CRYOGENIC MATERIAL PROPERTIES DATABASE, UPDATE 2006*

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ABSTRACT

We present an update to a program simply titled the Cryogenic Materials Property Database. The primary goal for this program is to compile, critically evaluate, and provide old and new properties data in a more usable predictive equation form focusing on primary properties such as thermal conductivity, thermal expansion, specific heat, and Young's modulus for a temperature range of 4 to 300 K. To facilitate the widest possible access to this data we have established a website at www.cryogenics.nist.gov to provide this information. In this paper we present an updated list of the materials and properties currently in the database.

INTRODUCTION

Recent extensive efforts in a wide array of fields such as medicine, space exploration, weather forecasting, and many others have led to a growth in the use of standard and exotic materials for low temperature (cryogenic) applications. Cryogenics in the early 1950's led to much interest in material properties at low temperatures. While important fundamental theory and measurements of low temperature material properties were performed throughout the 1950's, 60's and well into the 70's much of this work has become fragmented and dispersed as many of these publications are out of print and difficult to find if available at all. More importantly much of this work is in a form that simply is incommensurate for use with computers as the graphs and tables formerly used are difficult to accurately determine and use. Even new publications present material primarily in graphs and occasionally tables which necessitates transcription into a user-friendly digital/numeric form that can be incorporated into existing computer codes and models.

Several years ago NIST began a program to gather cryogenic material property data and make it available in a form that is useful to scientists and engineers. We established an approach to use a few simple types of polynomial or logarithmic polynomial equations to determine the coefficients for different materials and their properties [1] over a fairly wide temperature range. This allows the end user the flexibility to use the equations in a manner they so choose by incorporating into commercial software or code of their own to predict material properties. Thus integrated and average values can easily be determined from the equations whether explicitly or numerically from data developed from the equations. The equations are meant to provide best reasonable accurate values rather than any physical insight into the property. As the equations are based upon original data they are not meant to provide 'standard' values unless based upon standard reference materials (SRM's) as stated.

PREDICTIVE EQUATIONS

In the previous work [1] we presented the general forms for the fit equations employed for Thermal Conductivity, Specific Heat, Linear Thermal Expansion, Coefficient of Thermal Expansion, and Young's Modulus. Below we summarize these again. We note that with all generalizations there may and probably will be exceptions from time to time. Thus, we reserve the right to employ variances in equation form(s) as appropriate to best present properties for any given material now and in the future.

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Thermal Conductivity, Specific Heat, and Expansion Coefficient

For most materials the general form of the equation for thermal conductivity, k, is

$$\log_{10}(k) = a + b(\log_{10} T) + c(\log_{10} T)^2 + d(\log_{10} T)^3 + e(\log_{10} T)^4 + f(\log_{10} T)^5 + g(\log_{10} T)^6 + h(\log_{10} T)^7 + i(\log_{10} T)^8, \quad (1)$$

where $a, b, c, d, e, f, g, h,$ and i are the fitted coefficients, and T is the temperature with units of W/(m-K) for thermal conductivity, J/(kg-K) for specific heat, and 1/K for expansion coefficient (CTE). These are common logarithms (ie. base 10) and we note that all the digits provided for the coefficients should be used as any truncation can lead to significant errors. For specific heat and coefficient of expansion simply substitute 'C_p' or '*CTE*' for 'k' in equations 1 and 2. It was determined that the eight terms were needed in order to fit the data over the large temperature range. Equation 1 of course solves as

$$k = 10^{a+b(\log_{10} T)+c(\log_{10} T)^2+d(\log_{10} T)^3+e(\log_{10} T)^4+f(\log_{10} T)^5+g(\log_{10} T)^6+h(\log_{10} T)^7+i(\log_{10} T)^8}. \quad (2)$$

While we have made every effort to maintain consistency in employing equation 1 for thermal conductivity, oxygen free copper is the exception thus far. We determined the best representation for the thermal conductivity for OFHC copper takes the form

$$\log_{10}(k) = \frac{a + cT^{0.5} + eT + gT^{1.5} + iT^2}{1 + bT^{0.5} + dT + fT^{1.5} + hT^2} \quad (3)$$

where coefficients are as before. Equation 3 is the thermal conductivity for an average sample of oxygen free copper with coefficients as before which solves as

$$k = 10^{\frac{a+cT^{0.5}+eT+gT^{1.5}+iT^2}{1+bT^{0.5}+dT+fT^{1.5}+hT^2}}. \quad (4)$$

It should be noted that thermal conductivity for oxygen free copper can vary widely depending upon the residual resistivity ratio, RRR, and this equation should be used with caution.

