sample									Armco iron		
		No. 1			No. 2			No. 3			No. 4		
°C	°K	λ	ρ	$10^8 L$	λ	λ	$10^8 L$	λ	ρ	$10^8 L$	λ	ρ	$10^8 L$
50	323	0·760	11·7	2·75	0·745	11·9	2·75	0·775	11·5	2·76	0·713	12·2	2·69
100	373	0·723	14·7	2·85	0·714	14·9	2·85	0·737	14·5	2·87	0·682	15·0	2·75
150	423	0·683	17·9	2·89	0·675	18·2	2·90	0·700	17·8	2·94	0·649	18·7	2·87
200	473	0·645	21·6	2·94	0·640	21·8	2·95	—	—	—	0·616	22·6	2·94
250	523	0·610	25·6	2·99	0·605	25·8	2·99	—	—	—	0·586	26·9	3·01
300	573	—	—	—	—	30·3	—	—	—	—	0·553	31·4	3·03
400	673	—	—	—	—	41·0	—	—	—	—	0·486	43·1	3·11
500	773	—	—	—	—	53·3	—	—	—	—	0·433	55·3	3·10
600	873	—	—	—	0·390	67·9	3·04	—	—	—	0·389	69·8	3·11
700	973	—	—	—	0·339	85·2	2·97	—	—	—	0·343	87·0	3·07
800	1073	—	—	—	0·295	104·2	2·86	—	—	—	0·297	105·5	2·92

0°C is 2·66 × 10^{-8} V^2 K^{-2} and the lower value of $2{\cdot}58_5$ × 10^{-8}, obtained by the National Bureau of Standards, for Armco iron, differs from this by −3 per cent. This order of uncertainty is double that suggested by the workers at the Oak Ridge National Laboratory [33], but they had only investigated two samples. Some of the uncertainty may be the result of experimental errors, but the appreciable lattice component, being independent of ρ, is also likely to be a contributing factor. Despite this last factor, these further results support iron as being one of the most acceptable reference materials at present available.

(iv) *Tungsten*

The two samples of tungsten studied were rods 0·4 cm in diameter and 10-cm long that were obtained from Messrs. Johnson, Matthey & Co. (Catalogue No. JM 740). The purity was about 99·99 per cent.* Figure 3 shows the results. For one of these samples, Tye [35] has already published thermal conductivity values over the range 50–390°C and electrical resistivity data from 20 to 1450°C, so, in this instance the new measurements relate to the extension of the temperature range for thermal conductivity to 718°C. When working in this higher temperature range only the energy outflow was measured. An Armco iron standard was used for this measurement. Tye's original work resembled the measurements of the present paper in that up to about 350°C the energy flow had been obtained as the mean of inflow and outflow observations, the latter then being measured calorimetrically. At temperatures of about 315 and 390°C these two experiments had yielded thermal conductivity values which agreed to within 1 per cent, and at 182°C the high temperature assembly yielded a value that was only lower by 2·7 per cent. Similarly, when the second sample was assembled in the high temperature apparatus, six sets of observations taken in the range 135–240°C, yielded values that were closely distributed about a mean curve located some 1·2 per cent above Tye's original curve. These results indicated the experimental conditions to be satisfactory, and measurements have been made on the first rod to 478°C and on the second to 718°C.

Values of the thermal conductivity and electrical resistivity as read from a smooth curve fitted to the results for both samples are given in Table 6. This table also contains the derived

* Spectroscopic analysis was stated to indicate about 0·01% Mo, with silicon very faintly visible and copper barely visible.

