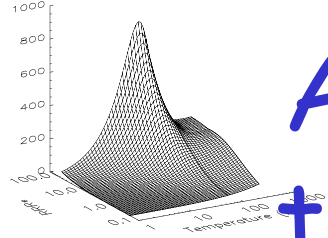
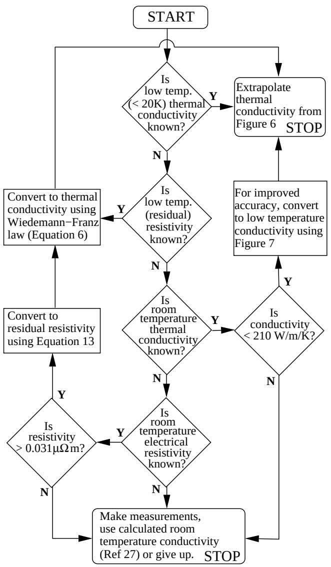


A method for predicting the thermal conductivity of aluminium alloys at cryogenic temperature



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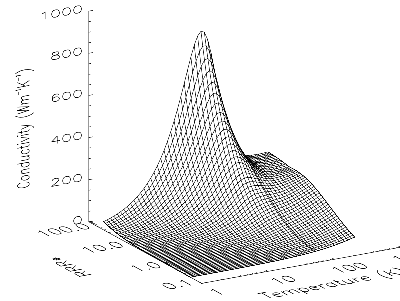
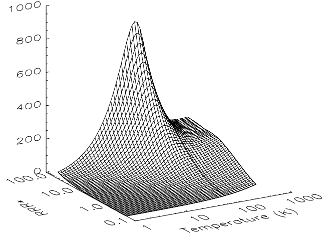


Presented at the European Space Cryogenics Workshop

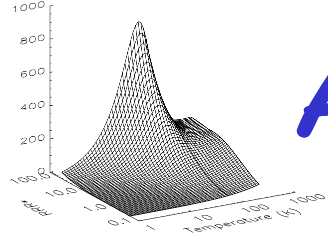
ESA/ESTEC 16th June 2005



Introduction

Aluminium alloys are very useful for structural components, especially in aerospace applications

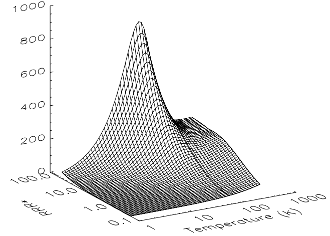
- High strength/density ratio
- Can be welded
- Many different types available
  - Lots of freedom to choose appropriate alloy for each application



Available measurements

For cryogenic applications, usually necessary to know the thermal conductivity

- Has been measured on only a few alloy types and tempers
  - 18 alloy types
  - 23 alloy/temper combinations
  - BUT: These are not the 18 alloys most likely to be used
  - AND: Many either not commercial types and tempers, or no longer in use



Note!

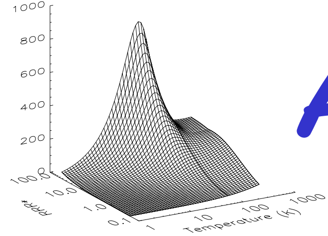
A commercial alloy is designated by the composition *and temper*.

- Temper denotes the heat and/or mechanical treatment that has been applied
  - Examples: precipitation hardening, cold working
- Alloys with the same composition but different temper can have very different conductivity – beware!

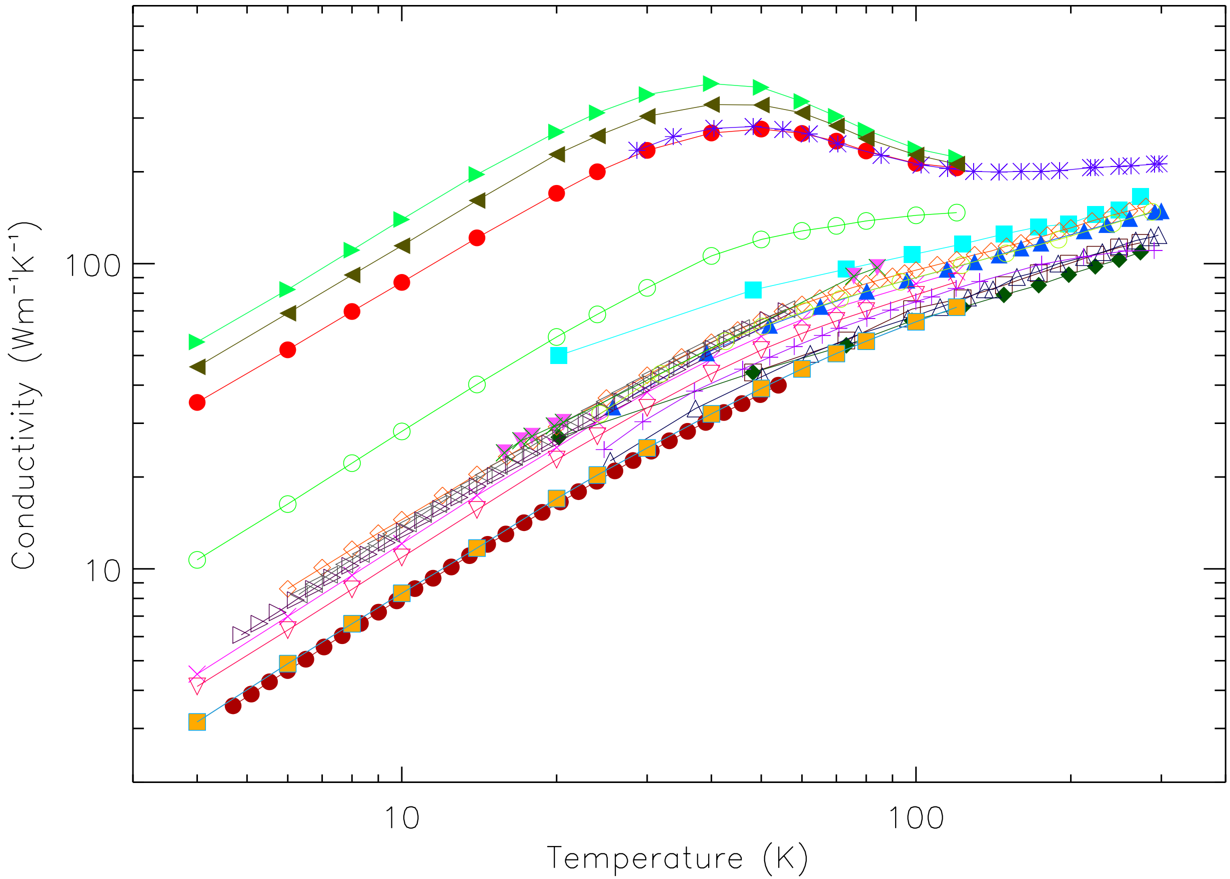
Chemical composition
(6xxx=Si/Mg alloy,
6061 denotes amounts of other elements)

Example: 6061 T6

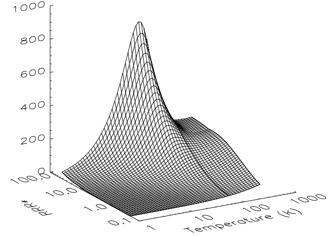
Temper (T6=solution treated and aged)



