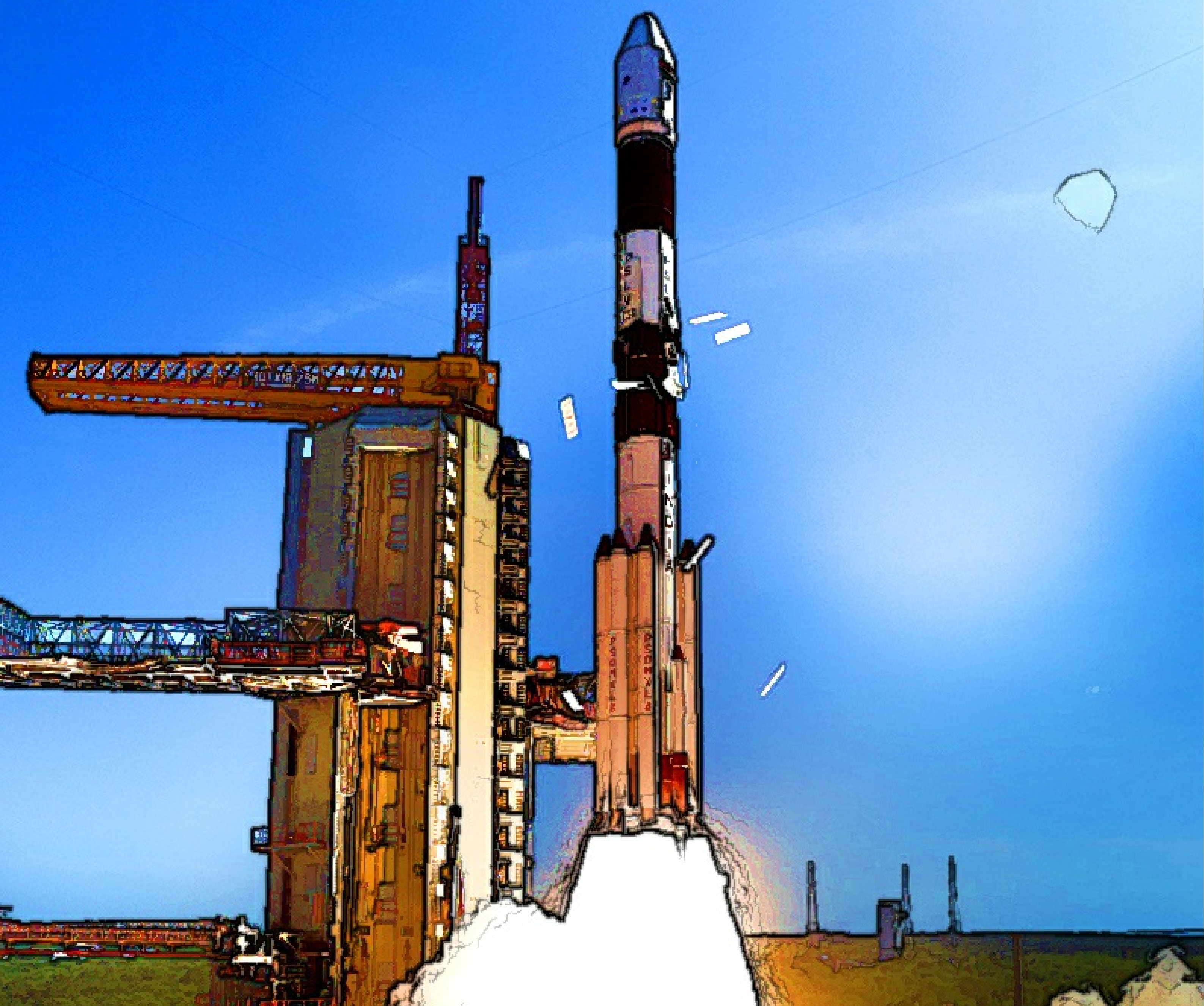
Cryogenic Engineering: Software Solutions: Part-I

Dr. M. Thirumaleshwar



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Dr. M. Thirumaleshwar

Cryogenic Engineering: Software Solutions

Part-I (Properties of cryogenic fluids, Properties of materials at low temperatures)

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Cryogenic Engineering: Software Solutions: Part-I
(Properties of cryogenic fluids, Properties of materials at low temperatures)
1st edition
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ISBN 978-87-403-0985-0

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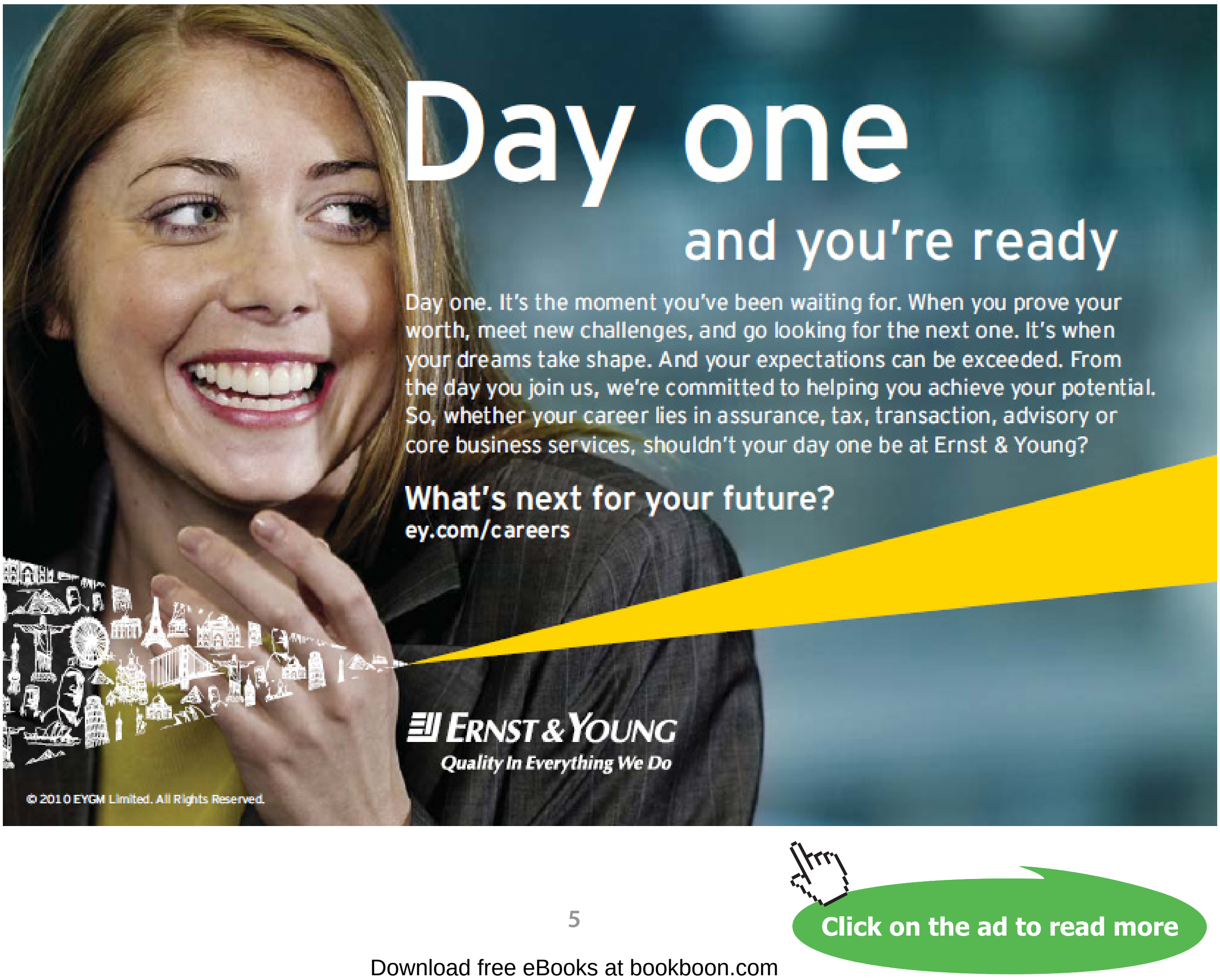

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Dedication

This work is lovingly dedicated at the lotus feet of

Bhagavan Sri Sathya Sai Baba

"There is only one religion, the religion of Love.
There is only one caste, the caste of Humanity.
There is only one language, the language of the Heart.
There is only one God, He is Omnipresent."

