Recommended values for the thermal conductivity of aluminium of different purities in the cryogenic to room temperature range, and a comparison with copper

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The thermal conductivity of pure aluminium at cryogenic temperatures varies by many orders of magnitude depending on purity and treatment, and there is little information in the literature on the likely values to be obtained for samples of a given purity. A compilation of measurements from the literature has been assembled and used to provide recommended ranges of values for aluminium of different purities (4N, 5N and 6N) in the normal (non superconducting) state. The number of direct thermal conductivity measurements is too limited to be used alone. Electrical resistivity measurements have thus also been used by converting to thermal conductivity using the Wiedemann-Franz law, which is shown to be valid. Since low temperature measurements can easily be extrapolated to higher temperatures, the results cover the range from 1.2 K (the superconducting transition temperature) to room temperature. Values for 5N purity copper have also been examined in a similar manner, to allow a comparison between the two materials. The main application of these results is in the design of cryogenic thermal links; a discussion of the advantages and disadvantages of both materials for this use is given. The use of silver is also investigated briefly. Trends in the behaviour of the conductivity of aluminium in the superconducting state (to temperatures as low as 50 mK) are also discussed.

Keywords: metals (A); thermal conductivity (C); electrical conductivity (C)

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1. INTRODUCTION

At room temperature, pure aluminium is a good electrical and thermal conductor; the only metals with higher conductivity are copper, silver and gold. Moreover, aluminium provides the highest conductance per unit mass, making it attractive in situations such as aerospace applications where mass must be minimized.

Aluminium has not been traditionally used as a thermal conductor at low temperatures for two main reasons. Below 1.2 K [1], aluminium becomes superconducting; superconductors are excellent electrical conductors but poor thermal conductors. It is also hard to make good thermal contact to aluminium because of the insulating oxide layer which forms rapidly on bare aluminium surfaces; the effect of the oxide layer is much greater at low temperatures than near room temperature.

Copper is usually used when a good low temperature thermal conductor is required, since it suffers from neither of these problems. In addition, unlike aluminium, it can be usefully used structurally in the pure form. Aluminium *alloys* can be used structurally but have much poorer conductivity than pure aluminium [2].

Aluminium has, however, been used in specialist applications such as superconducting heat switches [3–7]. Techniques for overcoming the oxide layer problem have been developed, such as gold plating [7, 8] and various types of welding [3–6]. However, gold plating techniques are not necessarily reproducible [3] (aluminium is notoriously difficult to plate reliably), and welding is not always practical. For large cryogenic instruments (for example Ref. [9]), the mass of thermal links can be significant. Minimizing mass is particularly important for the increasing number of cryogenic instruments being designed for airborne and space environments. Aluminium is therefore sometimes chosen as a thermal link material in such instruments in order to reduce mass. Since structures such as helium vessels are often constructed from aluminium alloys in these instruments, aluminium thermal links offer the further advantage that they can be readily welded to aluminium alloys.

Aluminium has advantages over copper other than the lower density. It is more readily obtained in high purity form (99.999% pure), deformation has less effect on conductivity, and annealing (necessary for the best thermal performance) can be carried out in air; copper is usually annealed in vacuum or inert gas for satisfactory results.

Making a decision on whether to use aluminium or copper in a given situation is difficult due to the lack of useful values for the thermal conductivity of either material at low temperatures. At low temperatures the thermal and electrical conductivity of pure metals varies over many orders of magnitude, depending on the temper (history of cold work and annealing) and chemical purity.

The usual advice is that the low temperature thermal conductivity of a given piece of aluminium or copper can only be determined from measurements on the sample. While this is the only definitive method, it is not practical at the design stage of an instrument - at this point it is necessary to have information on the ranges of values which are likely for the materials under consideration.

It is not unusual for a decision to be made based on measurements of single samples of copper and aluminium, either made directly, or obtained from the literature. Due to the large variation possible between samples, this can lead to seriously misleading conclusions.

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Compilations of low temperature conductivity measurements generally present results for samples of different purity without any attempt at interpretation. Where recommended values are given, they correspond to samples with a particular, somewhat abitrary, conductivity.

The aim of this paper is to provide information on the range of conductivity values which are likely for aluminium of various purities and treatments. Since low temperature measurements can easily be extrapolated to higher temperatures, the results cover the range from low temperatures to room temperature. Values for high purity copper are also examined in order to make a comparison between the two materials.

2. APPROACH

The number of low temperature thermal conductivity measurements on pure aluminium described in the literature is quite small – too small to be useful in determining the likely range of values for different purities.

However, at sufficiently low temperatures, thermal conductivity can be determined from the electrical resistivity using the Wiedemann-Franz law [10]. This has been shown to be a good approximation for most pure metals [11]. There are many more electrical resistivity measurements than thermal measurements available for aluminium; this is not surprising since electrical measurements are much easier to make.

