A low temperature thermal conductivity database

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Abstract. Low temperature detectors necessarily require low temperature instruments. Constructing good low temperature instruments requires information on the properties of materials used in their construction, in particular the thermal conductivity. Unfortunately, this is poorly known for many materials. Collections of data in text books tend to be incomplete and in the worst cases are misleading. For most materials, what information is known is scattered through the literature. Searching out this data is time consuming, and in any case often results in conflicting information. We have started a programme to locate, consolidate and critically analyse thermal conductivity measurements from the literature, particularly for the challenging temperature range below 1 K. This has already produced useful results. We present some preliminary results here.

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INTRODUCTION

Low temperature detectors necessarily require instruments which operate at low temperatures. To construct such instruments, it is necessary to have a knowledge of material properties, and in particular thermal properties. In cryogenics, this knowledge is often *not* a detailed knowledge of properties such as thermal conductivity as a function of temperature, but the knowledge that certain materials perform satisfactorily in particular circumstances.

The difficulty of carrying out measurements at cryogenic temperatures, and the long timescales generally involved in warming up a cryogenic instrument to rectify problems mean that cryogenic design is generally extremely conservative. Instruments are generally constructed from a relatively small number of materials, used in traditional ways. However, low temperature detectors in areas such as astronomy and fundamental physics often require instruments with more demanding requirements than those that have come before, especially for applications in space [1].

The problem then is the lack of reliable engineering data. The most critical property is normally thermal conductivity. This is important for most components in a cryogenic system, and in particular for thermal links which carry cooling to detectors from a cooler such as a helium-3 sorption fridge, and for mechanical supports between stages at different temperatures. Unfortunately, thermal conductivity is extremely sensitive to changes in material composition. One problem we encounter is simply the lack of suitable measurements. However, another problem is that existing measurements are scattered through the literature, often in sources which are hard to obtain, and little effort has been made to critically examine them.

Many text books in cryogenics contain graphs and tables of thermal conductivity of various materials. However, they suffer from significant problems. Firstly, they almost always consist of single measurements for each material. This gives no information on likely variation between samples of the same material, but also gives no confidence that the one measurement selected is accurate. (Accurate thermal conductivity measurements are not easy to make). In some cases, the measurements presented are actually not direct measurements, but extrapolations from other measurements which are not always well justified. Conversely, they often fail to make use of (valid) extrapolations which could supplement limited direct data. A small number of books give graphs showing ranges of values for materials, but without information on the origin of these values it is impossible to know how many samples were measured to produce these values, and thus if these represent likely ranges, or include samples with extreme behaviour.

We are starting to rectify this problem by assembling a large collection of data on thermal conductivity, and using it to produce recommended thermal conductivity values for different materials. For a given material, we use all available measurements, as well as a knowledge of the physical principles underlying thermal conductivity, to reach our conclusions. In this paper, we present preliminary results for the first few materials we have considered. We should perhaps comment that we have started with materials for which good agreement has been found between different measurements; the good agreement generally seen in materials presented here should not be taken to imply that such good behaviour is universal!

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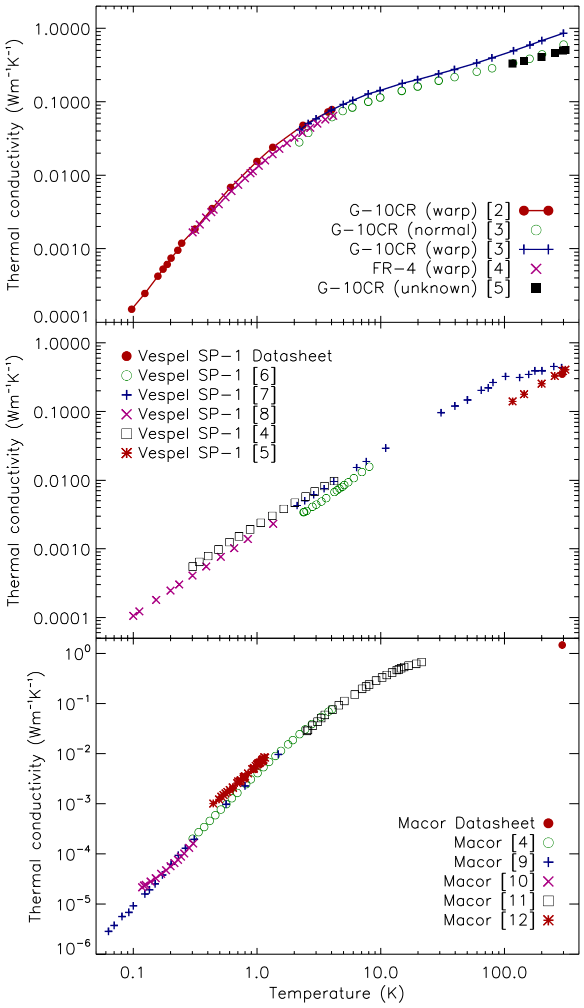