Available measurements



Found from extensive literature searching



Useful measurements

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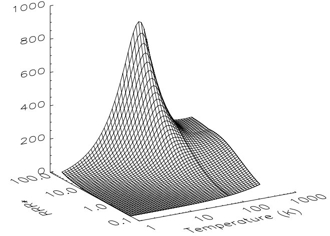
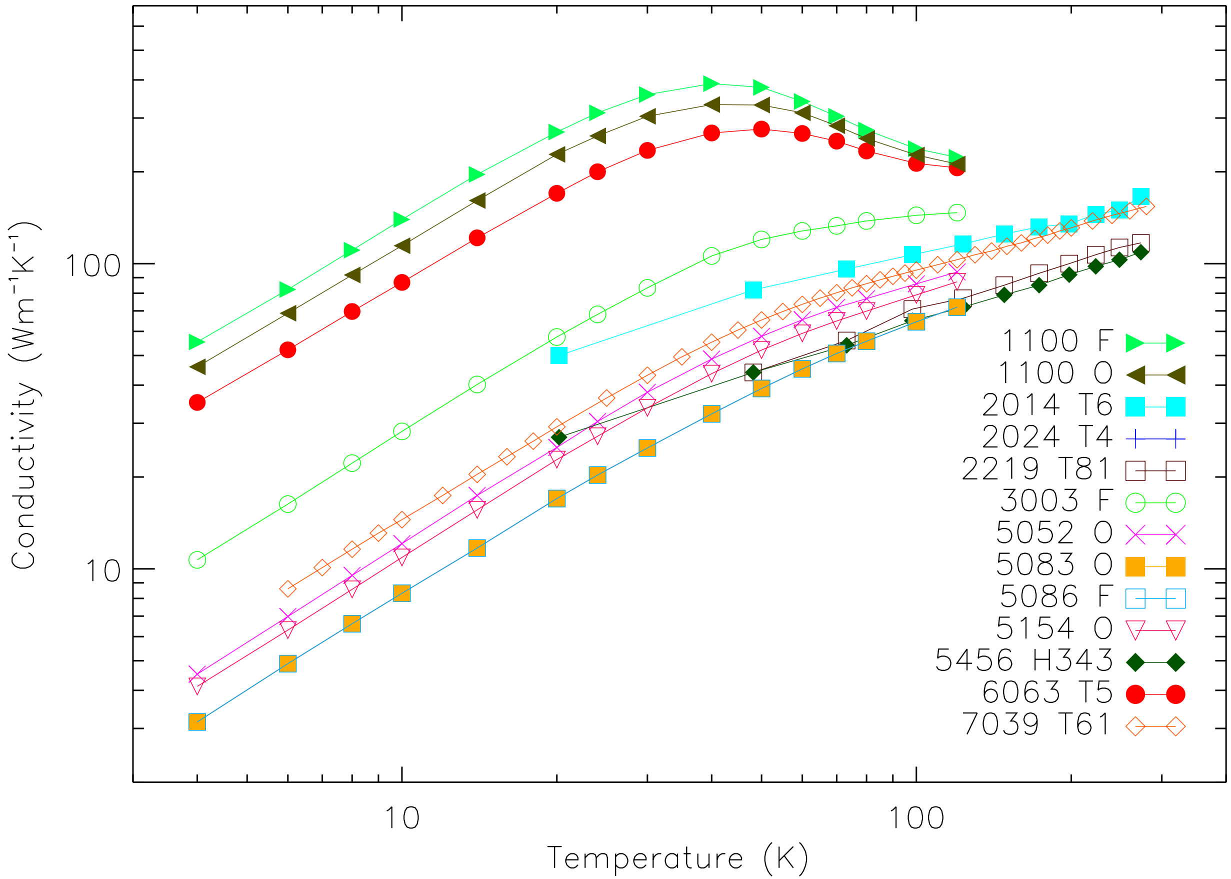
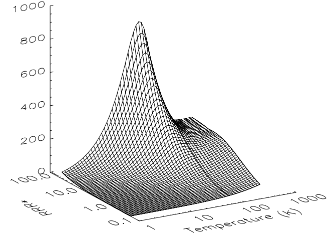
For cryogenic applications, usually necessary to know the thermal conductivity

- Has been measured on even fewer *useful* alloy types and tempers (i.e. well defined and currently available):
  - 12 alloy types
  - 13 alloy/temper combinations
- Measurements mostly made in the 60's
  - Composition and manufacturing processes for nominally identical alloy types likely to have changed
- Most measurements on US standard alloys

Useful measurements

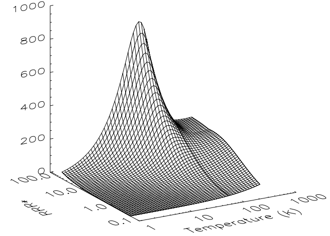






Solutions

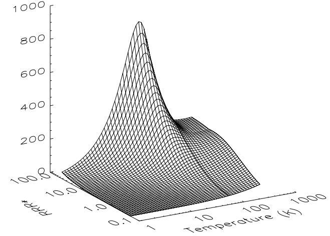
- Only use alloys for which measurements are available
    - Very limiting
- Accept poor knowledge of thermal conductivity
    - Only acceptable in some situations
- Measure conductivity of alloys under consideration
    - Time consuming and expensive
    - Hard to get accurate results, especially at higher temperatures
    - Therefore high likelihood of getting misleading results



Alternative solution

Use the Wiedemann-Franz law

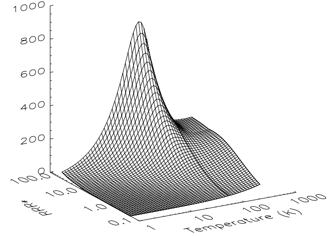
- Gives thermal conductivity of a metal as a function of electrical resistivity
- Good evidence that it works for aluminium alloys at low temperatures (to better than 10%)
- Just need to measure resisitivity
  - Straightforward; can be done with simple resistance bridge (e.g. one used for thermometry) and a dip probe in a helium dewar (sample screwed to a piece of wood works just fine)



Alternative solution

However

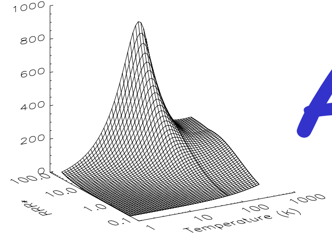
- Only useful at liquid helium temperatures (4 K) and below
  - At higher temperature, relationship between thermal conductivity and electrical resistivity not well known
  - How do we get round this?



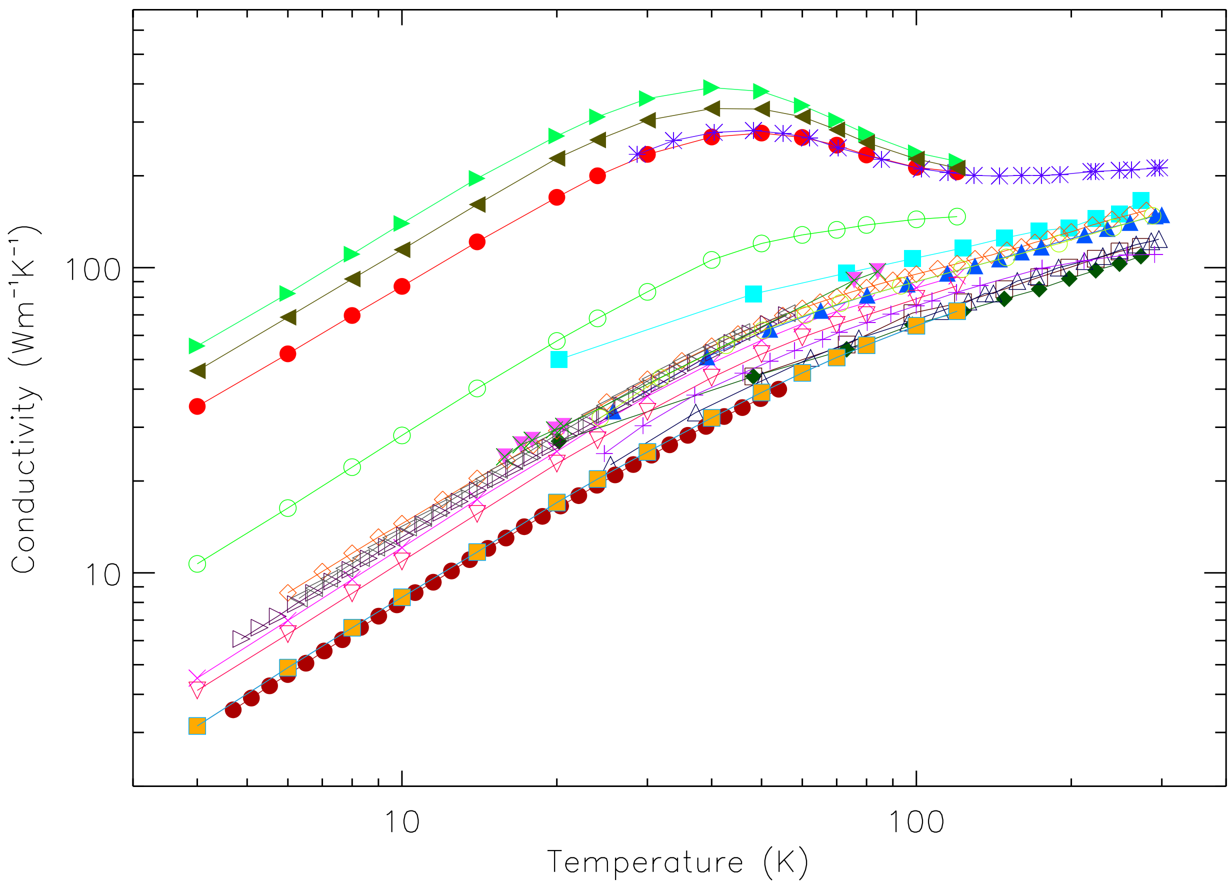
Alternative solution

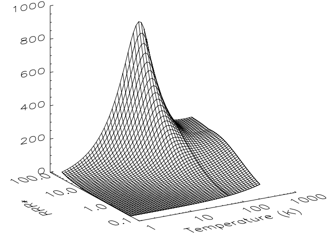
Make use of the “useless” results

- Available measurements mostly seem to fall into a simple pattern
- Removing three measurements (experimental error?) shows pattern more clearly