and Lorenz function, L, $V^2 K^{-2}$ *of high purity, Armco and Purefree irons*

sample			Purefree iron sample			Oak Ridge National Laboratory						Mean $10^8 L$ (for all except No. 6)
No. 5			No. 6			High purity iron			Armco iron			
λ	σ	$10^8 L$	λ	ρ	$10^8 L$	λ	ρ	$10^8 L$	λ	ρ	$10^8 L$	
0·719	12·5	2·78	0·608	15·8	2·98	0·748	11·72	2·71	0·696	12·72	2·74	2·74
0·686	15·6	2·87	0·600	18·7	3·01	0·698	14·70	2·75	0·665	15·81	2·82	2·82
0·654	19·1	2·95	0·588	22·0	3·06	—	18·06	—	—	19·21	—	2·89
0·621	23·0	2·97	0·570	25·9	3·12	0·621	21·84	2·87	0·602	23·00	2·93	2·94
0·588	27·0	3·04	0·552	30·0	3·17	—	26·10	—	—	27·29	—	2·99
0·555	31·2	3·02	0·532	34·6	3·21	0·555	30·72	$2{\cdot}97_5$	0·540	32·05	3·02	3·01
0·492	41·8	3·06	0·483	45·0	3·23	0·489	41·51	3·02	0·477	42·84	3·04	3·06
0·430	54·0	3·00	0·430	57·1	3·18	0·436	54·12	3·05	0·425	55·63	3·06	3·06
0·382	68·8	3·01	0·376	71·0	3·06	0·386	68·89	3·05	0·379	70·66	3·07	3·06
0·339	86·2	3·00	0·335	87·5	3·01	0·338	86·22	$2{\cdot}99_5$	0·333	88·02	3·01	3·01
0·294	105·2	2·88	0·298	107·2	2·97	0·297	105·53	2·92	0·293	107·61	2·94	2·90

values for the Lorenz function, and, for comparison, the corresponding data from recent measurements by Moore *et al.* [36] of the Oak Ridge National Laboratory.

The electrical resistivity measurements from the two laboratories are seen to agree to within about 2 per cent over the whole temperature range. The thermal conductivities agree equally closely except below 250°C where the present values increase more rapidly with decrease in temperature, the difference amounting to 5 per cent at 50°C. This difference is consistent with the higher purity of the present samples, as indicated by a $\rho_{273K}/\rho_{4\cdot2K}$ ratio of 150, as compared with a value of 35 for the ratio ρ_{300K}/ρ_4 as reported for the ORNL sample. The latter had a density of 99·8 per cent of the theoretical. This quantity for the NPL samples

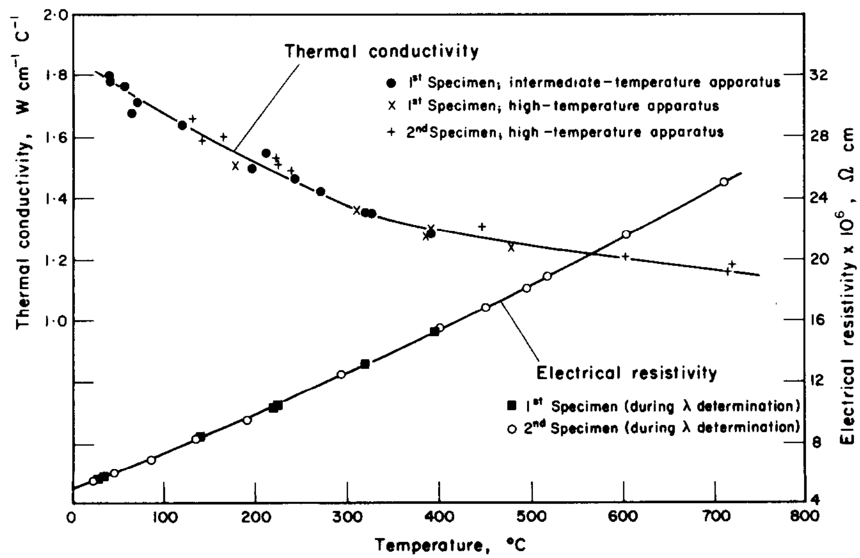

FIG. 3. Thermal conductivity and electrical resistivity of tungsten.