The approach taken in this paper was to create a database of as many low temperature electrical and thermal measurements on pure aluminium as practical. No attempt was made to restrict the results used to the most accurate measurements; indeed values were used even when the measurement method was not described. This was necessary in order to provide a sufficiently large number of results. The justification is that errors even as high as 20 or 30% are small compared to variation between samples, and thus will not significantly affect the overall conclusions. Rogue measurements which are in error by much larger amounts should be evident by their disagreement with the bulk of the data.

Sources of data include papers and compilations describing the results of thermal conductivity and electrical resistivity experiments. However, "incidental" results have also been included; these were obtained from various papers which mention the conductivity or resistivity of materials which were used in other experiments. The most common example of this is where the electrical resistivity was used as a measure of the purity of a material.

It is, of course, not possible to make a complete collection of all measurements in the literature. However, the attempt was made to be as complete as possible for direct thermal conductivity measurements. Electrical resistivity measurements are less complete, and the incidental measurements collected can only be a fraction of those in existence, since it is very difficult to search specifically for such papers.

At sufficiently low temperature (in the non-superconducting, or "normal" state), the thermal conductivity of aluminium is a linear function of temperature. The electrical resistivity is constant to a good approximation over a similar temperature range; the constant value is known as the residual resistitivity. The low temperature conductivity of a given sample can thus be easily categorised by either the thermal conductivity at a particular temperature or the residual resistivity. This is often quoted as the residual resistance ratio, RRR; this is the resistance at room temperature divided by the residual resistance.

Code	Range of values for purity, p
4N	$99.98 \leq p < 99.994$
4N5	$99.994 \leq p < 99.998$
5N	$99.998 \leq p < 99.9994$
5N5	$99.9994 \leq p < 99.9998$
6N	$99.9998 \leq p < 99.99994$

Table I: Scheme used to obtain purity codes where percentage purities were quoted.

At higher temperatures, electrical and thermal conductivity vary in a complex way with temperature. A set of equations describing this variation for aluminium are given in Ref. [12] [1]; these enable the thermal conductivity from the superconducting transition temperature to room temperature to be characterised by a single value such as the RRR. For convenience, conductivity in this paper is characterised by the value it would take at 1 K in the normal state. In fact, aluminium can be made to stay in the normal state below 1.2 K if a suitably large magnetic field is applied. The conductivity is then linear with temperature [3, 13].

Purities are characterised in this paper as the percentage (by weight) of pure aluminium, and denoted by codes such as 5N for 99.999% purity. If a sample was not described by such a code, but the purity was given as a percentage, a code was chosen using the ranges shown in table I. No attempt was made to assign a numerical purity to material only described in terms such as "high purity" or "ultra pure", since these terms are not strictly defined [14].

3. VALIDITY OF THE WIEDEMANN-FRANZ LAW

The thermal conductivity, κ, of a metal is related to the electrical resistivity, ρ, by the Wiedemann-Franz law [10]:

$$\kappa = \frac{LT}{\rho}, \tag{1}$$

where L is the Lorenz number, and T is temperature. For sufficiently low temperatures, L is expected to take the theoretical value of $L_0 = 2.45 \times 10^{-8}$ WΩK^{-2}.

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[1] Readers having difficulty in obtaining this reference should note that the equations are reproduced in Ref. [2]

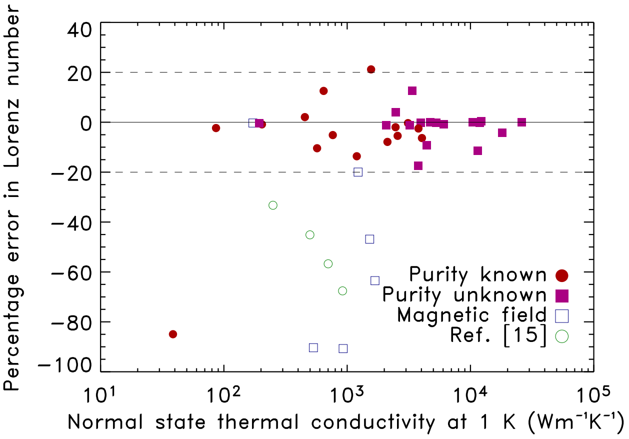

Figure 1: Percentage deviation of the Lorenz number L from the theoretical value L_0, for various measurements in the literature (i.e. $100(L - L_0)/L_0$). Symbol styles denote results taken as part of measurements in varying magnetic fields (□), measurements from Ref [15] (○), and remaining measurements using samples with known (●) and unknown (■) purities. The solid line corresponds to the theoretical value for L of 2.45×10^{-8} WΩK^{-2}, and the dotted lines correspond to errors of $\pm 20\%$. References: [7, 16–22] (●), [22–25] (■), [26–28] (□), [15] (○).

Various papers describe measurements of both the thermal conductivity and electrical resistivity of samples of pure aluminium at low temperatures. These results are plotted in Figure 1. Where RRR was quoted instead of residual resistivity, the room temperature resistance was taken as 2.7×10^{-8} Ωm [29] if the correct value was not given. This corresponds to a temperature of 298 K. While the exact temperature at which the room temperature measurements were made was often not stated, it is unlikely to be significantly higher than this or below 273 K. The change in resistivity between 273 K and 298 K is approximately 10% [29]; this is a similar size to experimental uncertainties, and the error introduced by using the wrong temperature to convert RRR to resistivity is thus acceptable. Thermal conductivity values were converted to the normal state value at 1 K by assuming a linear temperature dependence. Ref. [12] was used to ensure that measurements were at sufficiently low temperatures for this to be valid, and for the resistivity to be in the constant region.