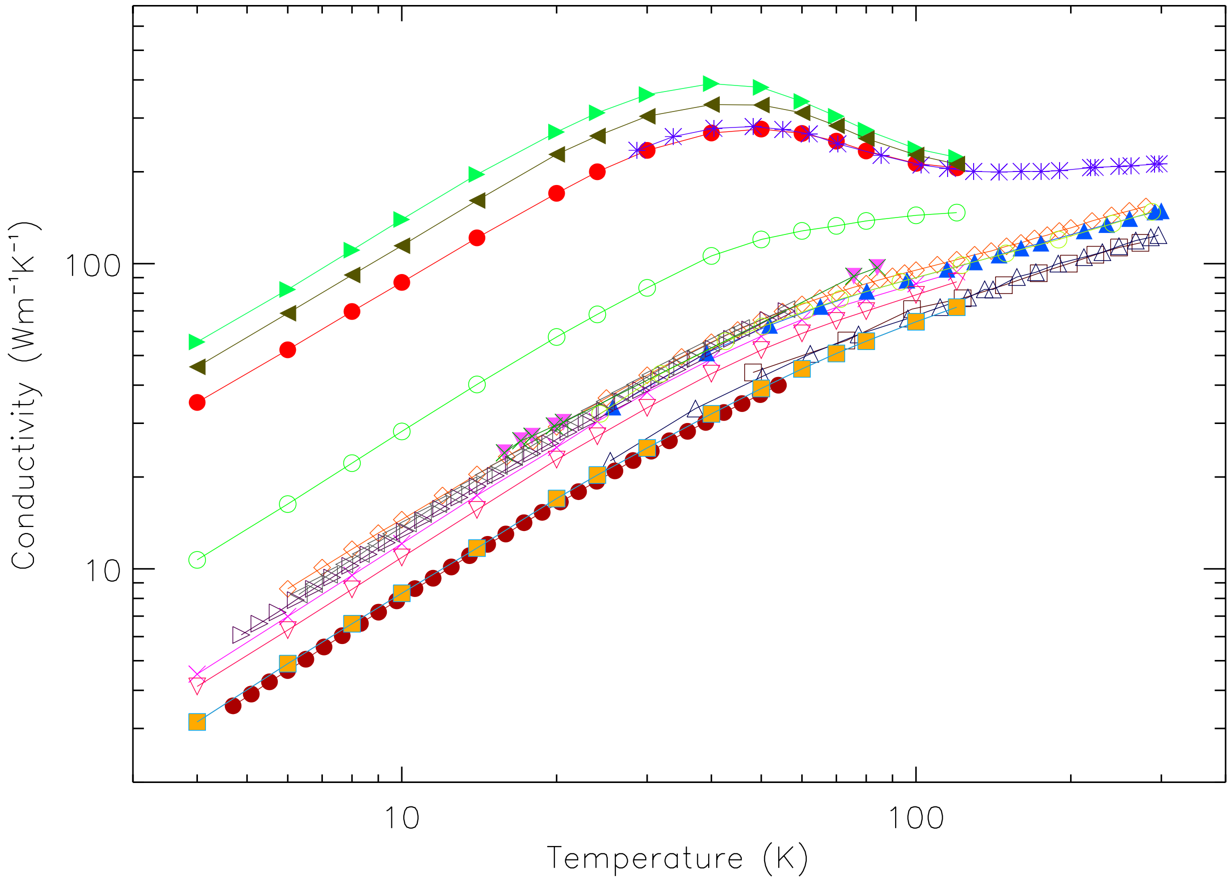


Available measurements



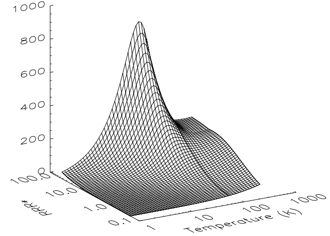


Pattern in data



Lines generally do not cross over

Suggests that a single parameter fit may be possible

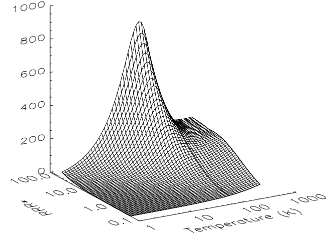


Alternative solution

Just need to find an expression to fit the data

- Such equations have been derived (semi-empirically) for *pure* aluminium (RRR>10)* by Hust and Lankford
  - (NBSIR 84-3007, National Bureau of Standards, Boulder Colorado (1984))
- Single parameter fits; just need to know RRR
- Do they work for aluminium alloys?
  - No!

* Ratio of room temperature and residual (low temperature) resistivity



Alternative solution

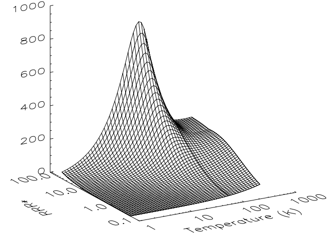
Equations:

$$\kappa = \frac{1}{W_0 + W_i + W_{i0}} \qquad W_0 = \frac{\beta}{T} \qquad \beta = \frac{\rho_0}{L_0}$$

$$W_i = P_1 T^{P_2} \left[1 + P_1 P_3 T^{(P_2 + P_4)} \exp\left(- \left(\left(\frac{P_5}{T} \right)^{P_6} \right) \right) \right]^{-1} + W_c$$

$$W_{i0} = P_7 \frac{W_i W_0}{W_i + W_0}$$

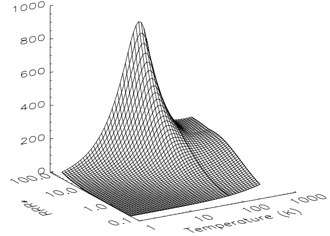
See *Cryogenics 45 (6) 421-431 (2005)* for more detail



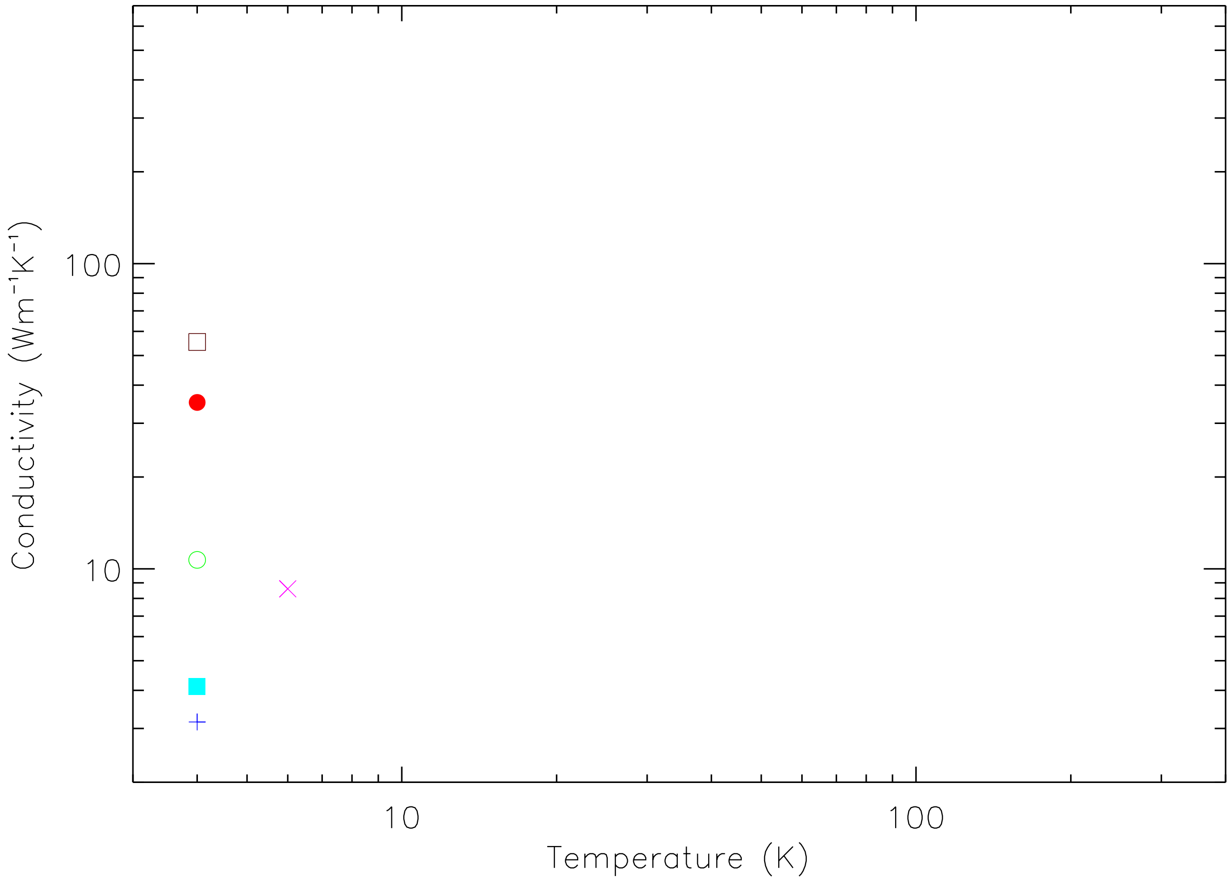
Alternative solution

However

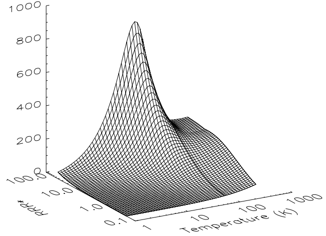
- I have shown that if we modify two of the terms in the equation from constants to appropriate functions of RRR, we can produce single parameter fits which agree with the data to better than 10%
  - This is within the uncertainty we would expect from experimental error in most cases
  - Physically, the modification corresponds to changing the strength of the electron-phonon interaction (temperature dependence is not altered)