Table 6. Thermal conductivity, λ, W cm⁻¹ C⁻¹, electrical resistivity, ρ, μΩ cm, and the Lorenz function, L, V² K⁻² of tungsten

Temperature		NPL values			ORNL values			Mean
°C	°K	λ	ρ	$10^8 L$	λ	ρ	$10^8 L$	$10^8 L$
0	273	—	5·0	—	—	5·002	—	—
50	323	1·77	6·1	3·34	1·686	6·157	3·21	3·28
100	373	1·68	7·3	3·29	1·602	7·344	3·15	3·22
200	473	1·52	9·8	3·15	1·479	9·822	3·07	3·11
300	573	1·38	12·6	3·04	1·389	12·438	3·02	3·03
400	673	1·30	15·5	3·00	1·322	15·186	2·98	2·99
500	773	1·25	18·3	2·96	1·267	18·073	2·96	2·96
600	873	$1{\cdot}20_5$	21·4	2·96	1·221	21·041	2·94	2·95
700	973	1·17	24·6	2·96	1·184	24·070	2·93	2·94
750	1023	1·15	26·2	2·94	1·168	25·606	2·92	2·93

has not been determined but a rather lower value would help to explain the close agreement of the room temperature electrical resistivities.

The high values of the Lorenz function indicate tungsten as having a relatively large lattice component of thermal conductivity, which decreases from about one-third of the total thermal conductivity at 50°C to about one-fifth at 750°C. Despite this large lattice component, surprisingly good agreement is shown between the Lorenz functions for the two sets of measurements of Table 6, and, on this much too limited evidence, it would seem that by using the mean values given in the last column of the table and measured electrical resistivity values, it should be possible to calculate the thermal conductivity of other tungsten samples to within some 3 per cent.

Tungsten, with its high melting point, is becoming a very strong candidate for use as a thermal conductivity reference material at temperatures of 1000°C and above. About a dozen independent determinations have been reported for the thermal conductivity of tungsten in the range 1300–3000°C, but the reported values are tremendously scattered, with the extremes in a ratio of about 1:3. There is another group of scattered values at temperatures around 200°K with extreme values in the ratio of about 1:1·25, but only one or two determinations had been made on tungsten in the intermediate region now partially covered by the recent NPL and ORNL investigations. Not only is the close agreement of these two sets of values a satisfactory feature, but the natural extrapolation of this mean curve to 3000°K has been shown [1] to lie within ±5 per cent of the experimental values of four different workers in this higher temperature region (Wheeler [37] Osborn [38], Gumenyuk and Lebedev [39] and Timrot and Poletskii [40]). Thus, there are encouraging signs that the work on tungsten is producing a material with a thermal conductivity that is becoming known with fair certainty to really high temperatures.

(v) *Inconel* 702

A piece of Inconel 702 was received in 1962 from the National Bureau of Standards at the time when they were exploring the possibilities of this material as a thermal conductivity standard. A chemical analysis of this material had been given in weight per cent as Ni 79·3, Cr 17·0, Al 2·5, Ti 0·59, Fe 0·36, Si 0·19, Cu 0·14, Co 0·08, Mn 0·04, C 0·066, P 0·002 and S 0·004 and the original stock was stated to be in a solution annealed condition, having been held at 1080°C for 1 h and then rapidly cooled in air.

Laubitz [41] has published the results of measurements made on samples from this same stock, but further work by Laubitz and Cotnam [42] led to the conclusion that property changes due to heat treatment would make Inconel 702 an unsuitable standard material. Measurements