"Help Ever, Hurt Never!"

...Bhagavan Sri Sathya Sai Baba

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Message by Prof. R.G. Scurlock, Emeritus Professor of Cryogenic Engineering

formerly
Director, Institute of Cryogenics,
University of Southampton, Southampton, U.K.

I should like to make several points briefly.

Firstly, I congratulate my former student in producing an up-to-date book on the properties and applications of cryogenic liquids. This is particularly important today for the development of computer modeling and CryoFD in the ever expanding range of cryogenic systems.

Secondly, since Dr. Thirumaleshwar mentions in Chapter 1 my proposal to extend the temperature range for cryogenics up to 250K, I should like to describe some of the background to the proposal.

In the 1970/71 definition of cryogenics by Kurti et al (specifying the temperature range up to 120K) they were aware of the complications presented by the development of cryo-medicine, cryo-surgery and cryo-preservation, using temperatures well above 120K but well below the temperatures of the refrigeration industry. They therefore proposed the term "cryology" to embrace a wider temperature range up towards the ice-point. This proposal has not progressed into common usage, and the Gap between 120K and 250K has remained in confusion with poor coverage in both research and teaching.

In 1979, when the Institute of Cryogenics, Southampton University, U.K. was set up, it rapidly became almost overwhelmed by the problems being met by innovative industries using temperatures in the Gap. Some 50% of the research and teaching activities became centred on these higher temperatures. What was found was that the heat transfer by convection, the unstable evaporation, the convective flow patterns etc in the temperature Gap were similar in dominance and kind to those at the lower temperatures below 120K; and it was possible to develop a unified approach, via Cryogenic Fluid Dynamics, CryoFD, applicable to all fluids, liquids and gases, below the ice-point.

It followed that cryogenics should be redefined to include the 1970/71 Cryology, (ie. the whole temperature range up to the ice-point) and this was first proposed in 1992 in "History and Origins of Cryogenics", and again in 2006 in "Low-Loss Storage and Handling of Cryogenic Liquids".

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However, some of the refrigeration industry has objected to being included as a sub-set of Cryogenics, and the most recent proposal in 2013 has removed their temperature range below the ice-point down to -23C from the definition.

The current proposal is therefore that Cryogenics should cover all temperatures up to 120K and the Temperature Gap up to 250K.

Finally, some examples of current activity in the Gap include:

a) The requirement for computer-controlled freezing protocols for the cryopreservation of stem cells.
b) The development of green energy cryogenic fuels for driving transport by sea, road and rail using LNG under pressure.
c) Providing a solution to engine failures from the formation of water ice crystals in jet fuel on long-haul aircraft flying in the stratosphere at temperatures down to 200K.
d) Other problems close to the ice-point, which have not been regarded as the province of the refrigeration industry.

My good wishes go to Dr. Thirumaleshwar for his continuing success in the field of Cryogenics.

Ralph Scurlock
Emeritus Professor of Cryogenic Engineering

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Preface

According to **National Institute of Standards and Technology (NIST), 'Cryogenic temperature range'** generally refers to temperatures below -150 C i.e. 123 K. Most of the 'permanent gases' liquefy below this temperature. Temperature range from 123 K up to room temperature is the domain of 'Refrigeration'.

However, some authorities believe that cryogenic temperature range should be extended up to 0 deg. C or 273 K. Prof. Ralph Scurlock, former Director of Institute of Cryogenics, Southampton, UK, under whom the author studied, states: "I regard the temperature range should extend upwards towards 273K. However, the refrigeration people objected to their temperatures, from -22 C up to zero C, being a subset of my cryogenics. So my last suggestion was for Cryogenics to extend upwards to 250K or -23 C to avoid their objection!"

Cryogenic fluids of interest are: Air, Nitrogen, Oxygen, Argon, Methane, Hydrogen, Neon, Fluorine, Helium-4, Helium-3 etc.

However, Nitrogen, Oxygen, Methane, Hydrogen and Helium-4 and Helium-3 attract more attention because of their applications.

Applications of cryogenics are many and in diverse fields. To name a few areas: Rocket propulsion, High energy Physics, Electronics, Superconducting magnets and their various applications such as magnetic levitation, whole body imaging etc., Space simulation and cryo-pumping, Medical applications to preserve whole blood, tissue, bone marrow, and animal semen for long periods of time, cryo-destruction of cancerous tissues, Food processing, Manufacturing processes in mechanical and chemical engineering, Recycling of plastic materials etc.

In engineering colleges, post graduate degree in cryogenic engineering is offered with the following general syllabus:

Introduction, properties of cryogenic fluids, properties of materials at low temperatures.
Gas liquefaction systems.
Gas separation and gas-purification systems.
Cryogenic refrigeration systems.
Storage and handling of cryogens.
Cryogenic instrumentation.
Vacuum technology.
Applications of cryogenic systems.

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This series, viz. **Cryogenic Engineering: Software solutions** focuses on the solutions of problems in cryogenic engineering using software such as Mathcad, Engineering Equation Solver (EES) and EXCEL. Only the essential theory and summary of equations required for calculations are given at the beginning of each chapter. Thus, this book should be helpful to students when used in conjunction with any standard text book on this subject.

Advantages of using computer software to solve problems are many:

i. It helps in solving the problems fast and accurately
ii. Parametric analysis (what-if analysis) and graphical visualization is done very easily. This helps in an in-depth analysis of the problem.
iii. Once a particular type of problem is solved, it can be used as a *template* and solving similar problems later becomes extremely easy.
iv. In addition, one can plot the data, curve fit, write functions for various properties or calculations and re-use them.
v. These possibilities create interest, curiosity and wonder in the minds of students and enthuse them to know more and work more.

This book, viz. **Cryogenic Engineering: Software solutions – Part-I** deals with: Introduction, properties of cryogenic fluids and properties of materials at low temperatures. Primarily, here we have a collection of information and data from various sources, the focus being on the data that will be useful for engineers to design cryogenic systems. Several Functions are written in EES, EXCEL and Mathcad for various thermal and mechanical properties of materials. These Functions should be very much useful in executing computer designs of cryogenic systems without any need to refer to data tables and graphs for properties of materials. Several graphs for cryogenic properties of materials from NIST publications are also presented. Rest of the chapters will be dealt with in subsequent parts which will follow.

S.I. Units are used throughout this book. Wide variety of worked examples presented in the book should be useful for those appearing for University, AMIE and Engineering Services examinations.

Acknowledgements: Firstly, I would like to **thank all my students**, who have been an inspiration to me in all my academic efforts.

I am grateful to **Rev. Fr. Valerian D'Souza,** former Director of St. Joseph Engineering College (SJEC), Mangalore, for his love, deep concern and support in all my academic pursuits.

Sincere thanks are due to **Rev. Fr. Joseph Lobo**, Director, SJEC, for his kindness, regard and words of encouragement.

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I would also like to thank **Dr. Joseph Gonsalves**, Principal, SJEC and **Dr. Thirumaleshwara Bhat**, Head, Dept. of Mechanical Engineering, SJEC, for giving me un-stinted support in my academic activities.