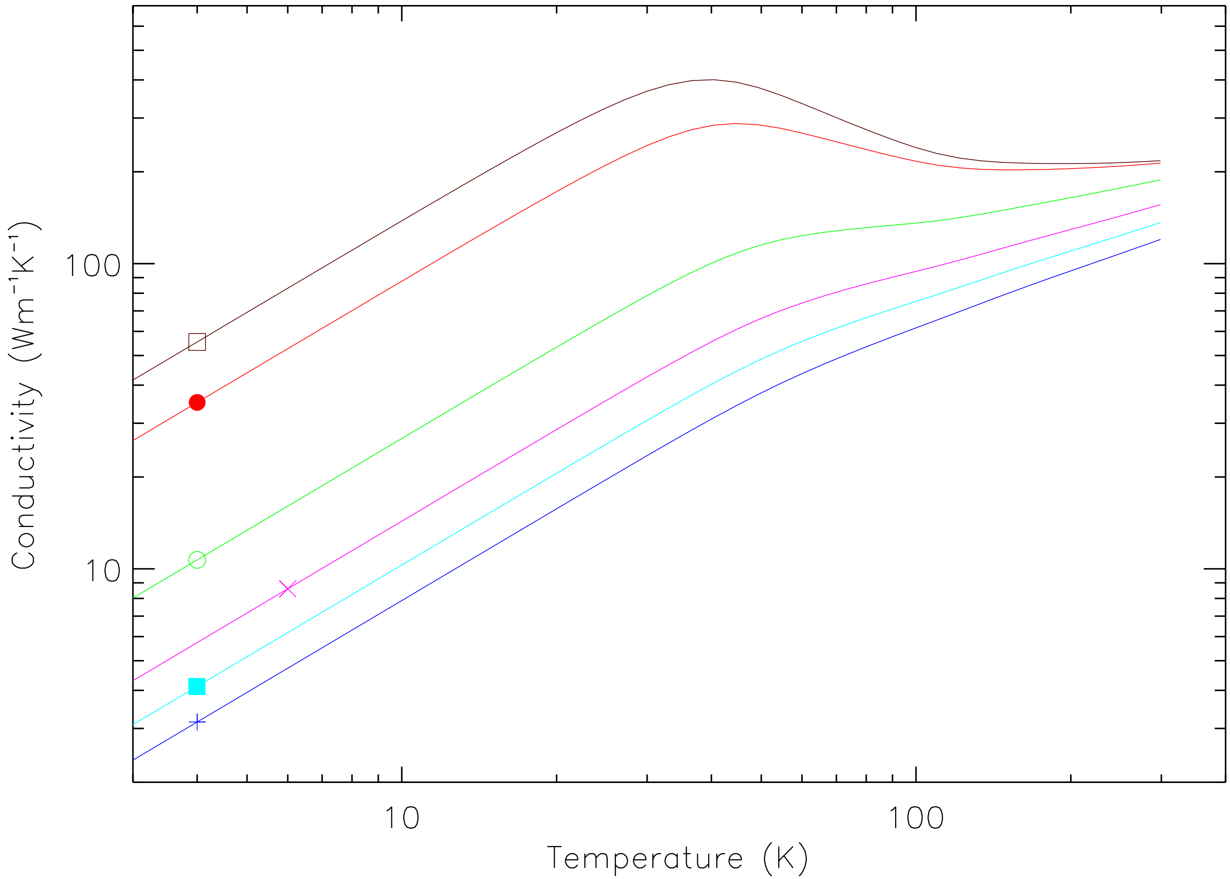
Example



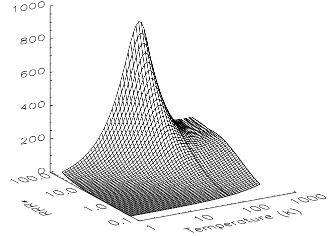
Take lowest temperature datapoint for several measurements



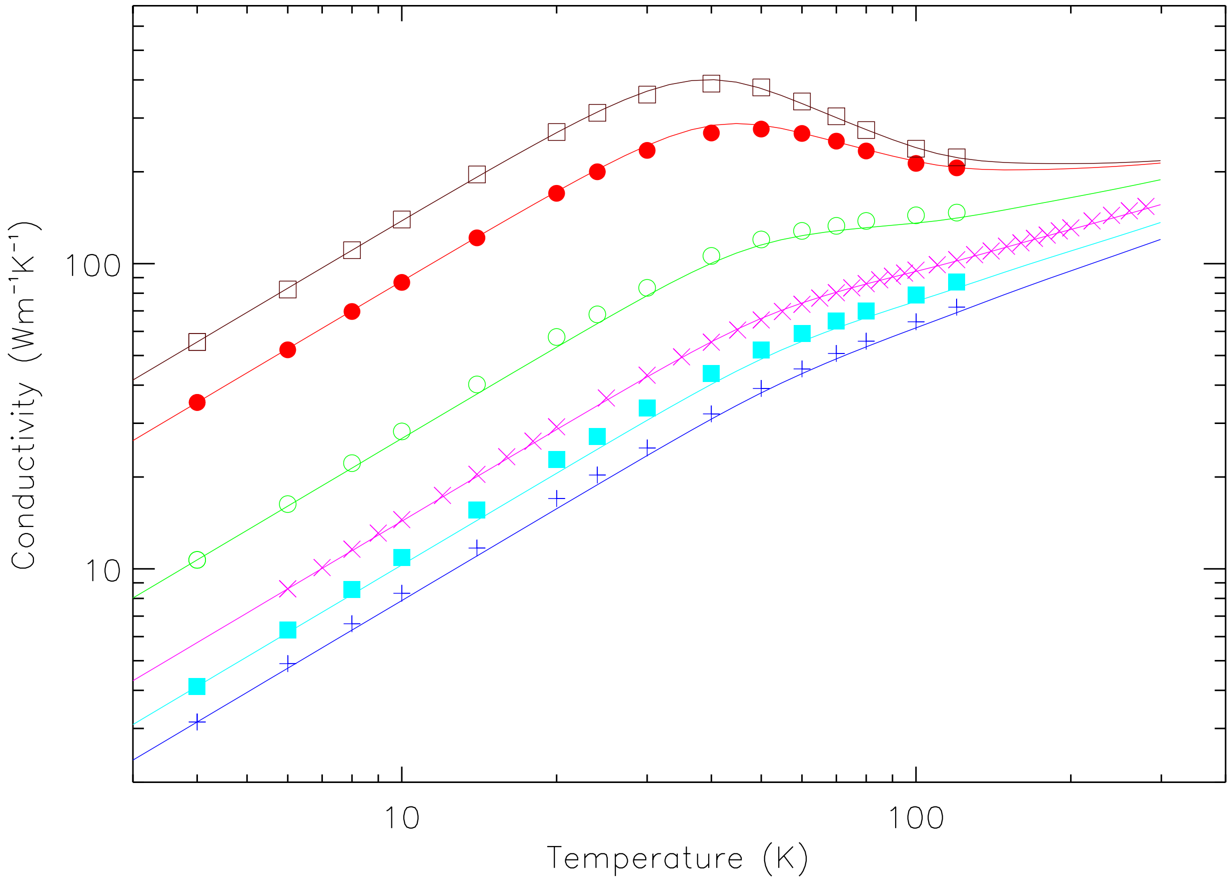
Example



Extrapolate from each point to higher temperatures
(No allowance made for noise)