FIGURE 1. Thermal conductivity of G-10CR, G-10 and FR4 [2, 3, 4, 5] (results in Ref. [2] for G-10 are similar to their G-10CR values), Vespel SP-1 [4, 5, 6, 7, 8] and Macor (machineable glass ceramic) [4, 9, 10, 11, 12].

MATERIALS

Figure 1 shows three materials. G-10 is a glass fibre reinforced epoxy, probably the most popular fibre reinforced polymer used at cryogenic temperatures. It is generally used for printed circuit boards, and a "cryogenic grade", G-10CR, is also available. Contrary to popular belief, the name "G-10" does not describe a particular material; it is a NEMA specification describing electrical and mechanical properties (this standard is not freely available, but the US military equivalent, MIL-I-24768/2 is). The actual composition is not well defined. Different materials therefore may be (and are) sold as meeting the G-10 specification, and are commonly referred to as G-10 (or FR-4, a fire retardant replacement, which is itself often incorrectly called G-10/FR-4). The thermal conductivity of G-10 is not specified, even at room temperature. It is therefore likely that samples of G-10 from different manufacturers will have different thermal conductivity values. To avoid this, the G-10CR specification exists, which *does* specify particular source materials and processing; G-10CR can thus be considered a material, unlike G-10. The point of this discussion is that using G-10, rather than G-10CR is a gamble; measurements showing similar conductivity of G-10 samples to G-10CR that have been used to suggest that G-10 is as good as G-10CR have missed this point. Fig. 1 shows good agreement between measurements on G-10CR in overlapping temperature ranges, and we can thus easily construct a recommended curve.

Vespel SP-1 is an unfilled polyimide commonly used in cryogenics. Measurements are in reasonably good agreement, except for those from Ref. [5]. Since no details of the experimental method are given, we cannot judge the likely accuracy of these results, and have omitted them when calculating the range of recommended values.

Macor, a machineable glass ceramic, is another popular material in cryogenics, and has an extremely low thermal conductivity around 10 mK. Measurements are in gratifying agreement. Omitting the results from [12] on the grounds that they are somewhat different from the remaining measurements, we obtain a smooth curve. We have no data between about 20 K and room temperature. The change in conductivity is small, so a smooth interpolation is presumably not too far from the correct values.

Results for manganin are shown in Fig. 2. This is an alloy commonly used for cryogenic wiring. Results are again in good agreement, with some of the small differences between materials attributed to differences in composition. Here, as well as direct thermal conductivity values, we show a prediction [16] from the Wiedemann-Franz law [28]. Again, a smooth curve can easily be drawn through the values. However, the behaviour is somewhat strange. Below 1 K, and between around 2 K and 10 K, the conductivity has the expected linear variation with temperature for a metal. However, between 1 K and 2 K it rises somewhat. The rise is shown by a single measurement (Ref. [17]), which agrees nicely with other measurements at higher and lower temperatures. However, it is physically unexpected. The Weidemann-Franz result from Ref. [16] agrees with the lower temperature values. The temperature at which the electrical measurement these values are based on is not given, but is almost certainly 4 K, yet it agrees with the thermal conductivity values at lower temperatures. Further measurements would therefore be desirable.