I am indebted to my former colleagues at the Cryogenics section of Technical Physics Division, Bhabha Atomic Research Centre (BARC), Bombay and Centre for Advanced Technology, Indore for their sincere cooperation in a true spirit of team-work in all the projects that we undertook.

I salute and admire the vision and foresight of former Heads of Technical Physics Division, BARC viz. late Mr. C. Ambasankaran, Mr. R.Y. Deshpande, Dr. S.R. Gowariker and late Mr. S.S. Ramamurthy in initiating and guiding many of the 'first of its kind' projects for Indian Space Research Organization (ISRO), designed and executed by the Cryogenics section.

I am especially grateful to Prof. R.G. Scurlock, for writing a message for this book. It was indeed gracious of my former Professor, under whom I studied for M.Sc. in Cryogenics at the University of Southampton, UK during 1970–72, and worked as a Visiting Research Fellow during 1993–94, to honor me by writing this message.

My special thanks to **Bookboon.com** for publishing this free ebook . **Ms Karin Jakobsen and Ms Sophie Tergeist** and their editorial staff have been most helpful.

Finally, I would like to express my sincere thanks and appreciation to my **wife, Kala,** who, as usual, has given continuous support, help and encouragement in all my academic activities, making many silent sacrifices.

M. Thirumaleshwar
March 2015

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About the Author

Dr. M. Thirumaleshwar graduated in Mechanical Engineering from Karnataka Regional Engineering College, Surathkal, Karnataka, India, in the year 1965. He obtained M.Sc (cryogenics) from University of Southampton, U.K. and Ph.D.(cryogenics) from Indian Institute of Science, Bangalore, India.

He is a Fellow of Institution of Engineers (India), Life Member, Indian Society for Technical Education, and a Foundation Fellow of Indian Cryogenics Council.

He has worked in India and abroad on large projects in the areas involving heat transfer, fluid flow, vacuum system design, cryo-pumping etc.

He worked as Head of Cryogenics Dept. in Bhabha Atomic Research Centre (BARC), Bombay and Centre for Advanced Technology (CAT), Indore, from 1966 to 1992.

He worked as Guest Collaborator with Superconducting Super Collider Laboratory of Universities Research Association, in Dallas, USA from 1990 to 1993.

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He also worked at the Institute of Cryogenics, Southampton, U.K. as a Visiting Research Fellow from 1993 to 1994.

He was Head of the Dept. of Mechanical Engineering, Fr. Conceicao Rodrigues Institute of Technology, Vashi, Navi Mumbai, India for eight years.

He also worked as Head of Dept. of Mechanical Engineering and Civil Engineering, and then as Principal, Vivekananda College of Engineering and Technology, Puttur (D.K.), India.

He was Professor and coordinator of Post-graduate program in the Dept. of Mechanical Engineering in St. Joseph Engineering College, Vamanjoor, Mangalore, India.

A book entitled **"Fundamentals of Heat and Mass Transfer"** authored by him and published by M/s Pearson Education, India (2006) **has been adopted as a Text book** for third year engineering students by the Visweswaraya Technological University (V.T.U.), Belgaum, India.

He has authored a ***free ebook*** entitled **"Software Solutions to Problems on Heat Transfer"** wherein problems are solved using 4 software viz. Mathcad, EES, FEHT and EXCEL. This book, containing about 2750 pages, is presented in 9 parts and all the 9 parts can be downloaded *for free* from www.bookboon.com

He has also authored ***free ebooks*** **on Thermodynamics** entitled **"Basic Thermodynamics: Software Solutions" and "Applied Thermodynamics: Software Solutions"** wherein problems are solved using 3 software viz. Mathcad, EES, and TEST. Each of these titles is presented in 5 parts and all the books can be downloaded *for free* from www.bookboon.com

He has also authored **three motivational, free ebooks**, published by www.bookboon.com, entitled as follows:

1. Towards Excellence…How to Study (A Guide book to Students)
2. Towards Excellence…How to teach (A guide book to Teachers)
3. Towards Excellence…Seminars, GD's and Personal Interviews

Dr. M. Thirumaleshwar has attended several National and International conferences and has more than 50 publications to his credit.

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About the Software used

Following three software are used while solving problems in this book:

1. Mathcad 7 (Ref: www.ptc.com)
2. Engineering Equation Solver (EES) (Ref: www.fchart.com), and
3. EXCEL

For a brief introduction to Mathcad, EES and EXCEL see the chapter 1 of the following *free ebook* by the author:

"Software Solutions to Problems on Heat Transfer – CONDUCTION Part-I":
http://bookboon.com/en/software-solutions-to-problems-on-heat-transfer-ebook

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1 Introduction and Properties of Cryogenic fluids

Learning objectives:

1. In this chapter, first, some general properties of cryogenic fluids, compiled from various sources are given. Amount of cryogenic fluids required to cool metals is also tabulated.
2. Next, ***extremely useful* general information on Cryogenic Fluids available from the Gas Encyclopedia – Air Liquide website, viz**. http://encyclopedia.airliquide.com/encyclopedia.asp is explained.
3. Brief summary of properties of cryogenic fluids, collected from various sources, are given for fluids such as Liquid Nitrogen, Liquid Oxygen, Liquid Argon, Liquid Neon, Liquid Fluorine, Liquid Hydrogen, Liquid Helium (both Helium-I and superfluid He-II), and Helium-3.
4. Next, saturation properties of cryogenic fluids from NIST chemistry website, i.e. http://webbook.nist.gov/chemistry/fluid/ are presented for N2, He-4, H2, Ne, F2, and Ar. Graphs of various properties are also given.
5. Finally, properties of gases at 1 atm, along with many graphs, are given for He, H2, Ne, N2, O2, F2, and Ar, again from NIST chemistry website, i.e. http://webbook.nist.gov/chemistry/fluid/

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1.1 Introduction [1, 2, 3]:

According to National Institute of Standards and Technology (NIST), Boulder, USA, 'Cryogenic temp range' generally refers to temperatures below -150 C i.e. 123 K. Most of the 'permanent gases' liquefy below this temperature. Temperature range from 123 K up to room temperature is the domain of 'Refrigeration'.

However, some authorities believe that cryogenic temperature range should be extended up to 0 deg. C or 273 K. Prof. Ralph Scurlock, former Director of Institute of Cryogenics, Southampton, U.K., under whom the author studied, states: "I regard the temperature range should extend upwards towards 273K. However, the refrigeration people objected to their temperatures, from -22 C up to zero C, being a subset of my cryogenics. So my last suggestion was for Cryogenics to extend upwards to 250K or -23 C to avoid their objection!"

Cryogenic fluids of interest are: Air, Nitrogen, Oxygen, Argon, Methane, Hydrogen, Neon, Fluorine, Helium-4, Helium-3 etc.

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However, Nitrogen, Oxygen, Methane, Hydrogen and Helium-4 and Helium-3 attract more attention because of their applications.

Applications of cryogenics are many and in diverse fields. To name a few areas: Rocket propulsion, High energy Physics, Electronics, Superconducting magnets and their various applications such as magnetic levitation, whole body imaging etc., Space simulation and cryo-pumping, Medical applications to preserve whole blood, tissue, bone marrow, and animal semen for long periods of time, cryo-destruction of cancerous tissues, Food processing, Manufacturing processes in mechanical and chemical engineering, Recycling of plastic materials etc.