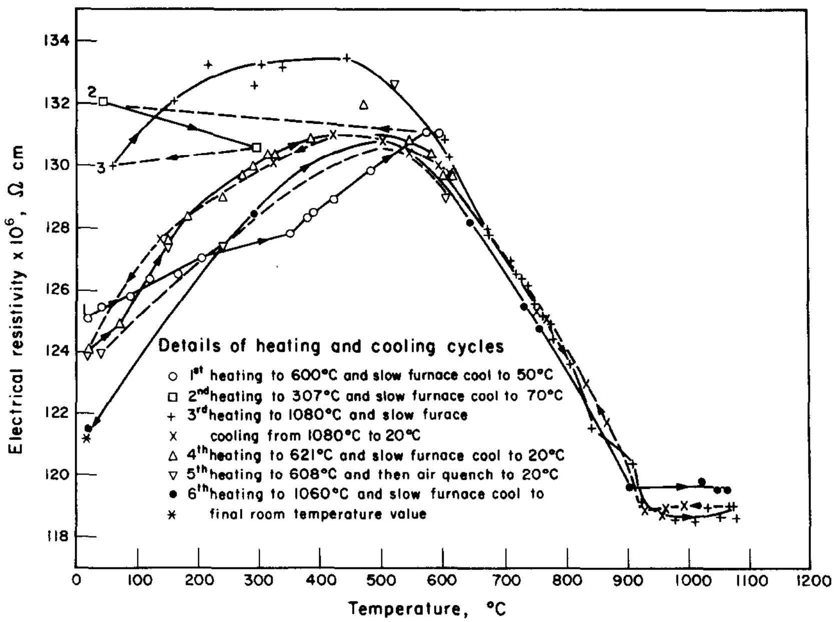

FIG. 4. Inconel 702—electrical resistivity vs. temperature: investigation of effect of heat treatment.

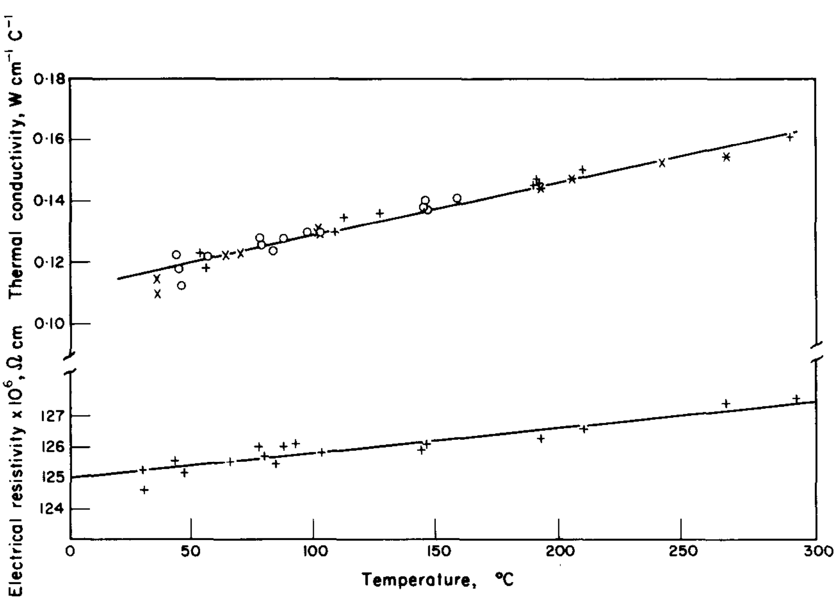

FIG. 5. Inconel 702, solution annealed, thermal conductivity and electrical resistivity against temperature.

at the NPL on the electrical resistivity of a rod 1·25 cm in diameter and 15-cm long had already indicated quite a strong dependence on heat treatment. These results are plotted in Fig. 4 where the accompanying legend indicates the sequence of temperature change. These measurements show that at room temperature the electrical resistivity can vary from about 121 to 132 μΩ cm, that on heating, distinct curves are followed to about 620°C by which temperature the curves have converged and remain so to about 900°C above which some divergence and possible hysteresis is observed.

Thermal conductivity and electrical resistivity measurements had previously been made on a bar 2·5-cm dia. by the methods already described. These results are plotted in Fig. 5. This Inconel 702 sample was heated inadvertently to above 600°C soon after the positions of the test and standard rods had been reversed, and when only a few observations had been made in the overlap range and to about 300°C. It was on subsequent cooling that a definite change in the room-temperature electrical resistivity was noticed and further work on this sample was discontinued. Table 7 contains the smoothed results of this experiment, together with values (λ_{calc}) derived from the equation:

$$\lambda = 2{\cdot}2 \times 10^{-8}\,(T/\rho) + 0{\cdot}060,$$

which had been fitted to a series of nickel–chromium alloys examined previously [2].

These calculated values are seen to agree with those measured in this work to within 3 per cent.

This table also contains the results of Laubitz [41] and of Flynn and Robinson [43] for the same initial state of this alloy. The agreement is remarkably close, despite the lattice component at 50°C amounting to some 50 per cent of the total thermal conductivity.