In many cases, the two measurements were made on different samples taken from the same source material. This is a potential source of error since spatial variation of purity in the original material will cause different samples to have different properties [30, 31]. Even where measurements were made on the same sample, it was usually warmed up to room temperature and handled between measurements. This can also introduce errors due to changes in temper between the measurements (either by annealing taking place at room temperature, or cold work caused inadvertently during handling).

However, Figure 1 shows that in general the agreement is very good, to better than 20% – this is adequate for the purposes of this paper. It is quite possible that most of the error is due to experimental uncertainty and the effects described above.

There are a few significant deviations; in every case $L < L_0$. All the samples from Ref. [15] show low values of L; these appear to be real, but it is not clear why these results contradict the majority of other measurements. With one exception, the remaining results which deviate by more than approximately 20% were obtained from measurements of the effect of magnetic fields on thermal conductivity. Although the measurements were made in nominally zero field, it is possible that a magnetic field was still present. This could affect the results either by the reduction of the thermal conductivity where resistivity measurements were made in a separate apparatus, or by the variation of Lorenz number with magnetic field [11] where resistivity was measured along with thermal conductivity. It is interesting that in Ref [27] the Lorenz number can be seen to peak sharply at a small but non zero value of magnetic field.

In copper, the few observations of deviation from the Wiedemann-Franz law [32–34] seem to be connected with deformation; again, $L < L_0$. There is little information for aluminium; one group [35] found that deformation *increased* L_0 for 3N purity Al but not for 5N or 6N purity. The Wiedemann-Franz law will be assumed to be valid for the remainder of this paper.

4. RESULTS - NORMAL STATE

Figures 2 to 5 show thermal conductivity values for aluminium samples of different purities. Where necessary, measurements have been converted to normal state conductivity at 1 K by extrapolation using Ref. 12 or using the Wiedemann-Franz law. The RRR values shown on the y-axis of each graph are calculated assuming a room temperature resistivity of 2.7×10^{-8} Ωm [29]. Coincidentally, the RRR value is numerically almost identical to the thermal conductivity at 1 K in SI units.

For each purity range and condition, there is considerable scatter in the values. For the annealed condition, there are likely to be two main causes for this scatter: differences in purity of the original material and differences in the annealing conditions. It is well established that the improvements due to annealing depend on annealing time and temperature. Tests on samples with 5N and 6N purity show that there is a sharp increase in final RRR for annealing temperatures above approximately 100 °C [44, 65]; the RRR then increases with temperature. The majority of the improvement due to annealing takes place in the first 1 or 2 hours, though further improvement is seen up to at least 100 hours [44]. Significant annealing can occur even at room temperature [28, 43, 65–67], with substantial recovery from strain seen just 1 hour [66].

The upper useful temperature is often dictated by contamination from materials with lower melting points such as supports; a temperature of approximately 400 °C appears to be a good choice [44, 65]. Good results can be obtained by annealing in air at atmospheric pressure. According to Ref. [44], no improvement in RRR was seen for 5N purity by annealing in