Some properties of cryogenic liquids at their Normal Boiling Points [2]:

Property	Oxygen	Nitrogen	Neon	e-Hydrogen[a]	Helium-4	Air	Fluorine	Argon	Methane
Normal boiling point (K)	90.18	77.347	27.09	20.268	4.224	78.9	85.24	87.28	111.7
Density (kg/m^3)	1141	808.9	1204	70.78	124.96	874	1506.8	1403	425.0
Heat of vaporization (kJ/kg)	212.9	198.3	86.6	445.6	20.73	205.1	166.3	161.6	511.5
Specific heat (kJ/(kg K))	1.70	2.04	1.84	9.78	4.56	1.97	1.536	1.14	3.45
Viscosity ($kg/(m\,s) \times 10^6$)	188.0	157.9	124.0	13.06	3.57	168	244.7	252.1	118.6
Thermal conductivity(mW/(mK))	151.4	139.6	113	118.5	27.2	141	148.0	123.2	193.1
Dielectric constant	1.4837	1.434	1.188	1.226	1.0492	1.445	1.43	1.52	1.6758
Critical temperature (K)	154.576	126.20	44.4	32.976	5.201	133.3	144.0	150.7	190.7
Critical pressure (MPa)	5.04	3.399	2.71	1.293	0.227	3.90	5.57	4.87	4.63
Temperature at triple point (K)	54.35	63.148	24.56	13.803	–	–	53.5	83.8	88.7
Pressure at triple point ($MPa \times 10^3$)	0.151	12.53	43.0	7.042	–	–	0.22	68.6	10.1

Some more data for cryogenic fluids [7]:

Property	O2	N2	Ne	e-H2	He4	Air	F2	Ar	CH4
ρ_sat.vap(kg/m^3)	4.8	4.61	4.8	1.34	15.5	4.48	5.63	5.7	1.8
ρ_gas,293K(kg/m^3)	1.331	1.165	0.8385	0.08374	0.1663	1.205	1.58	1.66	0.6679
cp_sat.vap(kJ/kg.K)	0.964	1.03	1.17	-	8.25	1.02	0.812	0.53	2.09
cp_gas,293K(kJ/kg.K)	0.922	1.046	1.039	-	5.2	1.01	0.824	0.523	2.22
μ_sat.vap(Pa.s x 10^6)	6.85	5	4.5	-	1.25	5.6	7.5	7	4.49
μ_gas,293K(Pa.s x 10^6)	20.7	17.8	32	-	18.9	18	23.5	23	11
k_sat.vap(W/m.K)	0.00855	0.007	0.008	-	0.0106	0.0073	0.007		0.012
k_gas,293K(W/m.K)	0.0262	0.025	0.049	-	0.1465	0.0255	0.024	0.0167	0.0329
Liq evap by 1 W input in 24 hrs (lit.)	0.36	0.54	0.84	-	33.2	0.48	0.33	0.38	0.4

Approx. equivalents of 1 litre of liquid gas:

Liquefied gas (1 lit.)	Mass of liq. (kg)	Vol. of gas produced, lit (STP)
Helium	0.1252	700
Hydrogen	0.708	780
Nitrogen	0.808	688
Fluorine	1.108	654
Oxygen	1.140	799

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Amount of cryogenic fluid required to cool metals (σ), kg/kg [8]:

Fluid		He4		H2		N2
Initial temp. of metal		300K	77K	300K	77K	300K
		σ (kg/kg)	σ (kg/kg)	σ (kg/kg)	σ (kg/kg)	σ (kg/kg)
Using latent heat only	Aluminium	8.3	0.4	0.38	0.018	0.81
	Stainless Steel	4.2	0.18	0.2	0.0085	0.43
	Copper	3.9	0.27	0.17	0.012	0.37
Using enthalpy of gas	Aluminium	0.2	0.028	0.075	0.0097	0.51
	Stainless Steel	0.1	0.013	0.037	0.0045	0.27
	Copper	0.1	0.02	0.037	0.0065	0.23

While using the above Table, you may also remember that sp. volumes of Liquid He4, Liquid H2 and Liquid N2 are:

8 lit/kg, 14.1243 lit/kg and 1.2376 lit/kg respectively.

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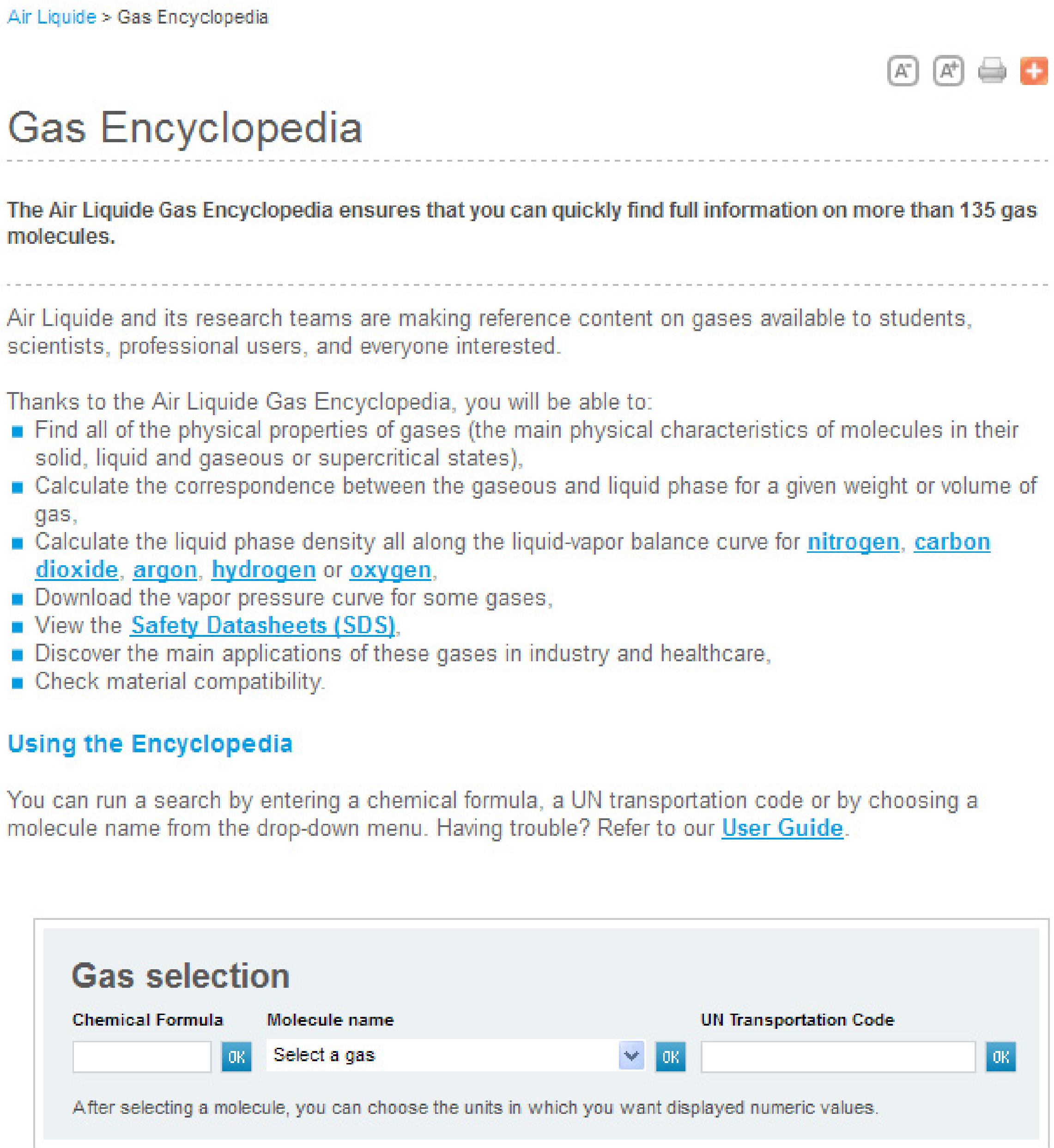
1.2 General information on Cryogenic Fluids:

Ref.[11], i.e. Gas Encyclopedia – Air Liquide website, viz.
http://encyclopedia.airliquide.com/encyclopedia.asp

gives very useful data concisely for about 135 fluids. In addition, useful data can also be collected from Ref.[1], [7] and [10].