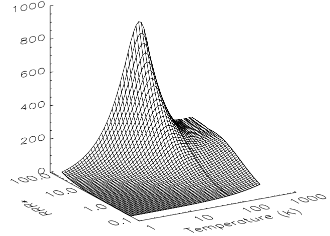


Example

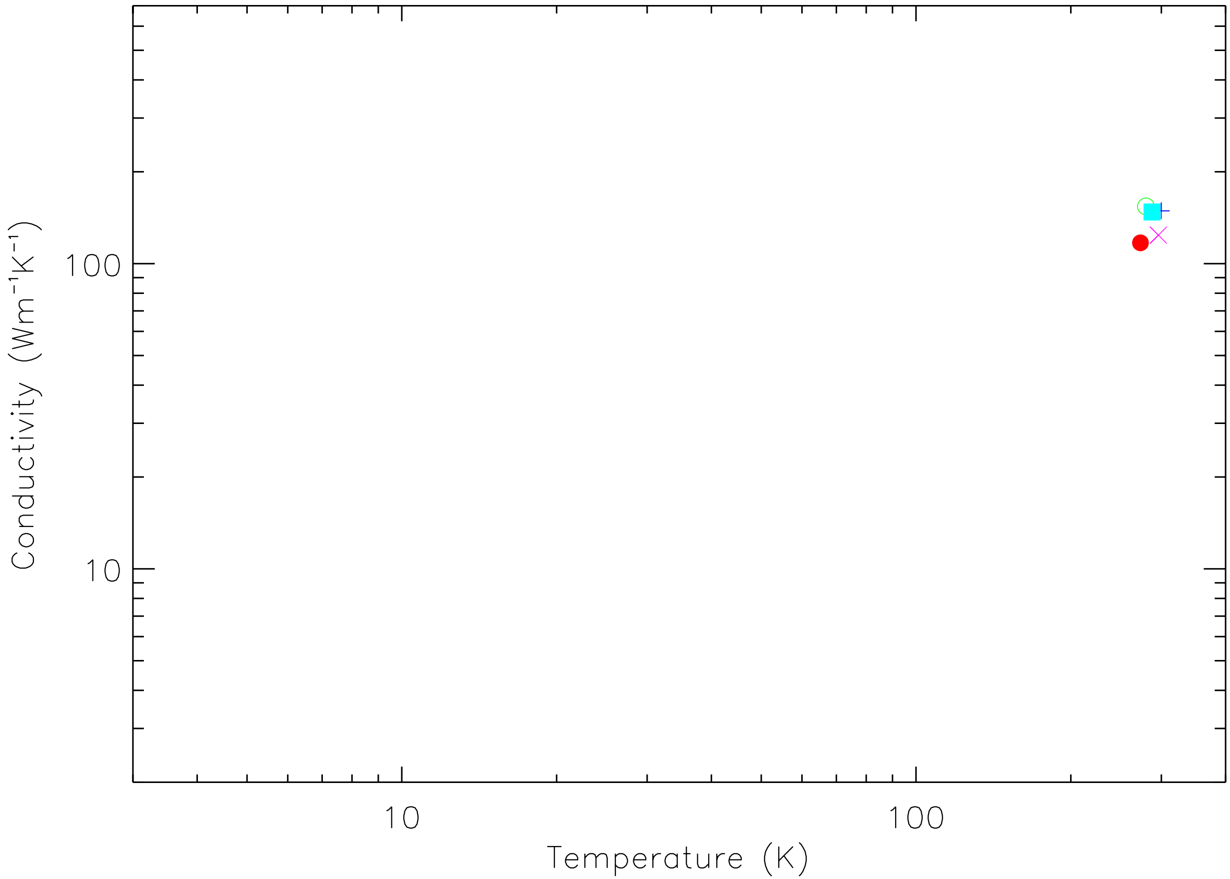


Compare to remainder of each dataset – excellent agreement!

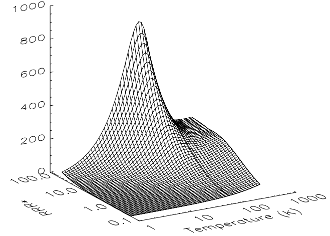
Doing this for *all* (good) datasets gives agreement to ~ 10% or better



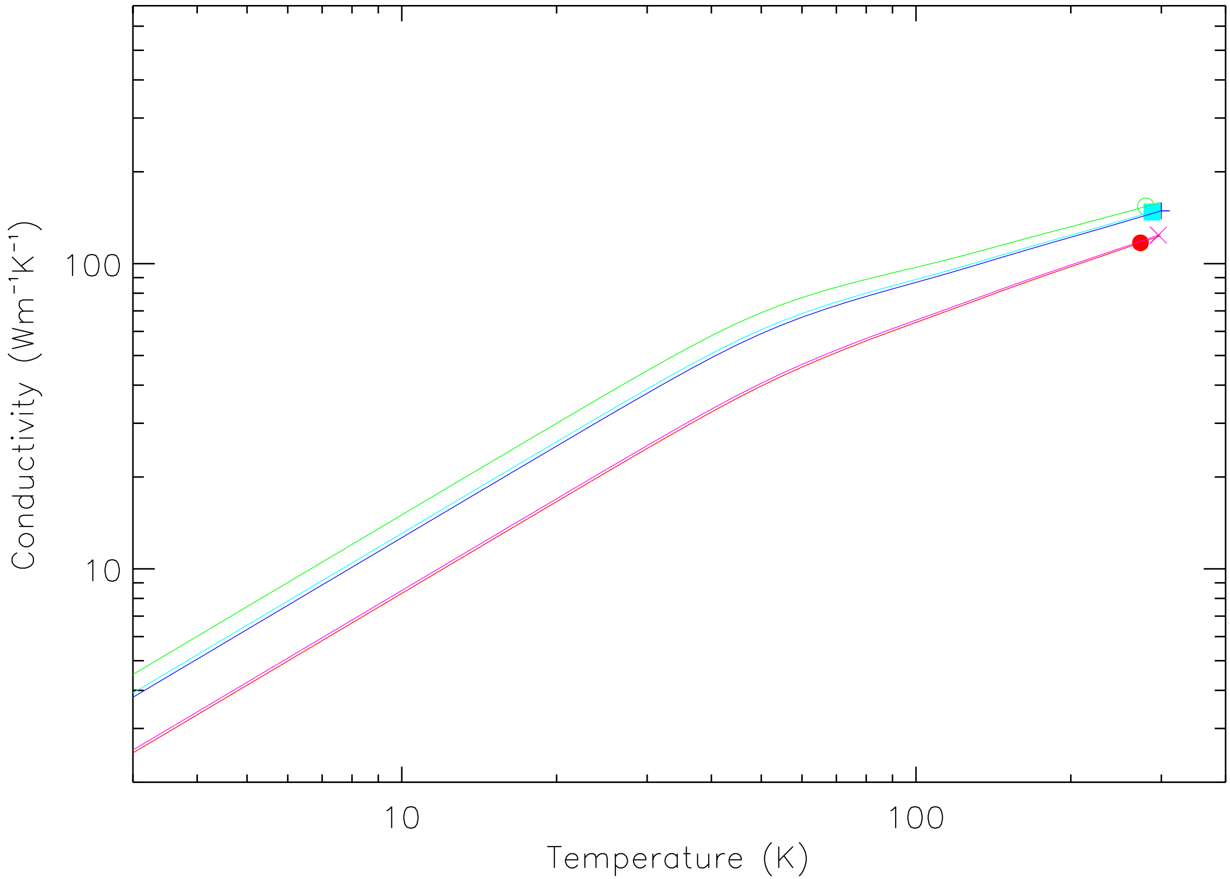
Example



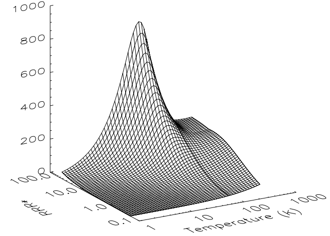
Can also do this with high temperature points