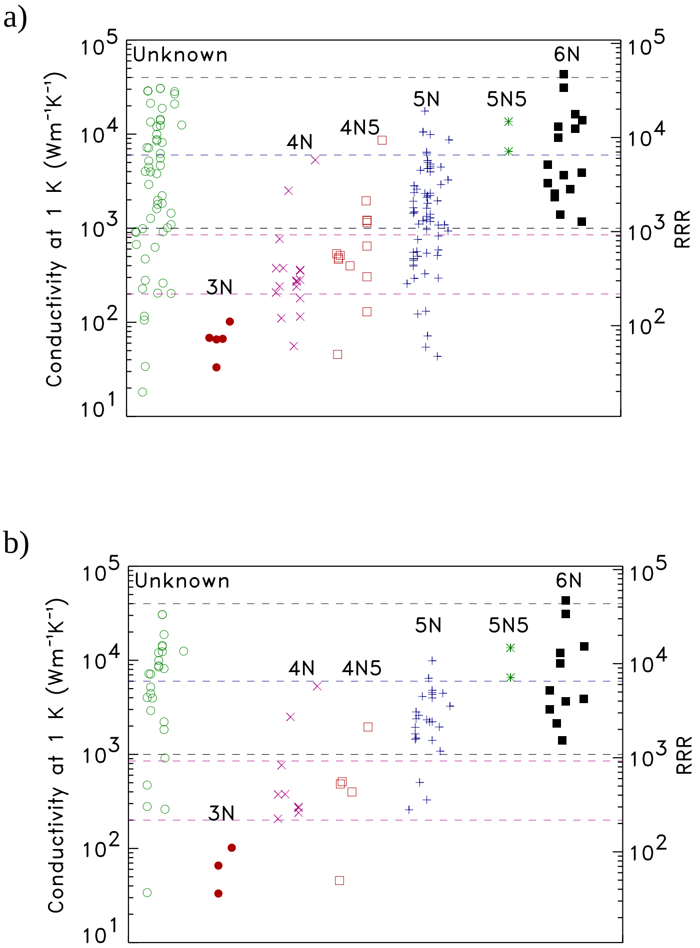

Figure 2: Normal state thermal conductivity values for aluminium at 1 K from thermal and electrical measurements. Values are shown in the upper graph for all tempers, and in the lower graph for annealed temper only, for different purities as marked. Horizontal dashed lines show ranges of values for annealed aluminium of different purities (see Figs 3 to 5). References for annealed samples: [16, 36] (●), [16, 17, 22, 36–40] (×), [3, 15, 16, 18, 22, 36, 37, 39–44] (+), [16, 21, 40, 42, 45, 46] (■), [22, 23, 37, 38, 40, 44, 47–49] (○), [50] (⋆), [22, 40, 51–53] (□). References for other tempers: [40, 54] (●), [13, 20, 22–24, 26–28, 31, 38, 40, 44, 47, 50, 54–56] (○), [3, 7, 15, 18, 19, 31, 39, 40, 42–45, 54, 57–60] (+), [40, 42, 61–63] (■), [20, 38, 51, 64] (□), [22, 31, 39, 60, 64] (×).

vacuum. In Ref. [21], air annealing was found to be produce higher RRR values than vacuum annealing for anneal times of "a few minutes", but for longer times, vacuum annealing produced better results.

Unfortunately, even for 5N purity, where there are a considerable number of measurements, results for samples obtained from different sources do not seem to correlate with the annealing conditions. It therefore seems likely that the annealing conditions are not the dominant cause of the scatter, and it should therefore not be assumed that the upper end of the conductivity range can be obtained by choosing optimum conditions. Material purity (and perhaps the types of impurity) is probably more important.

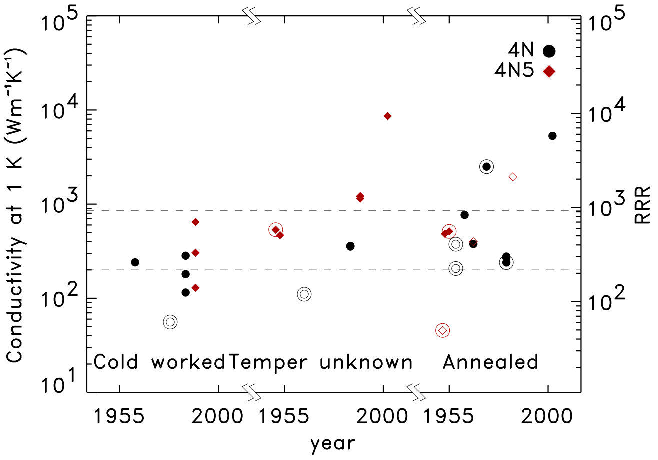

Figure 3: Normal state thermal conductivity values at 1 K for 4N (●, ○) and 4N5 (♦, ◊) purity aluminium. Open symbols show measurements that may be affected by size effects. Points corresponding to direct thermal conductivity measurements are ringed; other points are obtained from electrical resistivity measurements and the Wiedemann-Franz law. Symbols are plotted as a function of the approximate year of the measurement. Dashed lines show recommended upper and lower limits for 4N purity in the annealed state, based on these values. References: [16, 17, 31, 36–40, 64] (●), [20, 38, 51, 53, 64] (♦), [22, 40, 52] (◊), [22, 40, 60] (○).

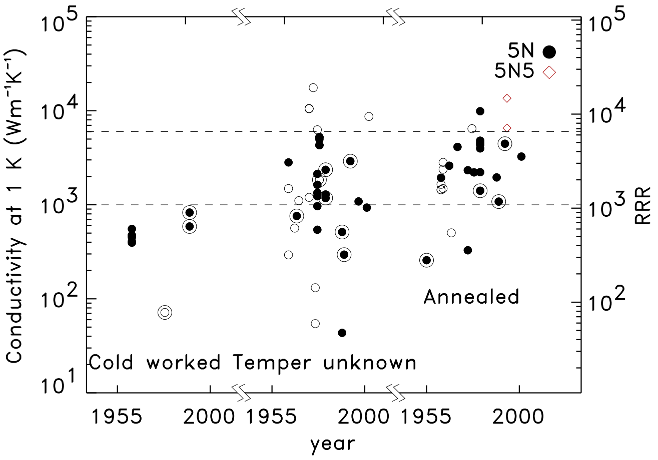

Figure 4: Normal state thermal conductivity values at 1 K for 5N (●, ○) and 5N5 (◊) purity aluminium. Other details are as for Figure 3. References: [7, 39, 40, 43–45, 54, 58, 60] (○), [3, 15, 16, 18, 19, 22, 31, 36, 37, 39–43, 58, 59] (●), [50] (◊).