Using Ref.[11] is demonstrated below:

1. As you click on the web address of Ref.[11], we get:



Air Liquide > Gas Encyclopedia

Gas Encyclopedia

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- Find all of the physical properties of gases (the main physical characteristics of molecules in their solid, liquid and gaseous or supercritical states),
- Calculate the correspondence between the gaseous and liquid phase for a given weight or volume of gas,
- Calculate the liquid phase density all along the liquid-vapor balance curve for **nitrogen**, **carbon dioxide**, **argon**, **hydrogen** or **oxygen**,
- Download the vapor pressure curve for some gases,
- View the Safety Datasheets (SDS),
- Discover the main applications of these gases in industry and healthcare,
- Check material compatibility.

Using the Encyclopedia

You can run a search by entering a chemical formula, a UN transportation code or by choosing a molecule name from the drop-down menu. Having trouble? Refer to our User Guide.

Gas selection

Chemical Formula OK
Molecule name Select a gas OK
UN Transportation Code OK

After selecting a molecule, you can choose the units in which you want displayed numeric values.

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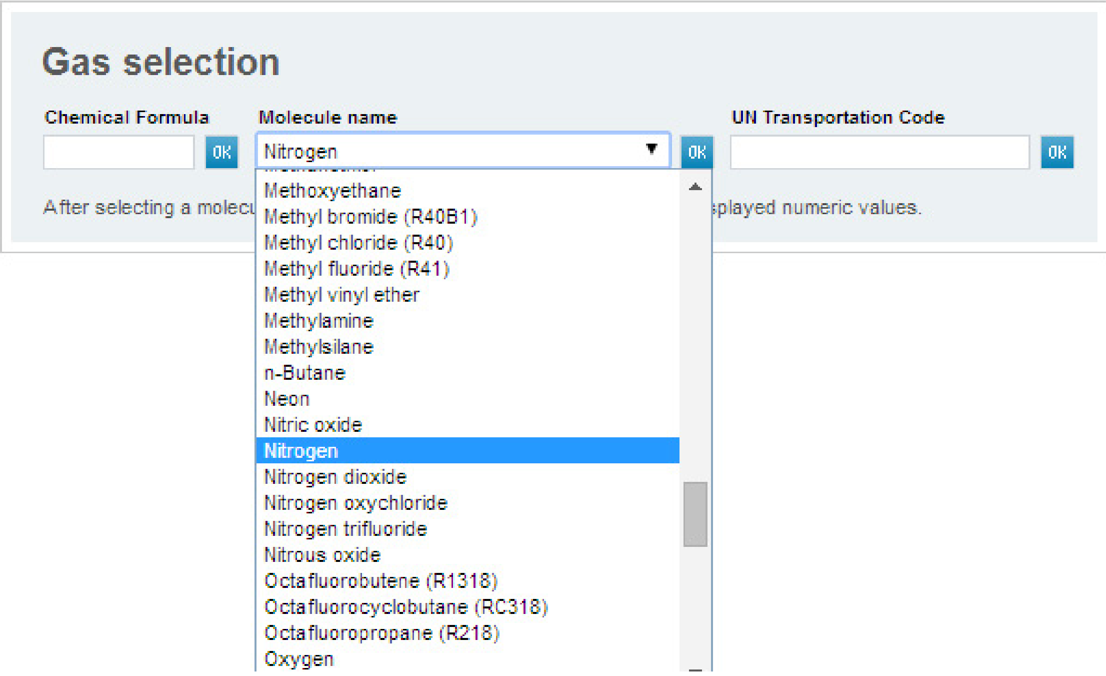
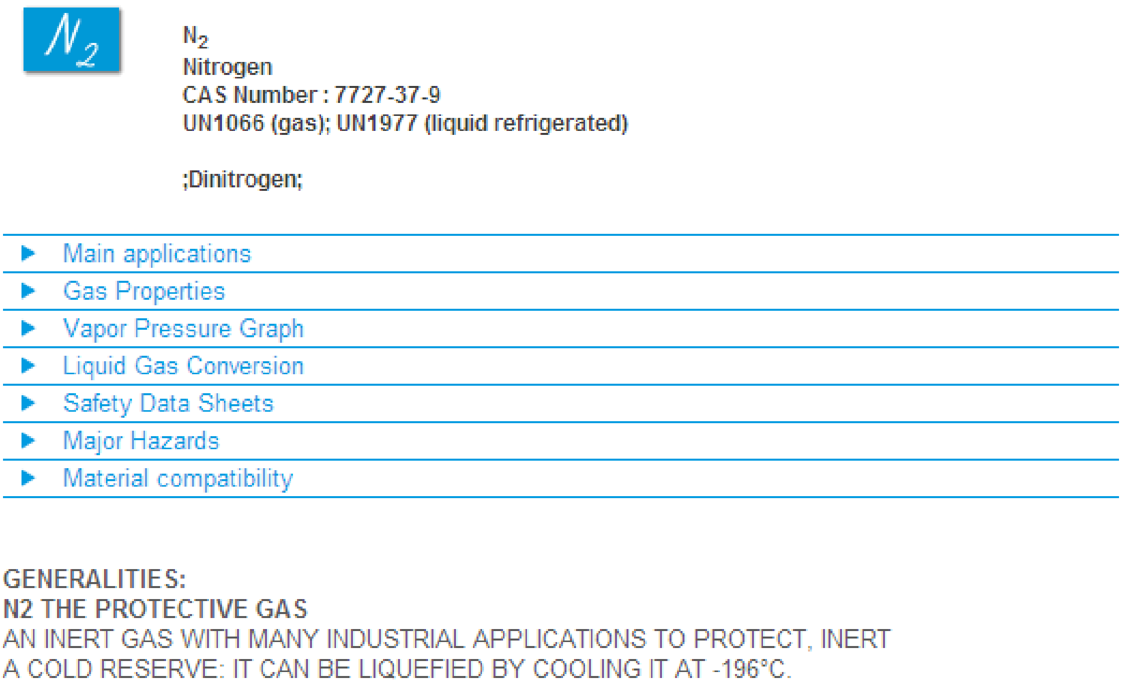
2. Select the gas required (say, Nitrogen) and hit Enter. We get:





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Nitrogen was discovered in 1772 by Daniel Rutherford who called it noxious air or fixed air. But it was Lavoisier who, in 1786, isolated it. The name nitrogen comes from Latin nitrogenium, where nitrum (from Greek nitron) means "saltpetre", and genes means "forming".

Nitrogen is mainly found in the atmosphere, where it accounts for 78 % by volume of the air we breath. But nitrogen is also found:
- in the Earth's crust, to a limited extent (in the form of nitrates, etc.),
- in organic form (in the living or dead plants and organisms which form humus)
- and in mineral form (ammonia), and thus contributes to soil fertility. In gaseous form, nitrogen is a neutral and colorless gas. It is inerting and does not sustain life.

A nouvelle cuisine: Great chefs are always ready to innovate by creating new recipes. Liquid nitrogen, at -196°C, enables these pioneers of molecular cooking to use their creativity by conceiving new tastes and textures.

