Cryogenic Material Properties Database

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ABSTRACT

NIST has published at least two references compiling cryogenic material properties. These include the Handbook on Materials for Superconducting Machinery and the LNG Materials & Fluids. Neither has been updated since 1977 and are currently out of print. While there is a great deal of published data on cryogenic material properties, it is often difficult to find and not in a form that is convenient to use. We have begun a new program to collect, compile, and correlate property information for materials used in cryogenics. The initial phase of this program has focused on picking simple models to use for thermal conductivity, thermal expansion, and specific heat. We have broken down the temperature scale into four ranges: a) less than 4 K, b) 4 K to77 K, c) 77 K to 300 K, and d) 300 K to the melting point. Initial materials that we have compiled include oxygen free copper, 6061-T6 aluminum, G-10 fiberglass epoxy, 718 Inconel, Kevlar, niobium titanium (NbTi), beryllium copper, polyamide (nylon), polyimide, 304 stainless steel, Teflon, and Ti-6Al-4V titanium alloy. Correlations are given for each material and property over some of the temperature range. We will continue to add new materials and increase the temperature range. We hope to offer these material properties as subroutines that can be called from your own code or from within commercial software packages. We will also identify where new measurements need to be made to give complete property prediction from 50 mK to the melting point.

INTRODUCTION

The explosive growth of cryogenics in the early 50's led to much interest in material properties at low temperatures. Important fundamental theory and measurements of low temperature material properties were performed in the 50's, 60's, and 70's. The results of this large amount of work has become fragmented and dispersed in many different publications, most of which are out of print and difficult to find. Old time engineers often have a file filled with old graphs; young engineers often don't know how to find this information. Since most of the work was performed before the desktop computer became available, when data can be found, it is published in simple tables or graphically, making the information difficult to accurately determine and use.

NIST has begun a program to gather cryogenic material property data and make it available in a form that is useful to engineers. Initially we tried to use models based upon fundamental physics but it soon became apparent that the models could not accurately predict properties over

a large temperature range and over different materials. Our current approach is to choose a few simple types of equations such as polynomial or logarithmic polynomials and determine the coefficients of different materials and properties. This will allow engineers to use the equations to predict material properties in a variety of ways including commercial software packages or their own code. Integrated and average values can easily be determined from the equations. These equations are not meant to provide any physical insight into the property or to provide 'standard' values but are for working engineers that require accurate values.

MATERIALS

Initial materials that we have compiled include oxygen free copper, 6061-T6 aluminum, G-10CR fiberglass epoxy, 718 Inconel, Kevlar 49, niobium titanium (NbTi), beryllium copper, polyamide (nylon), polyimide, 304 stainless steel, Teflon, and Ti-6Al-4V titanium alloy. These were chosen as some of the most common materials used in cryogenic systems in a variety of fields.

MATERIAL PROPERTIES

Thermal Conductivity

Widely divergent values of thermal conductivity for the same material are often reported in the literature. For comparatively pure materials (like copper), the differences are due mainly to slight material differences that have large effects on transport properties, such as thermal conductivity, at cryogenic temperatures. At 10 K, the thermal conductivity of commercial oxygen free copper for two samples can be different by more then a factor of 20 while the same samples at room temperature would be within 4%. It is also not uncommon for some experimental results to have uncertainties as high as 50%. Part of our program is to critically evaluate the literature to determine the best property values. Data references used to generate predictive equations will be reported.

The general form of the equation for thermal conductivity, k, is

$$\log(k) = a + b\log T + c(\log T)^2 + d(\log T)^3 + e(\log T)^4 +$$
$$f(\log T)^5 + g(\log T)^6 + h(\log T)^7 + i(\log T)^8, \tag{1}$$

where a, b, c, d, e, f, g, h, and i are the fitted coefficients, and T is the temperature. These are common logarithms. While this may seem like an excessive number of terms to use, it was determined that in order to fit the data over the large temperature range, we required a large number of terms. It should also be noted that all the digits provided for the coefficients should be used, any truncation can lead to significant errors. Tables 1A and 1B show the coefficients for a variety of metals and non-metals. Equation 2 is the thermal conductivity for an average sample of oxygen free copper. It should be noted that thermal conductivity for oxygen free copper can

Table 1A. Coefficients for thermal conductivity for metals.