There is a further effect which must be taken into consideration. For samples with sufficiently small dimensions, electron scattering from the boundaries will limit the conductivity [68]. In principle it is possible to correct for such size effects; however, the correction is not straightforward, since it depends on

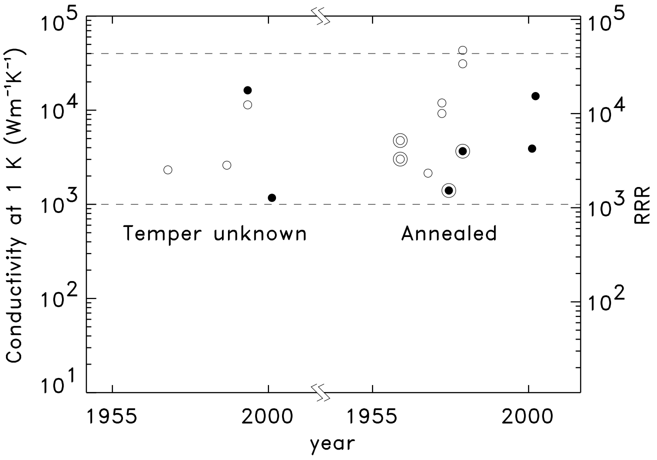

Figure 5: Normal state thermal conductivity values at 1 K for 6N purity aluminium. Other details are as for Figure 3. References: [16, 42, 45, 46, 62] (•), [21, 40, 61, 63] (○).

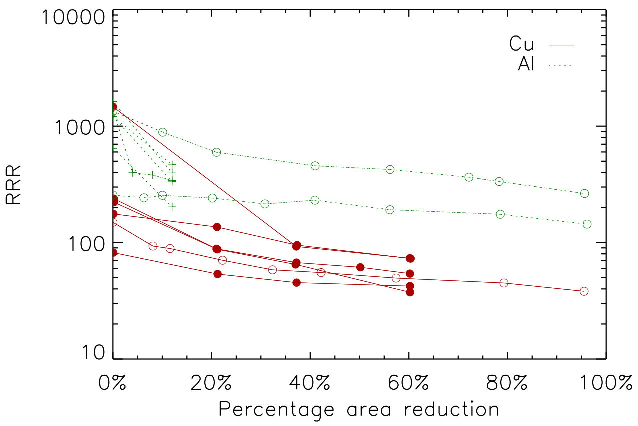

Figure 6: The effect of deformation on the RRR of pure aluminium (dashed lines) and copper (solid lines) for rod samples (Refs. [69] (•) and [70] (○)) and foils (Ref. [39] (+)). Samples are for 4N purity aluminium and OFHC copper, except where marked as 5N purity.

the smoothness of the boundaries as well as the sample geometry. Therefore no correction has been made to any results shown here, and measurements which were quoted only after correcting for size effects have not been used. Some results shown in Figs 2 to 5 are thus likely to be lower than the true bulk values. Points corresponding to an electron mean free path greater than 20% of the smallest dimension are plotted with open symbols in Figs. 3 to 5[2]. For the remaining points, the true (bulk) values should be no more than 25% greater than the measured values.

A recommended range of values is shown for each purity type in the fully annealed state. These ranges have been chosen to include the majority of data points. Excluded points may be due to experimental error. Alternatively, anomalously low values may correspond either to problems in the annealing process, material with lower purity than quoted, or samples suffering from significant size effects. Higher values may correspond to material of higher than quoted purity. While these ranges are somewhat subjective, since the raw data are presented here, readers may make their own decisions on appropriate ranges.

For 5N purity, the values for aluminium of unknown history are consistent with the annealed values in that the upper end of the range is similar to that for the annealed state, but the lower end is lower. This would be expected since the ‘unknown’ samples presumably include both annealed and un-annealed examples. There are too few measurements for other purities to draw similar conclusions.

The effect of deformation on RRR is shown in Figure 6. Similar behaviour has been seen when samples have been subjected to repeated small strains [64]. The effect of a given percentage area reduction (PAR) is, not surprisingly, different for 6.4 mm diameter rod samples [70] and for 200 and 80 μm thick foils [39]. However, the limiting values of conductivity seem to be similar.

The effect of deformation increases with increasing purity. This is also not surprising, since the contribution to the thermal resistance caused by deformation should not depend strongly on the purity. A low purity material, which already has a relatively high thermal resistance due to impurities, will thus be affected less than a high purity material which has relatively low impurity thermal resistance.

The conductivity of aluminium is also affected by neutron irradiation; further information is given in Refs 16, 39 & 71.

5. RESULTS - SUPERCONDUCTING STATE

The superconducting transition temperature, T_c, for pure aluminium is 1.2 K [1]. As the temperature is reduced below this value, the electron thermal conductivity decreases rapidly as the number of electrons not bound into Cooper pairs decreases [72]. The electron conductivity, κ_{el}, can be represented by an empirical equation [48]:

$$\kappa_{el} = \kappa_0 \exp\left[\alpha\left(1 - \frac{T_c}{T}\right)\right], \tag{2}$$

where κ_0 is the conductivity at T_c, and T is temperature. Fits using this equation are shown in Figure 7; a value of $\alpha = 1.8$ fits the majority of the data reasonably well at the higher temperatures.