(vi) *Stainless steel* (18 % Cr, 8 % Ni)

A sample of Staybrite steel of the 18/8 type was included among the heat resistant alloys alloys investigated by Powell [44], another sample was steel No. 15 of the series of steels next investigated at the National Physical Laboratory [45]. This last was the sample used as a reference standard when determinations were made of the thermal conductivity of liquid mercury. [46] At that time, several further measurements made in the range 25–100°C gave values which where lower than those previously reported. At 25°C where considerable extrapolation had been necessary, the difference was about 6 per cent, at 50° about 2·5 per cent and at 100°C both values agreed.

Seven further steels of this type have since been measured, one to 950°C and the others over various smaller temperature ranges. The chemical compositions, when known, are given in Table 8, and values read from smooth curves fitted to the experimental data for these samples are given in Table 9.

When the samples were supplied in the form of thin walled tubes, strips were cut and grouped together to give a cross sectional area comparable with that of a rod 1 cm or so in diameter.

The accuracy of the thermal conductivity

Table 7. Thermal conductivity, λ, W cm⁻¹ C⁻¹, *electrical resistivity, ρ,* μΩ cm, *and Lorenz function, L,* V² K⁻², *of Inconel* 702 *for the solution-annealed state*

Temperature		Present measurements				Flynn & Robinson [43]	Laubitz [41]
°C	°K	λ	λ_{calc}	ρ	$10^8 L$	λ	λ
50	323	0·120	0·117	125·4	4·66	—	
100	373	0·129	0·125	125·8	4·36	—	0·1283
200	473	0·146	0·142	126·6	3·91	0·145	0·1447
300	573	0·163	0·159	127·4	3·63	0·162	0·1627

Table 8. Details of stainless steel samples

Sample			Chemical composition, wt %, remainder Fe																
No.	Size (cm) Length	Size (cm) Dia.	C	Si	Mn	S	P	Cr	Ni	W	Cu	Al	As	Nb	Ti	Co	Mo	V	Remarks
i	38	7·6	0·15	0·19	0·26			17·87	8·04										Staybrite steel softened 1150/1200°C
ii	20·4	2·54	0·08	0·68	0·37	0·011	0·022	19·11	8·14	0·60	0·030	0·004	0·025						Heated to 1100°C and water cooled
iii	20	2·54	0·08	0·62	1·23			18·68	8·85					0·99	0·14				FCBC steel (De Havil-land). Heated to 1050°C and air cooled
iv.a	18	0·96 o.d. 0·63 i.d.	0·077	0·74	1·8	0·010	0·026	17·55	10·8						0·05				HP1 (A.E.R.E.)
c	20	2·54																	18/8 stainless steel. No other details (A.E.R.E.)
v.1 and v.2	15	1·27																	ICI supplied 2 rods (No. 1 and No. 2) stated to be stainless steel. No details
vi.15 and vi.17		1·90 o.d. 1·47 i.d.	0·05	0·5	1·53	0·022	0·020	17·86	11·04						0·37				Tube No. 15 and No. 17 from N.E.L. Cold-drawn, fully softened and descaled

Table 9. Thermal conductivity, λW cm^{-1}C^{-1}, electrical resistivity, ρ, Ω cm, and Lorenz function, L,V^{2}K^{-2} of stainless steels of Table 8, with derived values of λ_e and λ_g