Thermal Expansion and Young's Modulus

Thermal expansion is reported in the literature mostly as the integrated linear thermal expansion as a percent change in length from an original length usually measured at 293K which we refer to as Linear Thermal Expansion is expressed in general form as,

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

which has units of m/m otherwise known as unitless and the same coefficients. The general form for Young's modulus of elasticity, E, is similarly expressed as,

$$E = (a + bT + cT^2 + dT^3 + eT^4), \qquad (6)$$

which has units of GPa and fitted coefficients are the same again.

MATERIALS

Our database now extends from the original dozen to over 40 materials as listed in Table 1 which also shows the status of properties available for each material in the database. We continue to provide many of the most commonly used in cryogenics as well as many previously not so commonly used. For all materials we provide the appropriate selection and critical screening for best representation and fits for the data presented while we continue to focus on the original 5 properties; Thermal Conductivity, Specific Heat, Linear Thermal Expansion, Coefficient of Thermal Expansion, and Young's Modulus. One of the most important aspects for this program is to critically evaluate and provide proper reference source documentation for the data [1-79]. We provide a succinct cross-referenced list for all general materials and properties references in Table 2. We note that although this is not necessarily the most user-friendly approach, we refer the reader to our website for a comprehensive and user-friendly version (too long to include in this paper) which allows easy access and location of individual materials and properties source references. 20 recently added high heat capacity materials are shown in Figure 1. Table 3 lists the properties available for these materials (employed in NIST Regen3.2) [2,3] which are often used in regenerators. Figure 1 shows the more useful volumetric specific heat (ρC_p) for these materials which have significant peaks at low temperatures resulting in unsatisfactory fits for Equations 1 and 2. Therefore for the immediate future we are providing the data for these materials as part of an excel spreadsheet file

Table 1 Alphabetical list of updated materials currently in database (references 1, 4-47).

General Materials	Thermal Conductivity - *k*, W/(m-K)	Specific Heat - C_p, J/(kg-K)	Linear Thermal Expansion - $(L_T-L_{293})/L_{293}$, unitless ie. m/m	Coefficient of Thermal Expansion - $dL_{(T)}/(LdT)$, 1/K or m/(m-K)	Modulus of Elasticity – *E*, GPa
Aluminum 1100	X	X			
Aluminum 1100 - F	X				
Aluminum 3003-F	X	X	X		
Aluminum 5083-O	X	X	X		X
Aluminum 6061-T6	X	X			X
Aluminum 6063-T5	X				
Apiezon N	X	X			
Apiezon T		X			
Balsa	X				
Beechwood / phenolic	X		X		
Beryllium	X	X *in Process*	X		
Beryllium Copper	X		X		X
Brass	X		X		
Copper (OFHC) UNS 101	X	X		X	X
Copper (ETP)	X				
Copper (Pure)	X *in Process*	X *in Process*		X *in Process*	
Fiberglass Epoxy G-10	X		X		
Glass fabric / polyester G-11	X				
Glass mat / epoxy	tbd	tbd	tbd	tbd	
Inconel 718	X		X		
Indium	X	X		X	
Invar (Fe-36Ni)	X	X	X		X
Kevlar-49	X				X
Lead	X	X			
Molybdenum	X		X		
Niobium Titanium (NbTi)			X		
Nickel Steel (Fe-2.5Ni)	X	X	X		X
Nickel Steel (Fe-3.5Ni)	X	X	X		X
Nickel Steel (Fe-5.0Ni)	X	X	X		X
Nickel Steel (Fe-9.0Ni)	X	X	X		X
Perlite	X				
Phosphor Bronze		X *in Process*		X *in Process*	
Platinum	X	X			
Polyamide (Nylon)	X	X	X		
Polyethylene Terephthalate (Mylar)	X				
Polyester	X *in Process*		X *in Process*		
Polyimide (Kapton)	X	X			
Polystyrene	X	X	X		
Polyurethane	X	X	X		
Polyvinyl Chloride	X	X	X		
Sapphire	X *in Process*		X *in Process*	X *in Process*	
Silicon	X *in Process*		X *in Process*	X *in Process*	
Stainless Steel 304	X	X	X		X
Stainless Steel 304L	X	X	X		
Stainless Steel 310	X	X	X		X
Stainless Steel 316	X	X	X		X
Stainless Steel 304-SRM735	X				
Stycast 2850 FT			X *in Process*		
Teflon-PTFE	X	X	X		
Ti-6Al-4V	X	X	X		

[*] Contribution of NIST, not subject to copywright in the U.S.