The electron conductivity normally dominates the thermal conductivity of aluminium. However, far enough below the transition temperature it becomes small enough for the lattice conductivity to become significant, and even to dominate. The measurements therefore deviate from the fits for electron

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[2] This is calculated from the conductivity using Eq. (1) in Ref. [68] with a value of $l_b\rho_b = 5.5 \times 10^{-16}\Omega\text{m}^2$.

conductivity. Lattice conductivity is not expected to depend significantly on the sample purity, but should be affected by cold work and annealing. The samples shown here have a wide range of values, and there is insufficient information to be able to make predictions based on sample properties. Deformation has been seen to lower the lattice conductivity of 4N aluminium [49][3], but – surprisingly – results for 6N purity [42] show little change.

Even the temperature variation is uncertain. A T^3 variation, as seen in crystalline dielectrics, is often assumed. The temperature ranges available here are too small to confidently assign power-law exponents. However, while a T^3 dependence fits some of the results reasonably well, others are fitted better by a T^2 or lower dependence. One group has concluded that a T^2 variation should be expected for deformed high purity samples (4N and above), and a T^3 variation otherwise [57].

The conductivity of superconducting aluminium below about 200 mK is thus a rather uncertain property.

6. COMPARISON WITH COPPER AND SILVER FOR THERMAL LINKS

As with aluminium, the highest readily available purity of copper is 5N. It is therefore instructive to compare likely values of conductivity for 5N aluminium and copper. The conductivity of 5N copper was examined in the same manner as described above for aluminium. The results are shown in Figure 8. The upper limits are similar, but the values for annealed copper cover a much larger range than for aluminium. This is probably due to the large reduction in conductivity caused by even a few ppm (parts per million) of magnetic impurities in copper [73, 93]. Since the 5N specification only describes the total impurity content and not the quantity of individual elements, different samples meeting the specification can have very different conductivities. The amount of magnetic impurity is likely to depend on the copper ore used and the purification process, suggesting that the range of conductivity values of material produced by a given supplier will be smaller. This is supported by Ref. 73, where samples from a single supplier over a period of ten years were found to have RRR values which varied only between 900 and 1900.

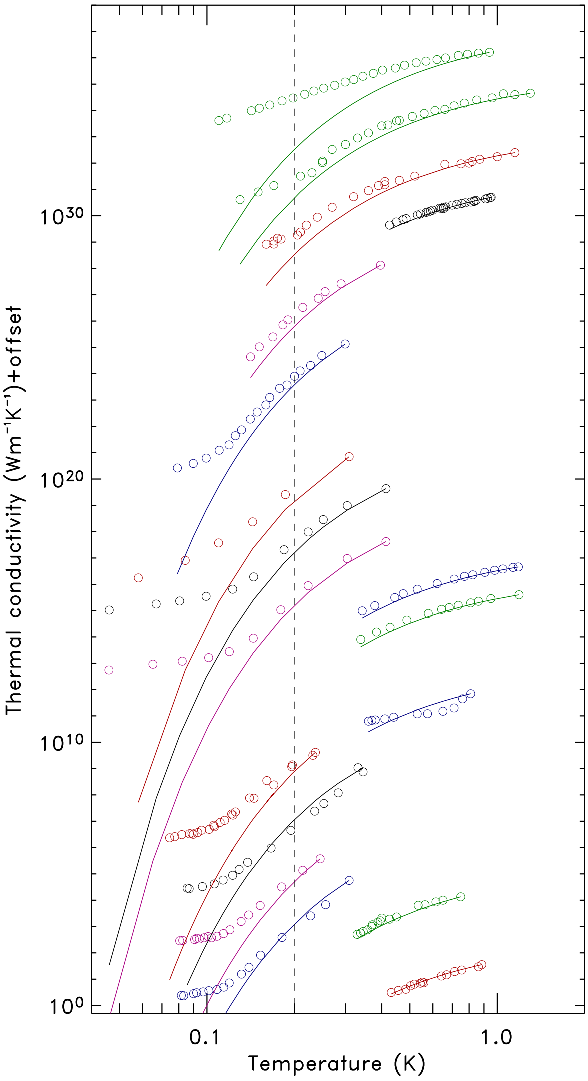

Figure 7: Thermal conductivity in the superconducting state for various aluminium samples, showing exponential fits to the electron conductivity (Eq. 2). For clarity, measurements have been offset by arbitrary amounts along the y axis. The vertical dashed line shows the approximate temperature below which lattice conductivity is likely to be significant enough to cause the measurements to deviate from the fits. References: [7, 19, 22, 31, 42, 48, 49, 54, 57].