Nitrogen: **SUPPLY MODE**	Cylinders, Liquefied gas tank, Pipeline, On-site generator,

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Main applications

Industries	Applications
Chemicals	Nitrogen can be used for blanketing, as well as for : - Storage for protecting raw materials or finished products in liquid form from the formation of peroxides and/or gum, and from contamination by oxygenated components - Regeneration of purification beds (alumina and molecular sieve) - Preparation of catalysts and transportion of polymer powders - Medium for the exhaust of emitted heat in fluid bed reactors - Temperature Control in reactors.
Pharmaceuticals	Nitrogen is used for inerting, cryo-grinding, lyophilisation, drying, liquid phase transfer of products or synthesis intermediates; cryo-condensation of waste gases and low temperature storage.
Food and Beverage	Liquid nitrogen: N_2 is the most used cryogenic fluid, to chill, freeze or store food products. Gaseous nitrogen: N_2 is very commonly used in contact with foodstuffs to avoid oxidation or micro-organism growth by inerting of liquids. Modified Atmosphere Packaging (MAP) preserves and protects foods (pure nitrogen or mixed with CO_2) (§ALIGAL™).
Glass, Cement and Lime	Nitrogen is used as an inert gas especialy to create, in combination with hydrogen, a reductive atmosphere over the tin bath in the float glass process.
Healthcare	Low-temperature preservation of living tissues and cells
Laboratories & analysis	Nitrogen is used as a carrier gas in gas chromatography for various industrial and hospital analyses and quality control. Nitrogen is the balance gas of the calibration gas mixtures for environmental monitoring systems and industrial hygiene gas mixtures. Nitrogen is largely used as purge, dryier or blanket gas for analyzers or chemical reactors (under gaseous state or at low temperature liquid state).
Welding, Cutting & Coating	Heat treatment of various metals. Nitrogen is a component of the special mixtures used in CO_2 lasers (§ LASAL™).
Oil and Gas	Quality protection of products and facilities (blanketing)

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Electronics	Nitrogen is used as carrier gas for overall protection against impurities and oxidation in semiconductor and soldering processes. In its cold and liquid form, N_2 is used as a cooling medium in the environmental testing of electronic devices.
Automotive & transportation	Gas Assisted Injection Moulding requires pressures between 10 bar (145 psi) and 200 bar (2900 psi) and a nitrogen content of between 98.0 % and 99.9 %. Tires filling with nitrogen increases their lifetime and therefore decreases the recycling or treatment of this waste.
Other industries	Pneumatic transportation of powdered flammable materials (charcoal).

Gas Properties

Molecular Weight	Molecular weight : 28.013 g/mol
Solid phase	Melting point : 63.14999 K Latent heat of fusion (1,013 bar, at melting point) : 25.702 kJ/kg
Liquid phase	Liquid density (1.013 bar at boiling point) : 806.11 kg/m^3 Liquid/gas equivalent (1.013 bar and 15 °C (59 °F)) : 680.4 vol/vol Boiling point (1.013 bar) : 77.34999 K Latent heat of vaporization (1.013 bar at boiling point) : 199.18 kJ/kg

Density & temperature calculation of the liquid phase

Given the pressure (in bar), this module calculates the temperature and the density of the liquid phase on the liquid-gas equilibrium curve

Enter the pressure in bar (between 1 and 32) ______ **bar** **Calculate**

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If we enter, say, 2.5 bar in the above calculator, we get:

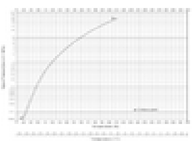
Enter the pressure in bar (between 1 and 32) 2.5 bar **Calculate**

Results:

Temperature : 85.9 K
Liquid Density : 764.01 kg/m^3

Critical point	Critical temperature : 126.19 K Critical pressure : 33.96 bar Critical density : 313.3 kg/m^3
Triple point	Triple point temperature : 63.14999 K Triple point pressure : 0.1252 bar
Gaseous phase	Gas density (1.013 bar at boiling point) : 4.6096 kg/m^3 Gas density (1.013 bar and 15 °C (59 °F)) : 1.1848 kg/m^3 Compressibility Factor (Z) (1.013 bar and 15 °C (59 °F)) : 0.99971 Specific gravity : 0.967 Specific volume (1.013 bar and 25 °C (77 °F)) : 0.8734 m^3/kg Heat capacity at constant pressure (Cp) (1.013 bar and 25 °C (77 °F)) : 0.0292 kJ/(kg.K) Heat capacity at constant volume (Cv) (1.013 bar and 25 °C (77 °F)) : 0.0208 kJ/(kg.K) Ratio of specific heats (Gamma:Cp/Cv) (1.013 bar and 25 °C (77 °F)) : 1.4013 Viscosity (1.013 bar and 0 °C (32 °F)) : 1.6629E-05 Pa.s Thermal conductivity (1.013 bar and 0 °C (32 °F)) : 0.024001 W/(m.K)
Miscellaneous	Solubility in water (1.013 bar and 0 °C (32 °F)) : 0.02348 vol/vol Concentration in air : 78.08 vol %

Vapor Pressure Graph



The vapor pressure curve may be obtained by clicking on the image. On the graph, pressure is in bar or 0.1 MPa, temperature in K or °C. The critical point is indicated by a black spot on the liquid-vapor equilibrium curve.

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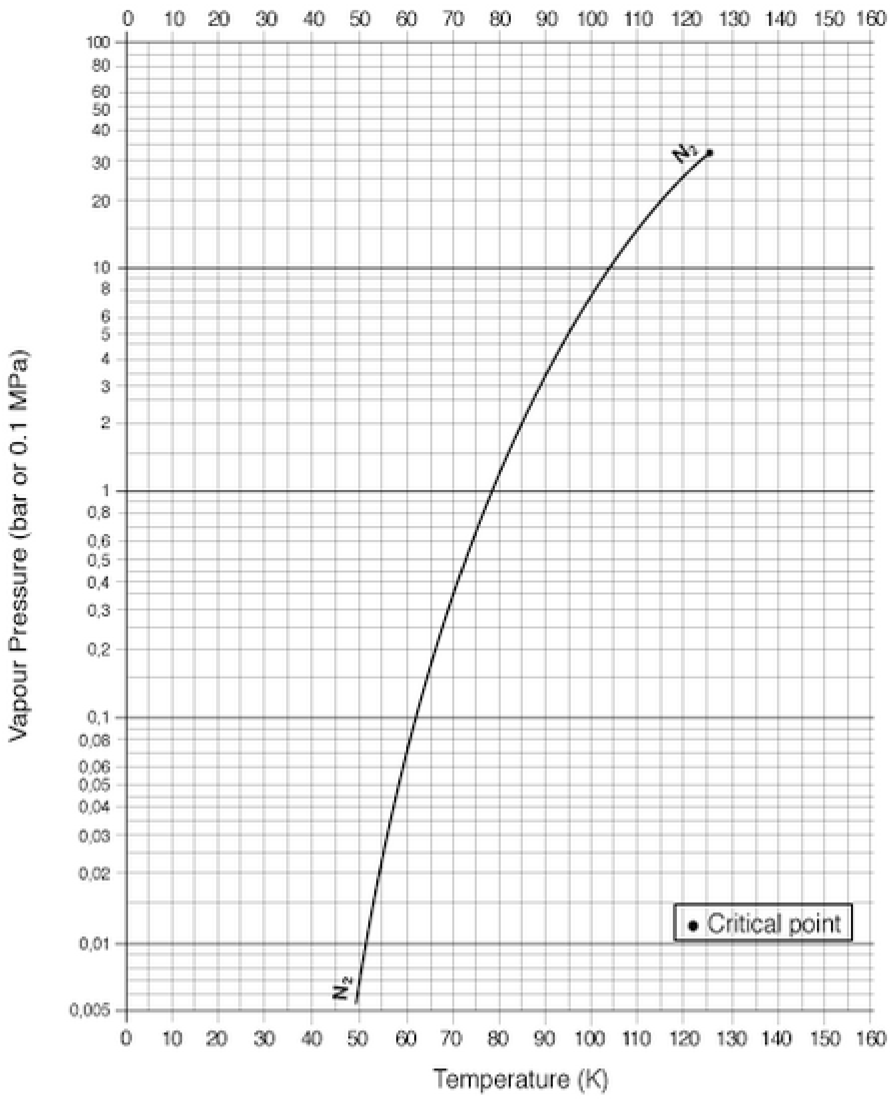
If we click on the graph, we get:



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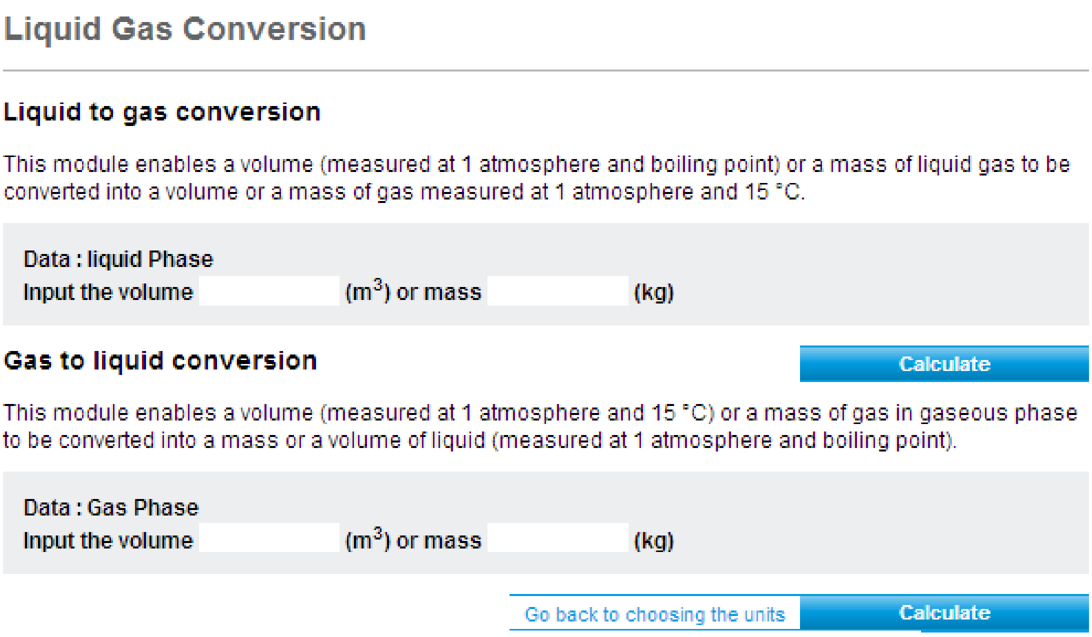
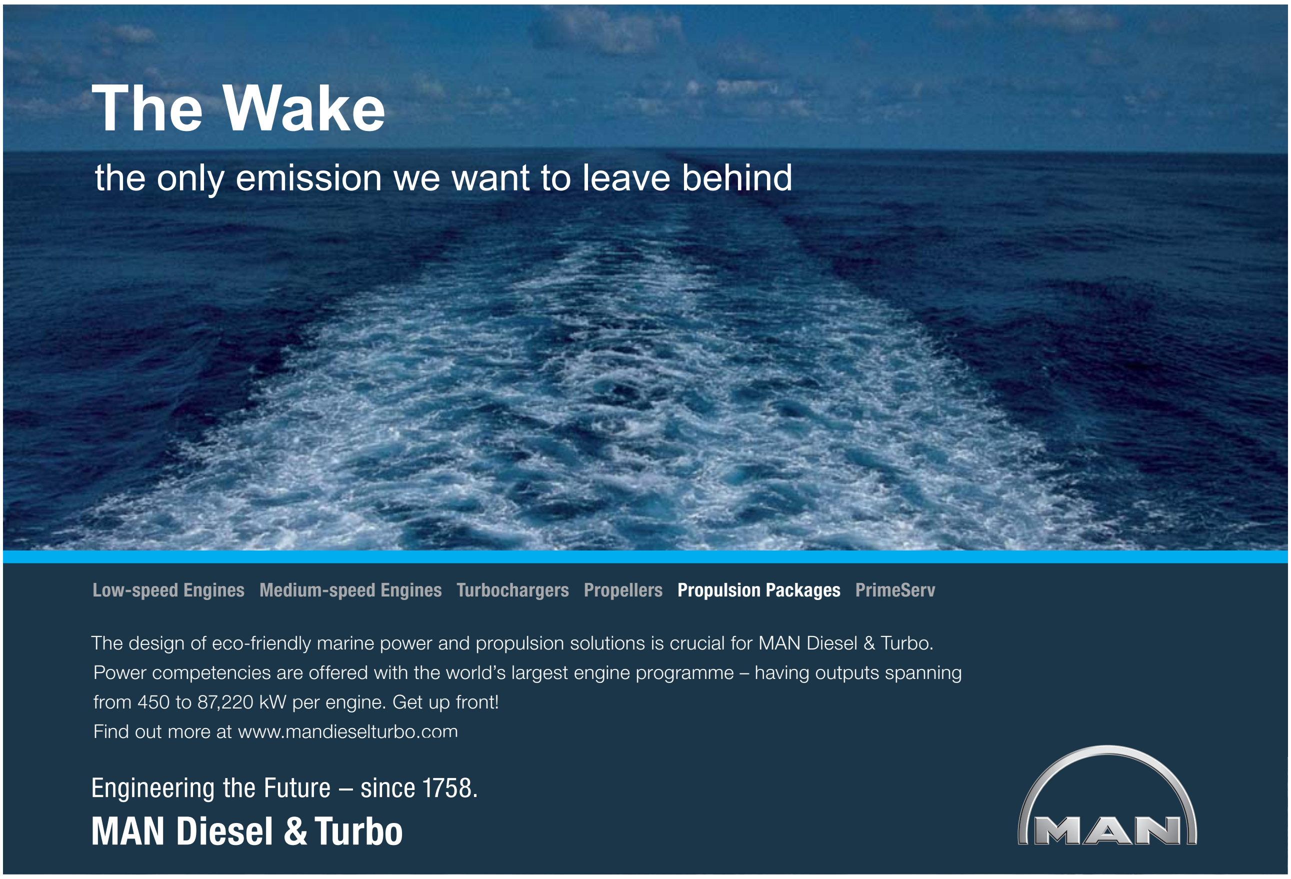
We can get Liquid/gas conversion from the calculators given below:





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Safety Data Sheets

Safety Data Sheets (SDS) include information on product ingredients, physical and chemical properties, potential effects on toxicology and ecology, identification of hazards, handling and storage instructions, as well as personnel protection recommendations and information related to transportation requirements, first-aid and emergency processes.

Major Hazards

Major hazard : High Pressure and Suffocation
Toxicity (Am. Conf. Of Gov. Ind. Hygienists ACGIH 2000 Edition) : Simple Asphyxiant
Flammability limits in air (STP conditions) : Non-flammable
Odour : None
UN Number : UN1066 (gas); UN1977 (liquid refrigerated)
EINECS Number : 231-783-9
DOT Label (USA) : NFG
DOT Hazard class (USA) : Non flammable Gas

Material compatibility

Air Liquide has assembled data on the compatibility of gases with materials to assist you in evaluating which products to use for a gas system. Although the information has been compiled from what Air Liquide believes are reliable sources (International Standards: Compatibility of cylinder and valve materials with gas content; Part 1: ISO 11114-1 (Jul 1998), Part 2: ISO 11114-2 (Mar 2001)), it must be used with extreme caution. No raw data such as this can cover all conditions of concentration, temperature, humidity, impurities and aeration. It is therefore recommended that this table is used to choose possible materials and then more extensive investigation and testing is carried out under the specific conditions of use. The collected data mainly concern high pressure applications at ambiant temperature and the safety aspect of material compatibity rather than the quality aspect.