Coeff.	6061 -T6 Aluminum	304 SS	718 Inconel	Beryllium copper	Ti-6Al-4V
a	0.07918	-1.4087	-8.28921	-0.50015	-5107.8774
b	1.09570	1.3982	39.4470	1.93190	19240.422
c	-0.07277	0.2543	-83.4353	-1.69540	-30789.064
d	0.08084	-0.6260	98.1690	0.71218	27134.756
e	0.02803	0.2334	-67.2088	1.27880	-14226.379
f	-0.09464	0.4256	26.7082	-1.61450	4438.2154
g	0.04179	-0.4658	-5.72050	0.68722	-763.07767
h	-0.00571	0.1650	0.51115	-0.10501	55.796592
I	0	-0.0199	0	0	0
data range	4-300 K	4-300 K	4-300 K	4-300 K	20-300 K

Table 1B. Coefficients for thermal conductivity for non-metals.

Coeff.	Teflon	Polyamide (nylon)	Polyimide (Kapton)	G10 CR (norm)	G10 CR (warp)
a	2.7380	-2.6135	5.73101	-4.1236	-2.64827
b	-30.677	2.3239	-39.5199	13.788	8.80228
c	89.430	-4.7586	79.9313	-26.068	-24.8998
d	-136.99	7.1602	-83.8572	26.272	41.1625
e	124.69	-4.9155	50.9157	-14.663	-39.8754
f	-69.556	1.6324	-17.9835	4.4954	23.1778
g	23.320	-0.2507	3.42413	-0.6905	-7.95635
h	-4.3135	0.0131	-0.27133	0.0397	1.48806
I	0.33829	0	0	0	-0.11701
data range	4-300 K	4-300 K	4-300 K	10-300 K	12-300 K

vary widely depending upon the residual resistivity ratio, RRR, and this equation should be used with caution. The thermal conductivities are displayed graphically in Figure 1.

$$\log k = \frac{2.2154 - 0.88068T^{0.5} + 0.29505T - 0.048310T^{1.5} + 0.003207T^2}{1 - 0.47461T^{0.5} + 0.13871T - 0.020430T^{1.5} + 0.001281T^2} \qquad (2)$$

Specific Heat

The specific heat is the amount of heat energy per unit mass required to cause a unit increase in the temperature of a material, the ratio of the change in energy to the change in temperature. Specific heats are strong functions of temperature, especially below 200 K. Models for specific heat began in the 1871 with Boltzmann and were further refined by Einstein and Debye in the early part of the 20th century. While there are many variations of these first models, they generally only provide accurate results for materials with perfect crystal lattice structures. The
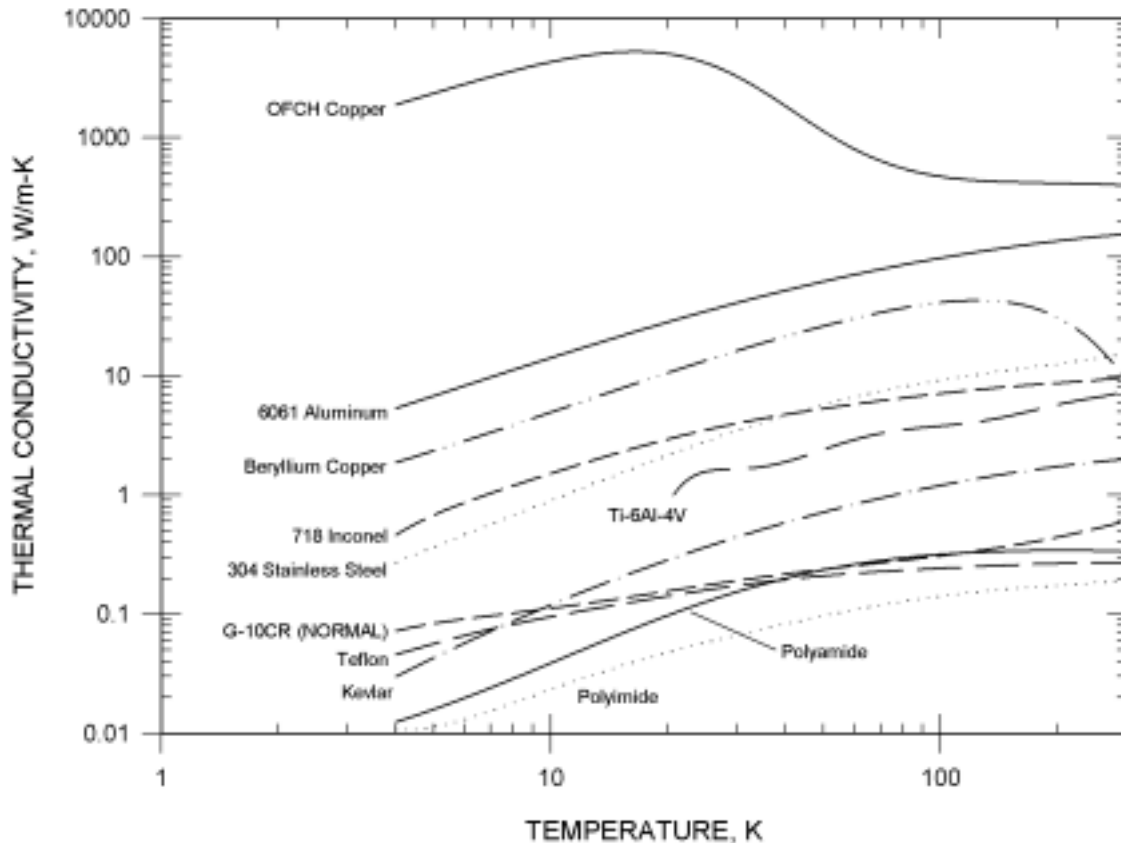