The conductivity of copper can be improved by annealing at temperatures just below the melting point in the presence of trace quantities of oxygen; a process usually known as “oxygen annealing”. It is well established that significantly higher conductivity values can be produced than by vacuum annealing, as can be seen from Figure 8. While the exact mechanism is not certain, the improvement seems to largely come about by reducing the effect of magnetic impurities [73, 93, 99]. Striking evidence of this is given by measurements on copper with controlled amounts of iron added [73, 93]; RRR values of over 2000 could be produced by oxygen annealing samples with an initial RRR as low as 5. The resistivity of samples with up to 100 ppm of iron added covered over two orders of magnitude before oxygen annealing, and yet had almost no dependence on iron content after annealing. This is particularly impressive since the amount of iron alone reduces the copper content to around 99.99%, yet the final RRR values are characteristic of the 5N purity base material. This suggests that oxygen annealed samples are likely to show much less sample to sample (and supplier to supplier) variation than vacuum annealed copper. While oxygen annealing is not a process that is generally offered commercially, it is fairly simple to carry out. It should be noted that oxygen annealing

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[3] The purity of these samples is given as 4N in Ref. [42]

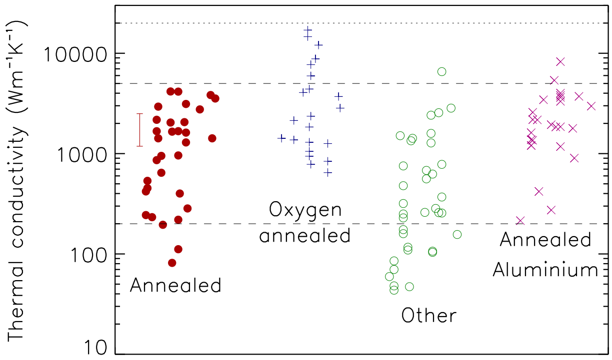

Figure 8: Thermal conductivity values for 5N purity copper at a temperature of 1 K, from thermal and electrical measurements. The results labelled "other" are for samples that were cold worked before measurement, or where the heat treatment is unknown. The "annealed aluminium" results show values from Fig. 4. The error bar shows the range of results obtained for 5N copper from a single supplier over a number of years [73]. Other references: [22, 39, 65, 69, 73–87] (●), [22, 39, 73, 74, 76, 78, 80, 84, 86–95] (○), [15, 22, 73, 78, 79, 82, 83, 87, 92, 93, 96–98] (+).

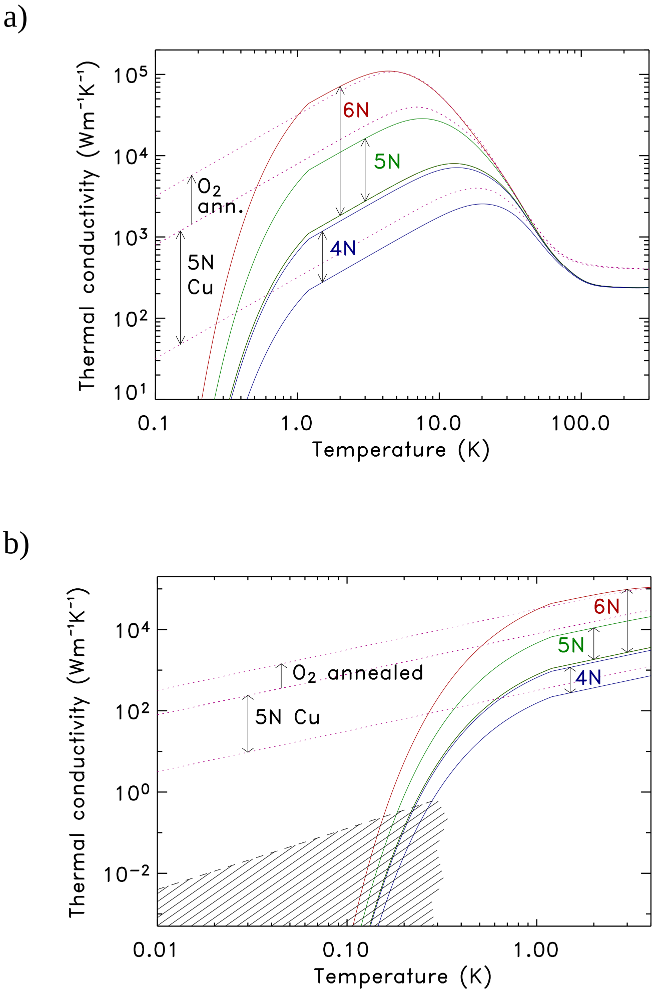

Figure 9: Recommended ranges for the conductivity of annealed aluminium with 4N, 5N and 6N purity (solid lines). Note that the lower limits for 5N and 6N purity are the same. Recommended values for vacuum annealed 5N purity copper are also shown, along with the higher conductivity values possible following oxygen annealing (dashed lines). The two graphs show the same information over different temperature ranges. The hatched area in the lower graph shows the region in which lattice conductance is likely to become significant; in this region the values shown here are lower limits on the conductivity.

is not a useful method for improving the conductivity of aluminium.