The three measurements we have on the titanium alloy Ti_6Al_4V agree reasonably well with each other and

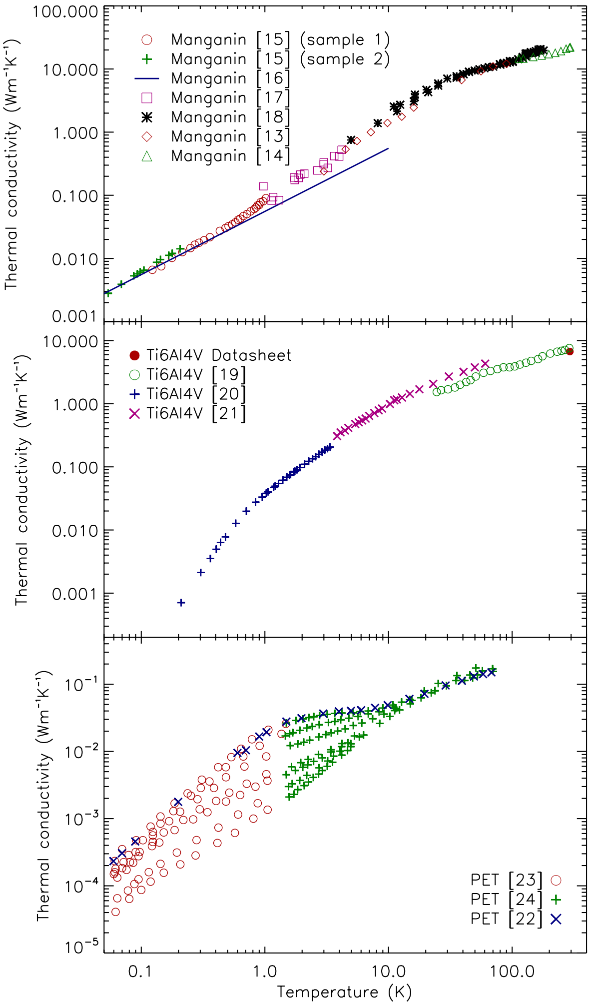

FIGURE 2. Thermal conductivity of manganin (typical composition 84% Cu, 12% Mn, 4% Ni by weight) [13, 14, 15, 16, 17, 18] (the results from Ref. [16] are an extrapolation from electrical resistivity), Ti_6Al_4V [19, 20, 21], and PET [22, 23, 24].

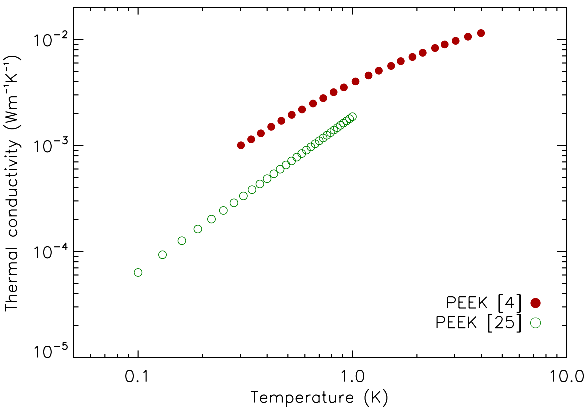

FIGURE 3. Thermal conductivity of PEEK [4, 25]

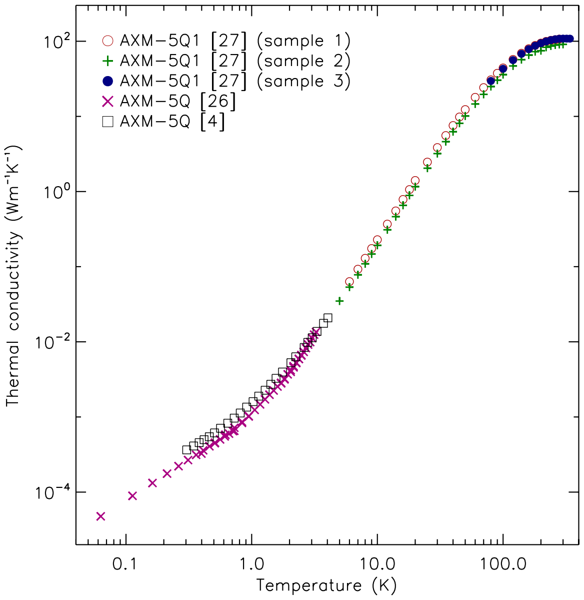

FIGURE 4. Thermal conductivity of AXM-5Q and AXM-5Q1 graphite [4, 26, 27]