Figure 1. Thermal conductivity of various materials.

Table 2. Coefficients for specific heat.

Coeff.	OFCH copper	6061 -T6 Aluminum	304 SS	G-10	Teflon
a	-1.91844	46.6467	22.0061	-2.4083	31.8825
b	-0.15973	-314.292	-127.5528	7.6006	-166.519
c	8.61013	866.662	303.6470	-8.2982	352.019
d	-18.99640	-1298.30	-381.0098	7.3301	259.981
e	21.96610	1162.27	274.0328	-4.2386	-104.614
f	-12.73280	-637.795	-112.9212	1.4294	24.9927
g	3.54322	210.351	24.7593	-0.24396	-3.20792
h	-0.37970	-38.3094	-2.239153	0.015236	0.165032
I	0	2.96344	0	0	0
data range	3-300 K	3-300 K	3-300 K	3-300 K	3-300 K

specific heat of many of the engineering materials of interest here is not described well by these simple models. The general form of the equation is the same as Equation 1. Table 2 shows the coefficients for the specific heat. Figure 2 graphically shows the specific heats.

Thermal Expansion

From an atomic perspective, thermal expansion is caused by an increase in the average distance between the atoms. This results from the asymmetric curvature of the potential energy versus interatomic distance. The anisotropy results from the differences in the coulomb attraction and the interatomic repulsive forces.