Sample	property	Temperature °K										
		293	323	373	473	573	673	773	873	973	1073	1173
i	λ		0·155	0·163	0·175	0·188	0·205	0·219	0·234	0·247		
	$10^6\ \rho$	67·8	70·3	74·3	81·9	89·1	95·0	100·1	104·8	109·4	114·0	
	$10^8\ L$		3·38	3·25	3·03	2·93	2·90	2·84	2·81	2·78		
	λ_e		0·112	0·123	0·141	0·157	0·173	0·189	0·203	0·217		
	λ_g		0·043	0·040	0·034	0·031	0·032	0·030	0·031	0·030		
ii	λ		0·156	0·164	0·172	0·182						
	$10^6\ \rho$	71·0	74·0	78·3	86·3	92·8	97·6*	102·6*	107·2*	111·1*	114·1*	117·1*
	$10^8\ L$		3·58	3·44	3·14	2·95						
	λ_e		0·107	0·116	0·134	0·151						
	λ_g		0·049	0·048	0·038	0·031						
iii	λ		0·151	0·160	0·176	0·191	0·205	0·218	0·231	0·244	0·257	0·272
	$10^6\ \rho$	73·4	75·8	79·9	86·6	93·0	98·9	104·9	108·7	112·4	115·8	118·2
	$10^8\ L$		3·54	3·43	3·22	3·10	3·02	2·96	2·88	2·82	2·77	2·74
	λ_e		0·104	0·114	0·133	0·151	0·166	0·180	0·196	0·211	0·226	0·242
	λ_g		0·047	0·046	0·043	0·040	0·039	0·038	0·035	0·033	0·031	0·030
iv.a	λ		0·147	0·154	0·165	0·178						
	$10^6\ \rho$	75·8	77·7	81·6	88·8	96·0						
	$10^8\ L$		3·54	3·37	3·10	2·98						
	λ_e		0·102	0·112	0·130	0·146						
	λ_g		0·045	0·042	0·035	0·032						
iv.c	λ		0·155	0·165	0·185	0·203	0·220	0·235	0·250			
	$10^6\ \rho$	71·8	74·0	77·5	84·5	92·2	98·5	103·0	107·0			
	$10^8\ L$		3·55	3·43	3·31	3·27	3·22	3·13	3·07			
	λ_e		0·107	0·118	0·137	0·152	0·167	0·183	0·199			
	λ_g		0·048	0·047	0·048	0·051	0·053	0·052	0·051			

Table 9.—continued

Sample	Property	Temperature °K 293	323	373	473	573	673	773	873	973	1073	1173
v.1	λ		0·147	0·155								
	$10^6 \rho$	73·9	75·6	78·7								
	$10^8 L$		3·44	3·27								
	λ_e		0·104	0·116								
	λ_g		0·043	0·039								
v.2	λ		0·147	0·156								
	$10^6 \rho$	74·1	75·7	78·9								
	$10^8 L$		3·45	3·39								
	λ_e		0·104	0·115								
	λ_g		0·043	0·041								
vi.15	λ		0·157	0·167	0·186	0·204						
	$10^6 \rho$	73·7	76·0	79·8	87·0	94·0						
	$10^8 L$		3·69	3·57	3·42	3·35						
	λ_e		0·104	0·114	0·133	0·149						
	λ_g		0·053	0·053	0·053	0·055						
vi.17	λ		0·155	0·164	0·182	0·202						
	$10^6 \rho$	76·0	78·5	83·0	91·0	97·5						
	$10^8 L$		3·77	3·65	3·50	3·44						
	λ_e		0·101	0·110	0·127	0·144						
	λ_g		0·054	0·054	0·055	0·056						
Mean	λ		0·152	0·161	0·176	0·191						
	$10^6 \rho$	73·1	75·3	79·1	86·3	93·1						
	$10^8 L$		3·55	3·41	3·20	3·10						
	λ_e		0·105	0·115	0·134	0·151						
	λ_g		0·047	0·046	0·042	0·040						

* Different specimen.

values is believed to be about 2·5 per cent and that of the electrical resistivity values about 1 per cent. It is clear from the values presented in Table 9 that real differences exist between the conducting properties of these samples. The electrical resistivities show differences of as much as 12 per cent at 20°C, but only 9 per cent at 300°C. The thermal conductivities, on the other hand, differ by 7 per cent at 50°C and by about 15 per cent at 300°C.

Samples (iv)c and (vi)15 and (vi)17 increase in thermal conductivity most rapidly with increase in temperature.

The Lorenz functions also differ rather more ($\sim$18 per cent) at 300°C than at 50°C ($\sim$12 per cent). Use of the mean values included in the tables would have given calculated thermal conductivities differing from the measured ones by up to ± 9 per cent.