with the datasheet room temperature value. The slight disagreement is presumably sample to sample variation, and we have assumed this in creating our recommended values.

The final material in Fig. 2 is PET (polyethylene terephthalate). This material is interesting in that it can be prepared with varying degrees of crystallinity, and these results show the effect of increasing the crystalline fraction.

Figure 3 shows two measurements on PEEK (polyetheretherketone), to illustrate an example in which we do not get good agreement. We have no explanation for this; there do not seem to be any errors in experimental method in either case, and both measurements were made by groups who have measured various other materials with good agreement with accepted values.

Figure 4 shows AXM-5Q graphite, a material which we have proposed as a replacement for AGOT graphite, a material used for thermally isolating supports at millikelvin temperatures.[1] Different measurements agree

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[1] This is a good example of why data in text books can not always be trusted; a single measurement on AGOT has appeared many times, and yet does not agree with theoretically expected behaviour, other similar graphites and a more recent measurement on AGOT, probably due to deficiencies in the original experimental method [26].

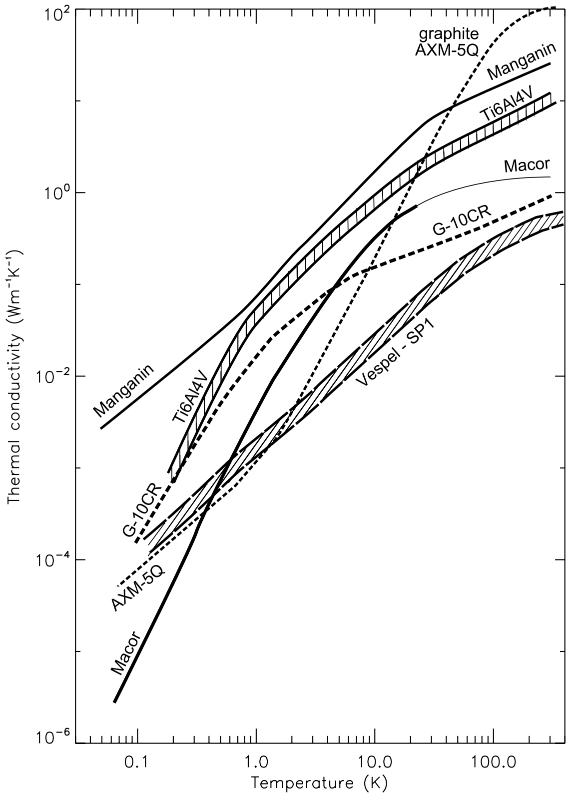

FIGURE 5. Our recommended thermal conductivity values (the thin line for Macor shows an interpolation between measured values and the room temperature datasheet value). Data sources: Graphite AXM-5Q and -5Q1 [4, 26, 27], manganin: (typical composition 84% Cu, 12% Mn, 4% Ni by weight) [13, 14, 15, 16, 17, 18], Ti_6Al_4V [19, 20, 21], Macor (machineable glass ceramic) [4, 9, 10, 11, 12], G-10CR (parallel to the fibre weave) [2, 3], Vespel SP-1 [4, 6, 7, 8].

well; there is in any case a known sample to sample variation of around ±10%. Here we include measurements on AXM-5Q1; this differs from AXM-5Q only in that it has undergone an extra stage of purification to remove metallic impurities, and the electrical and thermal conductivity at room temperature are similar to AXM-5Q [27].

Finally, Fig. 5 shows our recommended values.

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