Another difference between copper and aluminium is the effect of cold work on conductivity. Figure 6 shows several measurements of the RRR of deformed copper. The effect of cold work can be seen to be much greater for copper than aluminium, especially at the higher purities.

Silver is another obvious choice for a thermal link. However, while it is a marginally better conductor than copper at room temperature, this is unlikely to translate into a significant improvement at low temperatures. Indeed, compilations of thermal [22] and electrical [86] measurements of silver of various purities (including 6N) give maximum RRR values of only 2 600 and 10 000 respectively. In a brief literature search, aided by the excellent review article by Smith and Fickett [100], only one higher value was found; 20 000 for an oxygen annealed single crystal [101]. Since copper of just 5N purity can reach even this value, it seems that silver does not offer improved thermal conductivity at low temperatures.

7. RECOMMENDED VALUES

Figure 9 shows recommended values for the thermal conductivity of fully annealed aluminium of various purities. The curves are generated by taking the recommended normal state values at 1 K and applying the equations from Ref. [12] for the normal state, and Eq. 2 for the superconducting state. A thermal conductivity calculator using these equations can be found on the world wide web [102]. Since the lattice conductivity does not depend on purity, the different curves for the superconducting state cannot be continued below the point at which lattice conductivity dominates. This point will depend on the magnitude of the lattice as well as the electron conductivity. The area in which this is likely to occur is shaded.

For comparison, values for fully annealed 5N copper are also shown; copper does not become a superconductor and thus the conductivity remains linear with temperature down to arbitrarily low temperatures. These curves were also produced with the aid of Ref. [12].

Fig. 10 shows conductivity divided by density. This is the appropriate quantity for comparing the performance of thermal links made from different materials but with the same

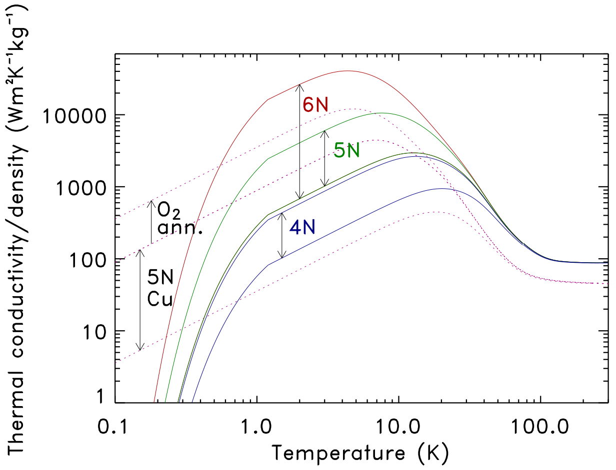

Figure 10: Recommended ranges for conductivity divided by density; this is the appropriate figure of merit for comparing thermal links with a fixed mass. Other details are as for Fig. 9.

mass; in aerospace environments it is often mass, rather than volume, that is the limiting factor for a thermal link. It can be seen that the lower density of aluminium gives it a considerable advantage, but that for temperatures below 4 K, oxygen annealed copper can still outperform 5N aluminium.

8. CONCLUSIONS

As with most pure metals, the thermal conductivity of aluminium at low temperatures varies by many orders of magnitude, depending on purity and thermal treatment. Aluminium is not suitable for thermal links at temperatures below 1.2 K since it is a superconductor. At higher temperatures, aluminium is an alternative to the more common choice of copper. Recommended conductivity values have been presented for various purities, in both the superconducting and normal states.

For both copper and aluminium, 5N is the highest purity that is readily available; recommended values for 5N copper have therefore also been produced to enable a comparison to be made between the two materials.

The range of conductivity values for annealed 5N copper is somewhat greater than that for aluminium, with the upper limits being similar. Much of the variation for copper is likely to be due to the use of different raw material and processing methods, and the variation for samples from a given manufacturer is probably considerably smaller. If a source of 5N copper with consistently high conductivity can be found, then 5N aluminium and copper can be assumed to have similar conductivity. Oxygen annealing of copper (annealing in the presence of trace quantities of oxygen) can give conductivity values somewhat higher than for aluminium of the same purity. In addition, the conductivity of oxygen annealed copper is likely to be much less sensitive than vacuum annealed copper to the source of copper, reducing the need to choose an appropriate supplier. However, this process is not generally offered commercially.

Copper has the advantage that making good thermal contact is easy; this is much harder for aluminium, where there is no established procedure. However, if this obstacle can be overcome, aluminium offers the advantages of better availability in high purity form, lower density, less reduction of conductivity by deformation and no requirement for annealing in vacuum or near vacuum.

For high performance cryogenic thermal links above 1.2 K, therefore, it is necessary either to find a source of 5N copper with good conductivity, to be able to oxygen anneal copper, or to have a method for reliably making good thermal contact to aluminium. The choice of whether to use copper or aluminium thermal links in a given situation thus depends largely on which of these three options is considered the least effort.

Measurements on silver have also been examined. While it has a slightly better conductivity than copper at room temperature, it does not appear to offer any advantages over copper (or aluminium) at low temperatures.

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