Table 2 Cross-references for materials in database [5-47] (most comprehensive at **www.cryogenics.nist.gov**).

Material	Props. Refs.		Material	Props. Refs.
Aluminum 1100	K-5		Nickel Steel (Fe-2.25Ni)	Y-5, Exp.-5, Cp-5, K-5
Aluminum 3003-F	K-5, Cp-5, Exp-4		Nickel Steel (Fe-3.5Ni)	Y-5, Exp.-5, Cp-5, K-5
Aluminum 5083-0	K-5, Cp-5, Exp-6, E-5		Nickel Steel (Fe-5.0Ni)	Y-5, Exp.-5, Cp-5, K-5
Aluminum 6061-T6	K-7, CP-5, Exp-5, E-5		Nickel Steel (Fe-9.0Ni)	Y-5, Exp.-5, Cp-5, K-5
Aluminum 6063-T5	K-5		Nickel Steel	K-5, Cp-5, Exp-5
Apiezon N	Cp-13,14,15,16, K-31		Nylon	Exp.- 6,7,12, K-7, 11
Apiezon T	Cp-31		Perlite	Cp-5
Balsa	K-5		PET/Mylar (polyethylene terephthalate)	K-23
Beechwood-Phenolic	Exp-5		Phosphor Bronze	Exp.-24, Cp-24
Beryllium	Exp-9, Cp-8,11, K-10		Platinum	K-11, Cp-11
Beryllium-Copper	K-7, Exp-2, Y-18		Polyamide (Nylon)	K-7, Exp-12, Cp-**U**
Brass	K-10, 33, Exp-32		Polyester	Exp.-5, K-5
Copper	K-22, Cp-22, 11, 7, Exp-22, Y-22		Polyiminde (Kapton)	K-38
Copper_ ETP	K-34,35		Polystyrene	Exp.-5, Cp-5, K-5
Copper_Pure	Exp.-6, K-5, Cp-11		Polyurethane	Exp.-5, Cp-5, K-5
G-10 Fiberglass Epoxy	Exp-5, 12, K-17,29,36, Cp-**U**		Polyvinyl Chloride	Exp.-5, Cp-5, K-5
Glass fabric/polyester	Tbd		Sapphire	Exp.-39,40, K-**U**
Glass mat/epoxy	Tbd		Silicon	Exp.-9, 41,
Inconel 718	K-34, Exp-34		Stainless Steel 304	K-5, 42, Cp-5,42,43, Exp-5,6, Y-5
Indium	K-18, Exp-18, Cp-18		Stainless Steel 304L	K-5, Cp-5, Exp-5
Invar (Fe-36Ni)	K-5, Exp-5, Cp-5, Y-5		Stainless Steel 310	K-5, Cp-5, Exp-6, Y-5
Kevlar	K-19,20, Y-37		Stainless Steel 316	K-5, Cp-5, Exp-6, Y-5
Lead	K-18, Cp-18		Stainless Steel 735	K-44,45
Molybdenum	K-10,21, Exp-9		Stycast - 2850FT	Exp.-46
NbTi	Exp-12		Teflon	Exp.-6, K-7, Cp-7
			Titanium 6Al-4V	Exp.-9, K-47, Cp-47

k: Thermal Conductivity, *Cp*: Specific Heat, *Exp.*: Thermal Expansion and CTE, *Y*: Young's Modulus