Different metals and alloys with different heat treatments, grain sizes, or rolling directions introduce only small differences in thermal expansion. Thus, a generalization can be made that literature values for thermal expansion are probably good for a like material to within 5%. This is because the thermal expansion depends explicitly on the nature of the atomic bond, and only those changes that alter a large number of the bonds can affect its value. In general, large
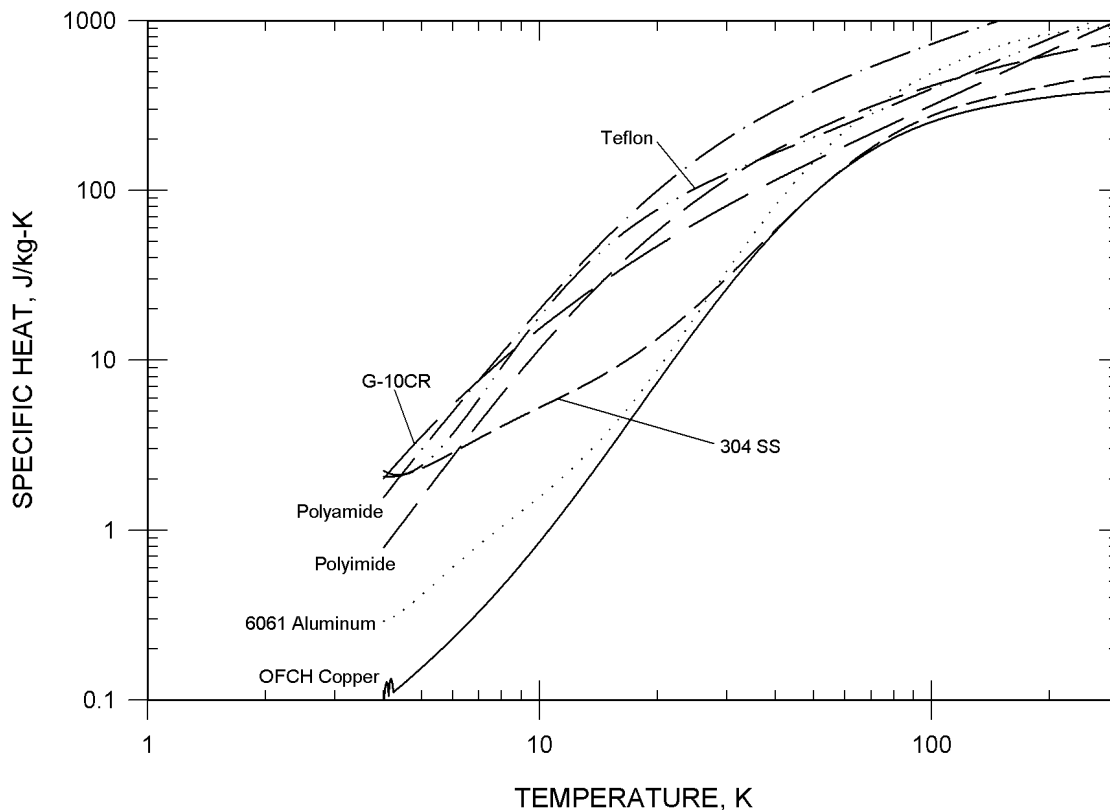

Figure 2. Specific heat of various materials.

Table 3A. Integrated Linear Thermal Expansion Coefficients for Metals.

Coeff.	6061 -T6 Aluminum	304 SS	718 Inconel	Beryllium copper	Ti-6Al-4V	NbTi
a	-4.1272E+02	-2.9546E+02	-2.366E+02	-3.132E+02	-1.711E+02	-1.862E+02
b	-3.0640E-01	-4.0518E-01	-2.218E-01	-4.647E-01	-2.171E-01	-2.568E-01
c	8.7960E-03	9.4014E-03	5.601E-03	1.083E-02	4.841E-03	8.334E-03
d	-1.0055E-05	-2.1098E-05	-7.164E-06	-2.893E-05	-7.202E-06	-2.951E-05
e	0	1.8780E-08	0	3.351E-08	0	3.908E-08
data range	4-300 K	4-300 K	4-300 K	4-300 K	4-300 K	4-300 K

changes in composition (10 to 20%) are necessary to produce significant changes in the thermal expansion (~5%), and different heat treatments or conditions do not produce significant changes unless phase changes are involved.[8]

Most of the literature reports the integrated linear thermal expansion as a percent change in length from some original length generally measured at 293 K,

$$(L_T - L_{293}) / L_{293}. \tag{3}$$

Where L_T is the length at some temperature T and L_{293} is the length at 293 K. While this is a practical way of measuring thermal expansion, the more fundamental property is the coefficient of linear thermal expansion, α,

$$\alpha(T) = \frac{1}{L}\frac{dL(T)}{dT}. \tag{4}$$

The coefficient of linear thermal expansion is much less reported in the literature. In principal, we can simply take the derivative of the integrated linear thermal expansion that results in the coefficient of linear thermal expansion. While we have had success with this method over limited temperature ranges, we have not yet determined an equation form for the integrated expansion value that results in a good approximation of coefficient of linear thermal expansion. For the time being, we will report the integrated linear thermal expansion as a change in length and provide the coefficient of linear thermal expansion when it is directly reported in the literature. The general form of the equation for integrated linear thermal expansion is

$$\frac{L_T - L_{293}}{L_{293}} = (a + bT + cT^2 + dT^3 + eT^4) \cdot 10^{-5}. \tag{5}$$

Tables 3A and 3B provide the coefficients for the various materials while Figure 3 plots the integrated linear thermal expansions.