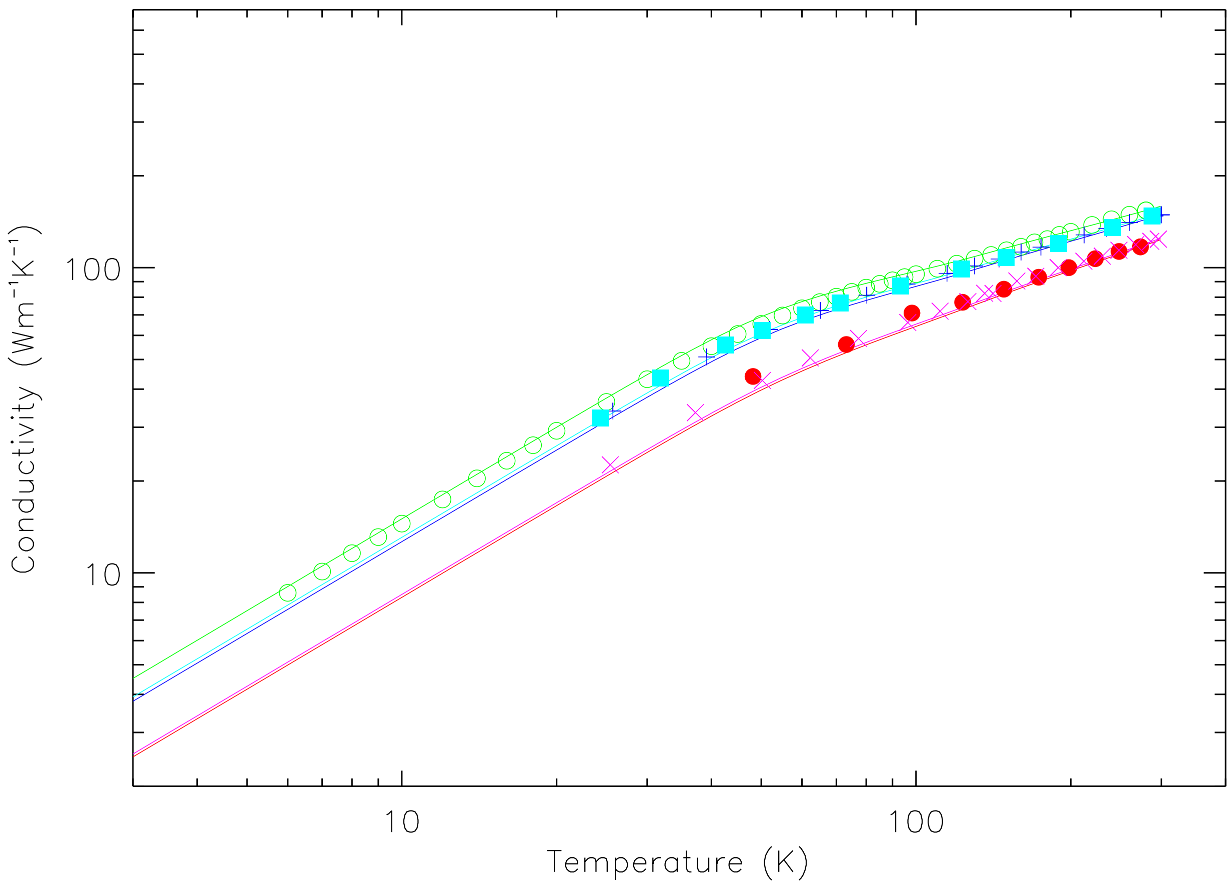
Example



This time we extrapolate to low temperatures



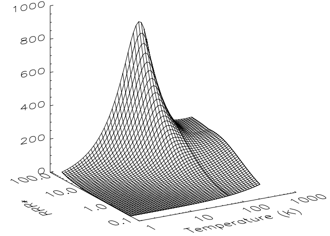
Example

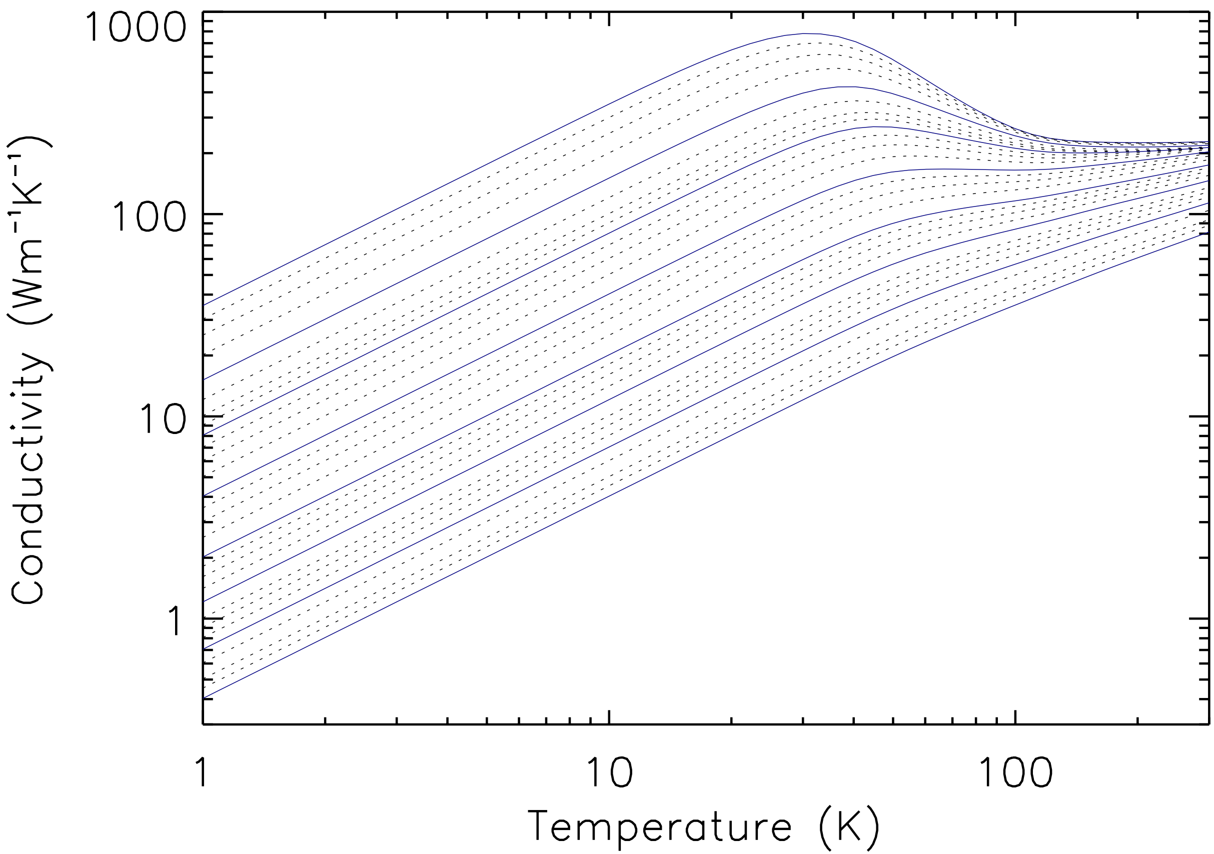


Error for the worst point is 12.5%

For three datasets, all points better than 10%

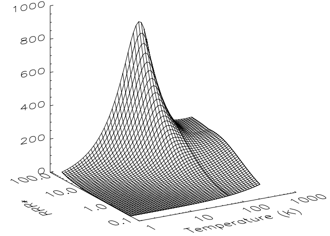
Predictions





All Al alloys should fall on (or interpolated between) these lines

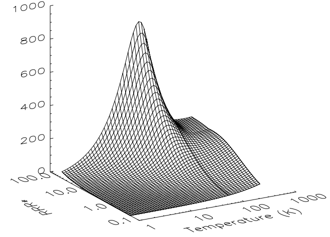
A measurement at any temperature can thus be extrapolated to other temperatures



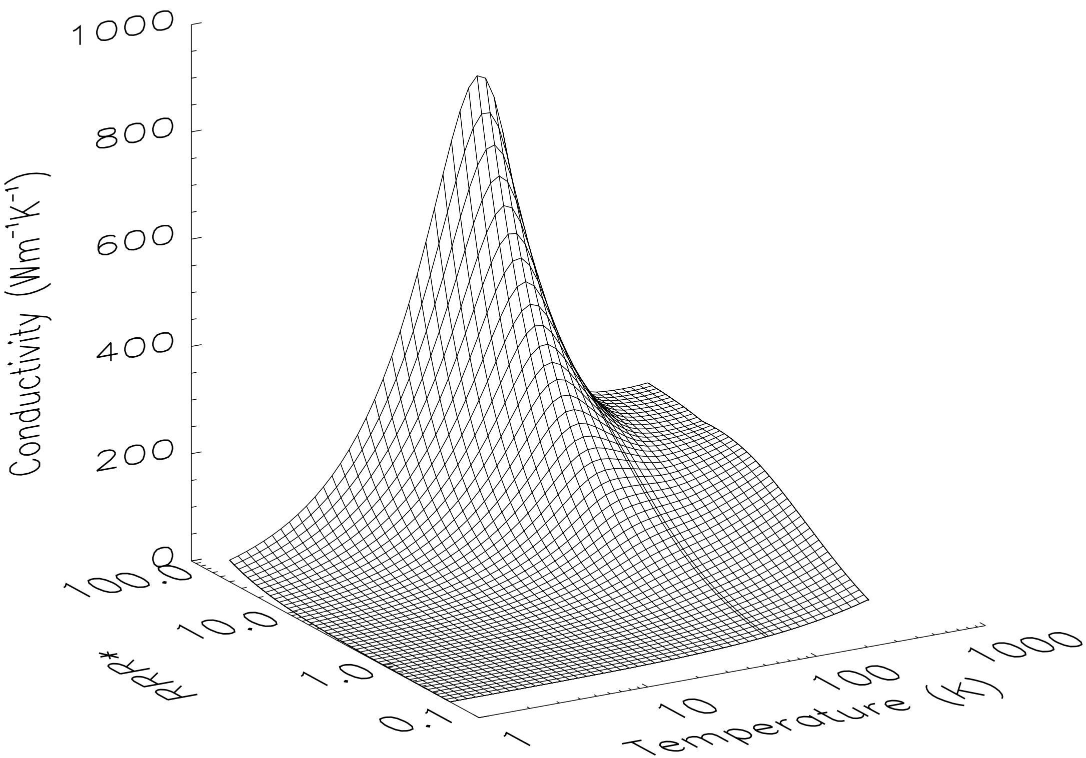
Note!