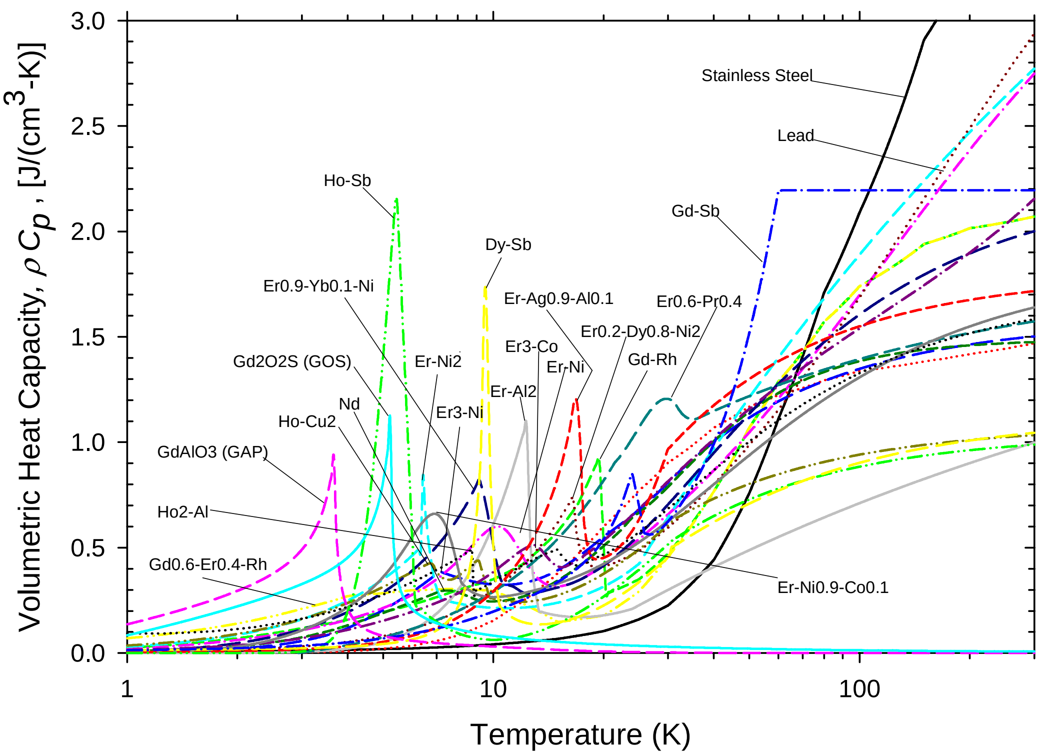

Figure 1 Regenerator materials in database and Regen3.2 (references [45-78]).

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Table 3 Updated regenerator materials in database and Regen3.2 (references [2,3, 48-81]).

Regenerator Materials	Thermal Conductivity - *k*, W/(m-K)	Volume Specific Heat - ρC_p, J/(cm^3-K)
GdRh		X *in Process*
ErNi	X *in Process*	X *in Process*
$ErNi_2$	X *in Process*	X *in Process*
$ErAl_2$		X *in Process*
$Er_{0.2}Dy_{0.8}Ni_2$		X *in Process*
$Er_{0.9}Yb_{0.1}Ni$		X *in Process*
Er_3Co		X *in Process*
$ErNi_{0.9}Co_{0.1}$	X *in Process*	X *in Process*
$Gd_{0.6}Er_{0.4}Rh$		X *in Process*
Er_3Ni		X *in Process*
Nd		X *in Process*
$Er_{0.6}Pr_{0.4}$		X *in Process*
$HoCu_2$		X *in Process*
$ErAg_{0.9}Al_{0.1}$		X *in Process*
Ho_2Al		X *in Process*
HoSb		X *in Process*
DySb		X *in Process*
GdSb		X *in Process*
GAP_$GdAlO_3$		X *in Process*
GOS_Gd_2O_2S		X *in Process*

NEW FEATURES IN DATABASE

There are many new features for the Cryogenic Material Properties Database on our website; www.cryogenics.nist.gov. These include a revised visual front end which provides both the fit equations as well as the appropriate solutions to aid in proper use. Often accuracies are difficult to ascertain from the original literature so we provide the accuracy for the fits of equations to original data sources. These range from ± 1% to ± 5% and we expect that total accuracies for many materials are within a few to 10 %. While these are not intended as overall data accuracies and should be used with caution they certainly represent reasonable values for engineering and scientific use. We encourage users to review the references documented individually for each material and property and to asses for themselves what accuracy they deem appropriate. The references may be viewed by clicking the button labeled "References for this Material". Additionally, a representative plot for each material property (similar to Figure 1 but for a single material of interest) of a given material has been added which can be viewed by clicking the appropriately labeled button.

FUTURE PLANS

We continue to receive positive responses to the Cryogenic Material Properties Database at www.cryogenics.nist.gov and plan to continually update with new materials and properties. We are in process of expanding the useful temperature range of the predictive equations to about 350 K. Check our web site often for updated information.

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