It would seem that some other factor than electronic conduction influences the thermal conductivity. This could be the lattice conductivity, which is given by:

$$\lambda_g = \lambda - \lambda_e,$$

and, by assuming the usual theoretical value of the Lorenz function to apply to the electronic component, λ_e, then:

$$\lambda_g = \lambda - 2{\cdot}443 \times 10^{-8}\, T\rho^{-1}.$$

Values of λ_e and λ_g derived from these equations are included in Table 9. λ_g is seen to differ appreciable both in actual value and temperature dependence. Furthermore, whereas λ_g has often been found to vary inversely as the absolute temperature, the present values are mostly seen to decrease less rapidly, while for samples (iv)c, (vi)15 and (vi)17, λ_g increases slightly with temperature. The values of λ_g depart by $+14$ per cent and -8 per cent from the mean value at 50°C and by $+30$ per cent and -20 per cent at 200°C. The highest values of λ_g vary least with temperature.

Full sample characterization would be required to attempt to reach an explanation of these results. The results for several samples of 18/8 stainless steel have been presented and examined in this way in order to direct attention to the very distinct differences that occur, and to show that much still remains to be discovered about heat conduction in these alloys. A detailed investigation would be both interesting and useful.

A question that arose was whether conductivity measurements made with the heat flow directed along the length of the tube would apply to a particular practical case in which the heat flow was normal to the wall of the tube.

In order to attempt to answer this experimentally difficult question, electrical resistivity measurements were made on small sections by the four-probe method. Since these measurements indicated the electrical resistivities for the two directions to agree to within about 1 per cent, the thermal conductivities were considered to agree within the same order. Whether the lattice component was the same in the two directions, now seems open to question.

3. A NEW METHOD FOR CHECKING THERMAL CONDUCTIVITY STANDARDS

The particular aspect of the work last described had arisen before the thermal comparator method had been developed [47, 48]. By means of a thermal comparator of the direct reading form it is now considered possible to detect differences of a few per cent in the thermal conductivity of samples that have been similarly prepared and are tested under the same conditions. Further developments of the method are thought likely to enable greater sensitivity to be attained. This method of course measures in a comparative manner the total thermal conductivity of a material. For this reason, and in the light of the importance of variations in the lattice component that have now become evident, attention is directed towards the advantage of the thermal comparator as a means of intercomparing and checking thermal conductivity samples. It could be used for instance with stainless steels to test whether samples of nominally the same steel, really do possess the same thermal conductivity.

The thermal comparator would also offer a most useful method for comparative check measurements on the various metallic and nonmetallic solids that are used as thermal conductivity standards. There had previously been no simple method available for the intercomparison of such samples, particularly of those that are non-conductors of electricity.

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Résumé—Afin de fournir plus de renseignements sur les conductivités thermique et électrique de matériaux proposés comme matériaux de référence pour la conductivité thermique, de nouvelles données sont présentées pour le cuivre (3 échantillons), le plomb, le fer (6 échantillons), le tungstène (2), l'Inconel 702 et l'acier inoxydable 18/8 (9 échantillons). La méthode du comparateur thermique est proposée afin de pouvoir facilement comparer entre eux les échantillons de référence standard. Cette méthode semble vraisemblablement adaptée spécialement aux matériaux ayant une composante élevée de conductivité thermique par phonons.

Zusammenfassung—Um weitere Informationen über die thermische und elektrische Leitfähigkeit von Materialien zu geben, die zur Verwendung als Referenzmaterialien bei der Bestimmung der Wärmeleitfähigkeit vorgeschlagen wurden, sind neue Werte angegeben für: Kupfer (drei Muster), Blei, Eisen, (sechs Muster) Wolfram (zwei Muster). Inconel 702 und 18/8 Stainless Steel (neun Muster). Zur Messung, die auch den Vergleich der Standardreferenzmuster untereinander erlaubt, wird die thermische Komparationsmethode vorgeschlagen. Diese Methode erscheint besonders angebracht bei Materialien mit einer grossen Phononkomponente der Wärmeleitfähigkeit.

Аннотация—Приводятся новые данные о тепло-и электропроводности материалов, используемых в качестве стандартов теплопроводности: для меди (3 образцов) свинца, железа (6 образцов), вольфрама (2) и нержавеющей стали инконель 702 и 18/8 (9 образцов). Предложен метод термического компаратора, позволяющий легко и просто сравнить между собой стандартные образцы. Метод представляет особый интерес для материалов, имеющих большой фононный компонент теплопроводности.