Aluminium alloys superconduct around 1 K

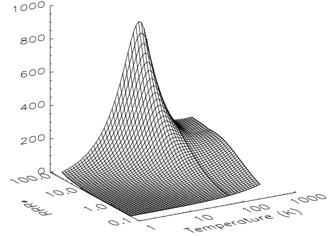
- These results are for the normal state only
- The transition temperature varies with alloy composition and (probably) temper
- Values seem to vary from <400 mK to 1.4 K with no obvious pattern other than that Al-Si and Al-Li alloys seem to have the highest value



Predictions

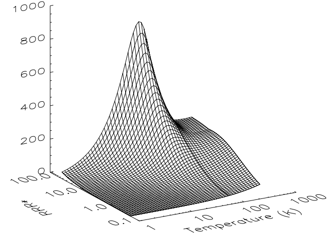


Conductivity as a function of RRR and temperature



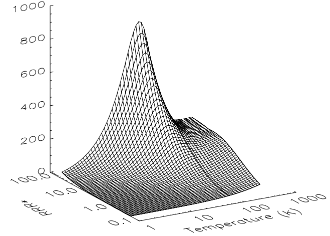
Uses

- Check likely validity of cryogenic measurements
- Extend cryogenic measurements to larger temperature range
- Predict conductivity of unmeasured alloy types from single low temperature resistivity measurement (easy and quick to make)
- Easily predict conductivity of actual materials used in an instrument to avoid errors due to sample variation, again from simple resistivity measurement.



Uses

- Can also use room temperature “datasheet” conductivity values.
- But:
  - Conductivity converges with increasing temperature, especially at high purities
  - Data-sheet room temperature conductivity values often not accurate enough to be useful.
    - Errors may be much larger than quoted (if quoted at all) – hard to be sure you have allowed properly for thermal radiation



Uses

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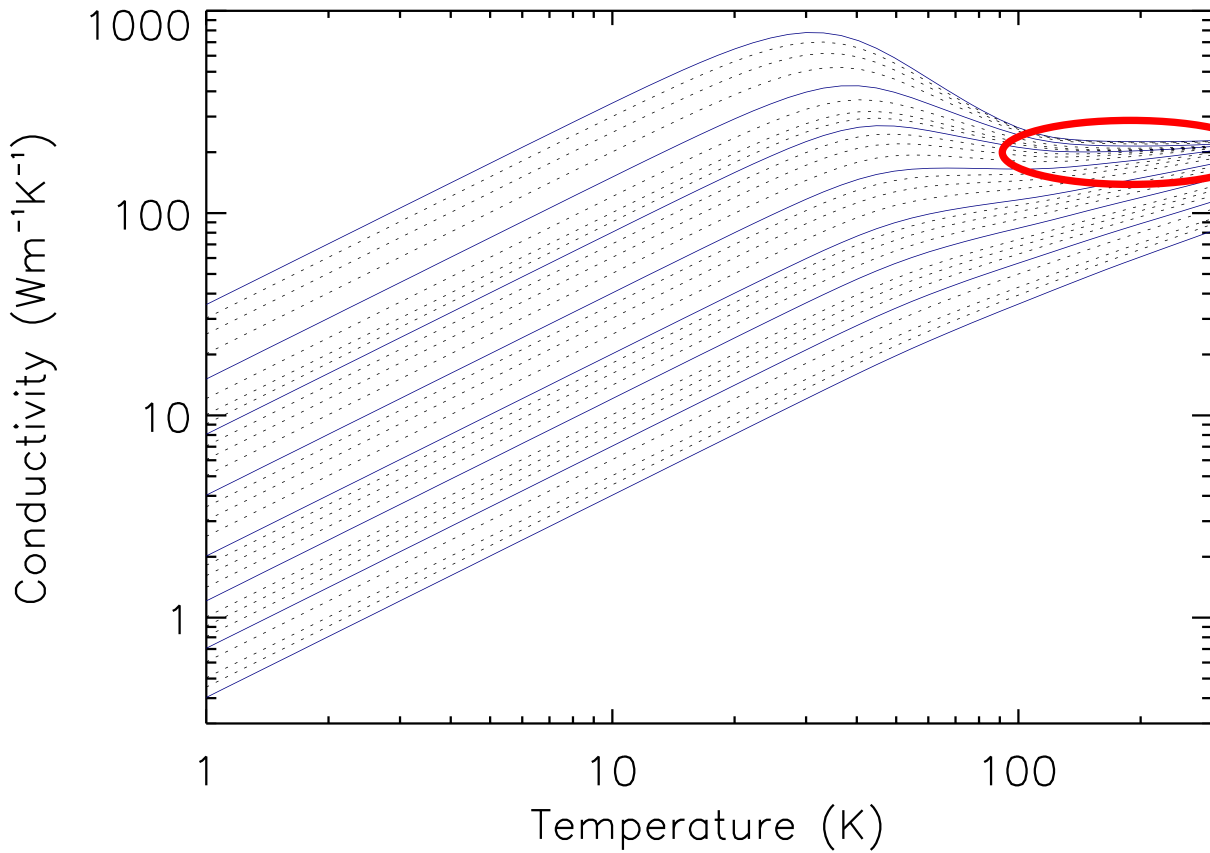
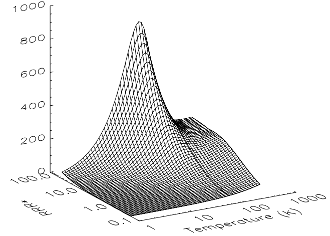
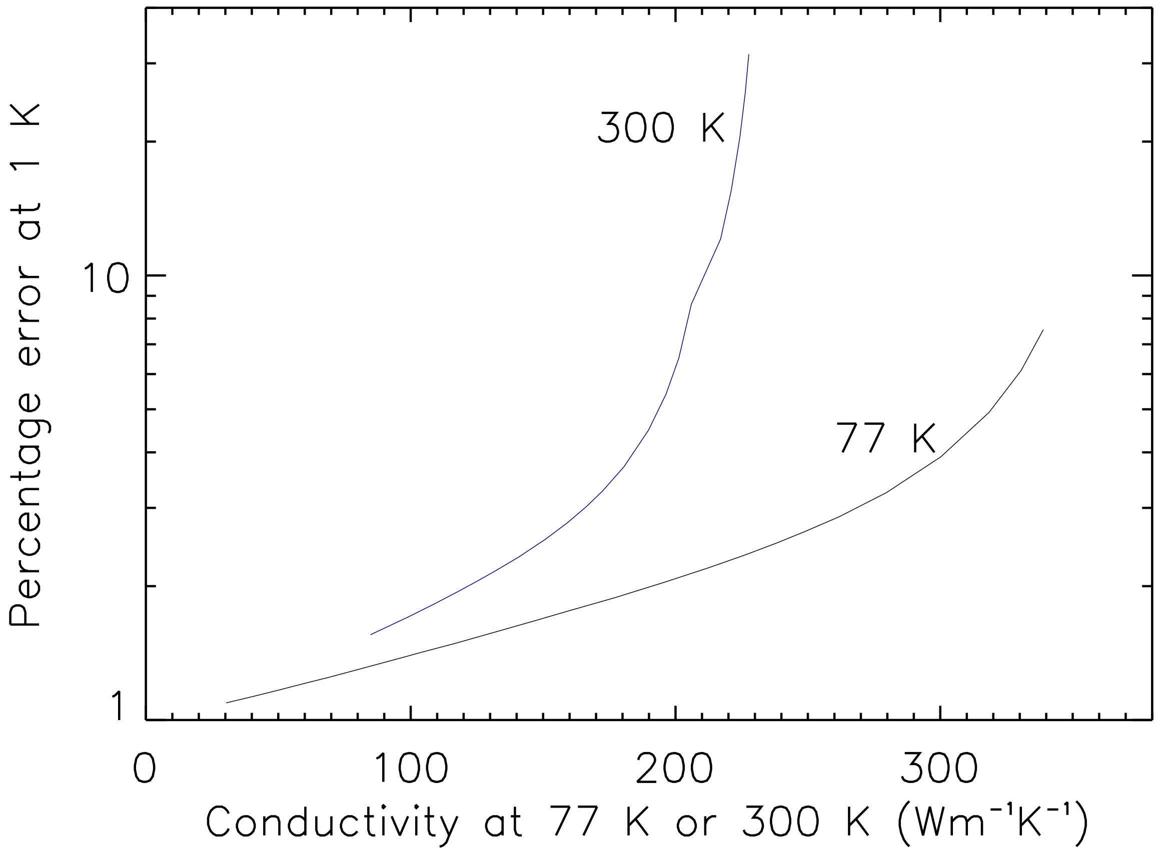


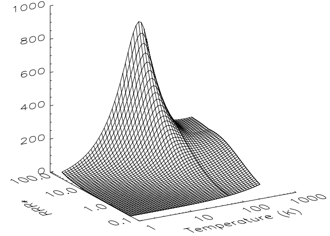
Lines converge here



Uses



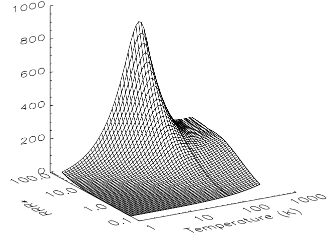
Percentage error in the extrapolated conductivity at 1 K for a 1% error in measured conductivity at 77 K and 300 K