FUTURE PLANS

We plan to continually add new materials, properties, and to expand the useful temperature range of the predictive equations for engineering use. We will report results in the literature but will also update our website on a continual basis. The initial phase of the program was a learning

Table 3B. Integrated Linear Thermal Expansion Coefficients for Non-metals.

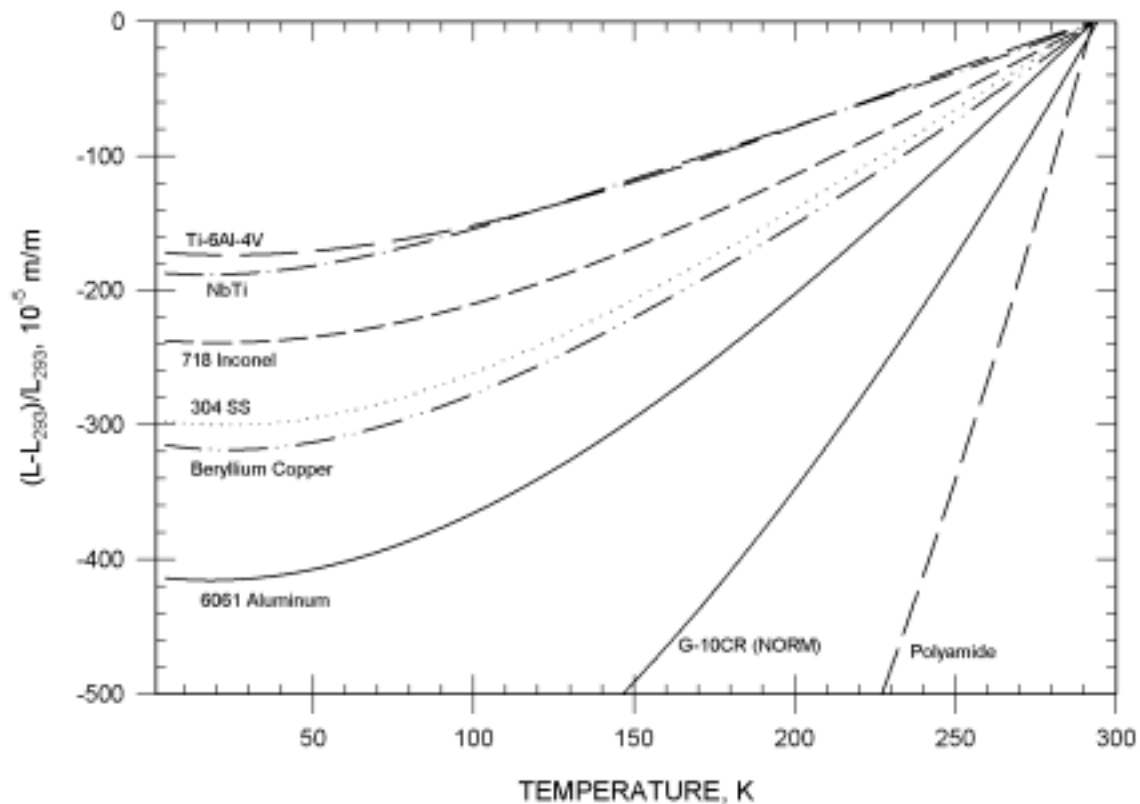| Coeff.	Teflon	Polyamide	G10 CR (norm)	G10 CR (warp)
a	-2.165E+03	-1.389E+03	-7.180E+02	-2.469E+02
b	3.278E+00	-1.561E-01	3.741E-01	2.064E-01
c	-8.218E-03	2.988E-02	8.183E-03	3.072E-03
d	7.244E-05	-7.948E-05	-3.948E-06	-3.226E-06
e	0	1.181E-07	0	0
data range	4-300 K	4-300 K	4-300 K	4-300 K

Figure 3. Integrated linear thermal expansion of various materials.

experience on how to handle the information in the literature as well as for the development of a standard set of basic equation types used to fit experimental data. By using just a few types of equations, we hope to make the information easier to use. We shall now focus on developing large numbers of equations for a variety of materials and properties. Please check our web site at http://www.boulder.nist.gov/div838/cryogenics.html for updated information.

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