(Partial) solution

Improve accuracy by using room temperature *resistivity* values

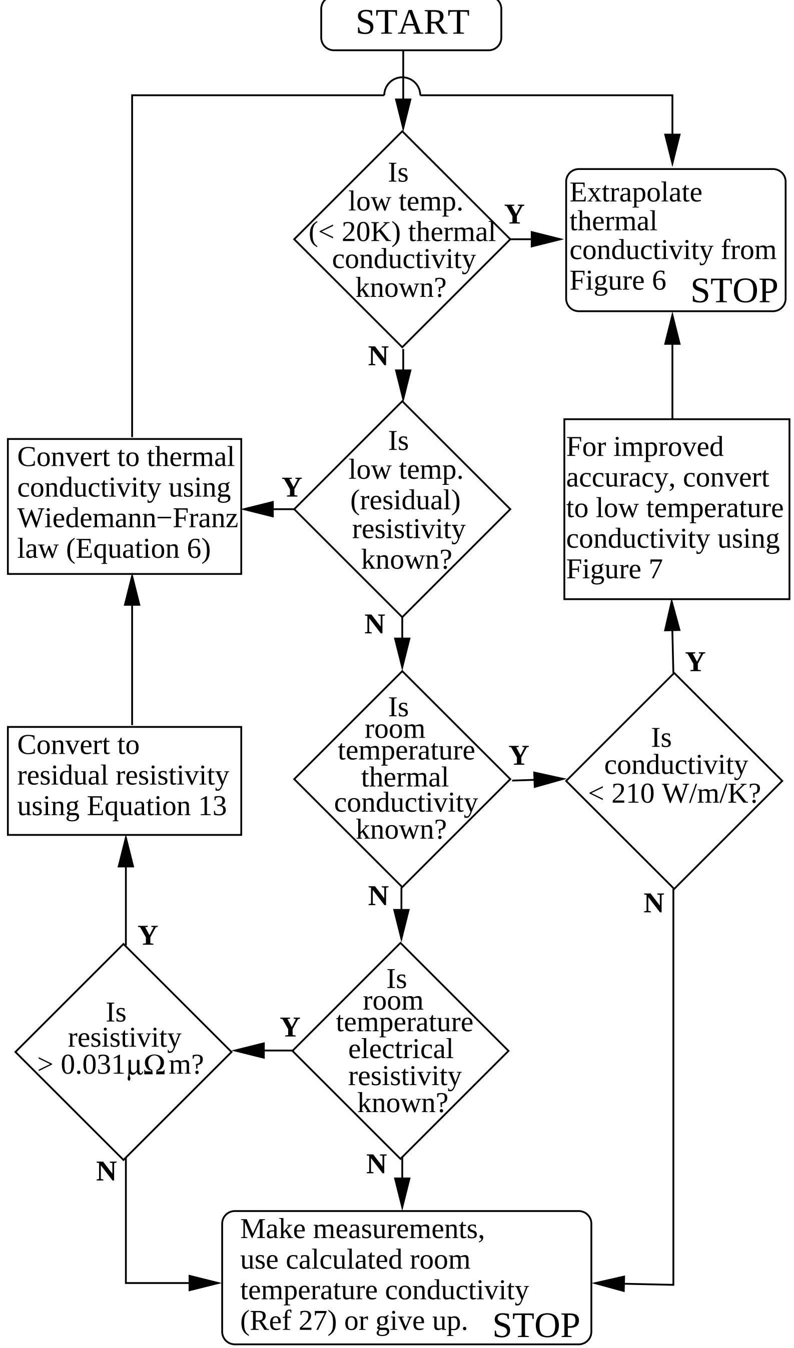
- Available for most alloy types; also easy to measure
- Can't use Wiedemann-Franz because not known to sufficient accuracy
- However, I have shown that the difference between room temperature and low temperature resistivity is a constant for most alloys ($\rho > 0.031 \mu\Omega$ m)
- Can therefore convert to low temp resistivity and apply Wiedemann-Franz law there

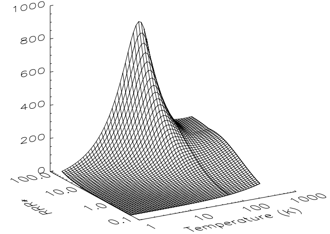


Procedure

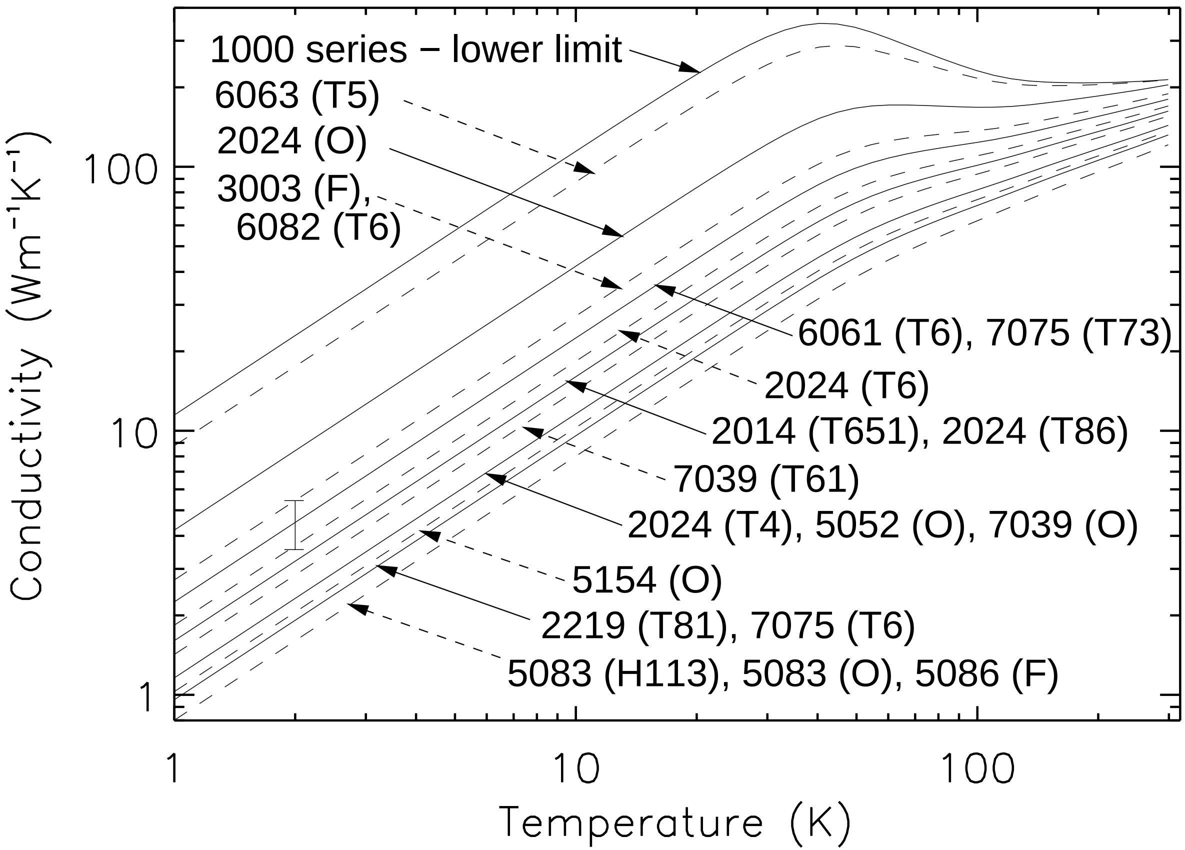
Flow chart for determining thermal conductivity depending on known information

Taken from Cryogenics 45 (6) 421-431 (2005)



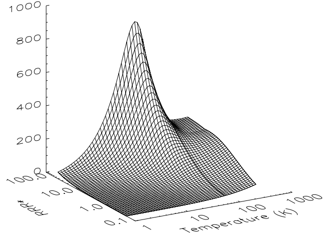


Recommended values



All based on low temperature thermal or electrical measurements

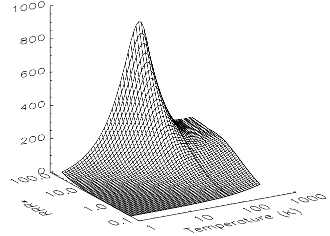
Could add many more based on room temp measurements



Conclusions

A simple set of equations allow:

- Aluminium alloy thermal conductivity from ~1 K to 300 K to be extrapolated from:
  - Thermal conductivity at a single temperature (including room temperature)
  - Low temperature (residual) resitivity
  - Room temperature resistivity
- Uses include:
  - Obtaining thermal conductivity when measured values not available
  - Checking accuracy of conductivity measurements
  - Predicting conductivity of actual materials used in a system to avoid uncertainty due to sample variation



Further information

- This presentation available on the web at
http://woodcraft.lowtemp.org/cryoworkshop2005.pdf

- More detail in:
A.L. Woodcraft, "Predicting the thermal conductivity of aluminium alloys in the cryogenic to room temperature range", Cryogenics 45 (6) 421-431 (2005),
published on-line today(!). Also available at:
http://reference.lowtemp.org/woodcraft_alalloy.pdf

- Calculator based on these results:
http://reference.lowtemp.org/alkappa.html