Material	Compatibility
Metals	
Aluminium	Satisfactory
Brass	Satisfactory
Copper	Satisfactory
Ferritic Steels (e.g. Carbon steels)	Satisfactory
Stainless Steel	Satisfactory

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Plastics	
Polytetrafluoroethylene (PTFE)	Satisfactory
Polychlorotrifluoroethylene (PCTFE)	Satisfactory
Vinylidene polyfluoride (PVDF) (KYNAR™)	Satisfactory
Polyamide (PA) (NYLON™)	Satisfactory
Polypropylene (PP)	Satisfactory

Elastomers	
Buthyl (isobutene - isoprene) rubber (IIR)	Satisfactory
Nitrile rubber (NBR)	Satisfactory
Chloroprene (CR)	Satisfactory
Chlorofluorocarbons (FKM) (VITON™)	Satisfactory
Silicon (Q)	Satisfactory
Ethylene - Propylene (EPDM)	Satisfactory

Lubricants	
Hydrocarbon based lubricant	Satisfactory
Fluorocarbon based lubricant	Satisfactory

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You can also select the Units desired:

Selection of the units

You can choose the units in which the values are displayed. By default, SI units are selected.

Quantity	Units
Mass	kg lb g
Volume	m^3 ft^3 l
Pressure	bar psi kPa
Temperature	°C °F K °R
Density	kg/m^3 lb/ft^3 mol/l $(lb\text{-}mol)/ft^3$
Enthalpy	kJ/kg Btu/lb kJ/mol kcal/kg kcal/mol Btu/lb-mol
Heat Capacity	kJ/(mol.K) Btu/(lb.°F) kJ/(kg.K) Btu/(lb-mol.°F) kcal/(kg.K) cal/(mol.K) J/(mol.K)
Viscosity	Poise lb/(ft.s) µPa.s Pa.s
Thermal Conductivity	mW/(m.K) Btu.ft/(h.ft^2.°F) cal.cm/(h.cm^2.°C) W/(m.K) (cal.cm)/(s.cm^2.°C)
Concentration	vol % vol ppm vol/vol
Solubility	vol/vol lb/ft^3 $(lb\text{-}mol)/ft^3$ mol/l g/l
Specific volume	m^3/kg ft^3/lb l/mol ft^3/lb-mol

We can get similar data for other fluids, by selecting the desired fluid, as shown above.

Nitrogen, Oxygen, Argon, Neon, Krypton, and Xenon are extracted from Air by low temperature distillation/adsorption.

Hydrogen is produced by commercial processes, for ex. from natural gas by catalytic conversion or by cryogenic purification of gases produced in oil refining.

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Main source of **Helium** is natural gas where He4 content may be from 0.2% to as high as 1 or 2%. Helium is produced from natural gas in a sequence of purification steps.

Liquid Nitrogen (LN2): LN2 is a clear, colorless fluid. It is **p**roduced by distillation of liquid air, since atmospheric air contains about 79% (by volume) of nitrogen. LN2 boils at 77.4 K at atmospheric pressure. By varying the pressure over LN2, we can get temperatures from 62 K (at 128 mbar) to 126 K (at 33 bar). Density of LN2 is 800 g/litre at 77 K, slightly less than that of water. Latent heat of vaporization of LN2 is about 199 J/g, i.e. 1 Watt of heat input evaporates about 22.6 cm^3/h of LN2. Its thermal conductivity is about 1.38 mW/cm.K, and its viscosity is about 1500 micropoises. One litre of LN2 produces about 700 litres of gas at NTP. Main applications are: in food freezing and preservation of blood, bull semen, tissues etc. Also it is used as an inert atmosphere, in cooling applications for microelectronics, metallurgy, vacuum technology etc.

Liquid Oxygen (LOX): LOX has a characteristic blue color. LOX boils at 90.2 K at atmospheric pressure and freezes at 54.4 K (at 1.2 mbar). It is slightly magnetic while other cryogenic fluids are not. It is produced commercially by distillation of liquid air. Its density at 90 K is 1140 g/litre slightly larger than that of water. One Watt of heat input results in an evaporation of 15 cm^3/h of liquid. LOX reacts with hydrocarbons, so contact with oil, grease etc should be avoided. One litre of LOX produces about 700 litres of gas at NTP. Oxygen is toxic in concentrations of 60% at atmospheric pressure.

Application areas: steel mills, cutting, combustion furnaces, medical, space etc.

Liquid Argon: Obtained from liquid air by distillation, since is present in air at about 0.93% by volume. Liquid argon boils at 87.3 K at atmospheric pressure. Temp interval between its boiling and melting temperatures is only 3.44 K. By varying the pressure over liquid argon the range of temp obtainable is: 83.8 K (at 690 mbar) to 150.9 K (at 50 bar). Density of liquid argon is 1400 g/litre at 87 K. Argon is inert and non-toxic. Liquid argon is colorless and clear. Solid Argon sinks in liquid argon. One Watt of heat input results in an evaporation of 16 cm^3/h of liquid. One litre of liquid produces about 784 litres of gas at NTP. *Main application* is as an inert atmosphere in welding, micro-component industries etc.

Liquid Neon: It is also produced as a by-product in an air separation plant. It is a clear, colorless liquid which boils at 27.1 K at atmospheric pressure and freezes at 24.6 K, 1 atm. Neon is about 10 times more expensive than helium. Neon boils at a higher temp as compared to hydrogen, but it has the advantage that it is inert and has a higher heat of vaporization per unit volume as compared to hydrogen, making it an attractive refrigerant. By varying the pressure over liquid neon the range of temp obtainable is: 24.5 K (at 425 mbar) to 44.5 K (at 27.8 bar). Liquid density is 1210 g/litre at 27 K. One Watt of heat input results in an evaporation of 35 cm^3/h of liquid. One litre of liquid produces about 1350 litres of gas at NTP. *Main application* is in lighting, ex: advertisement signboards etc.

Liquid Fluorine: It is light yellow in color, possesses pungent odour, and has a normal boiling point of 85.4 K. It freezes in to a yellow solid at 53.6 K, 1 atm, and on sub-cooling to 45.6 K, it transforms in to a white solid. Liquid Fluorine is the densest of cryogenic liquids, its density at normal boiling point being 1510 g/litre. Fluorine is highly reactive. It reacts with almost all inorganic substances; even ceramic powders can burn in fluorine. If it comes in contact with hydrocarbons, it reacts hypergolically with a high heat of reaction and the metal container may even be ignited. Stainless steel and Monel are generally used in Fluorine systems. Fluorine is highly toxic. For an exposure time of 1 h, fluorine is fatal in concentration of 200 ppm. Max. permissible concentration for human exposure is approximately 1 ppm-hr. One Watt of heat input results in an evaporation of 13.75 cm^3/h of liquid.

Main applications [11]: In Industry, Uranium hexafluoride (UF_6) is produced by direct fluorination of uranium oxide or UF_4 using fluorine. Sulfur hexafluoride (SF_6) or sodium fluoride are produced from fluorine. Also, as a rocket fuel, it has high specific impulse.

Liquid Hydrogen: Hydrogen is produced by many commercial processes. The most economical process is the one that involves catalytic conversion of hydrocarbons (such as: methane, propane, butane and others) present in natural gas or casing-head gases by water/steam. Tonnage production is from gases produced in oil refining using cryogenic techniques. Small scale production of hydrogen may be done by water electrolysis; however, this process is quite expensive production of 1 kg of hydrogen may require up to 60 or 70 kWh.

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Hydrogen is the lightest of gases and is used in balloons! Under atm pressure, it boils at 20.2 K. By varying the pressure over liquid hydrogen, the range of temp obtainable is: 13.8 K (at 70 mbar) to 33 K (at 12.7 bar). It is also the lightest liquid, with a density of 70 g/lit at 20 K, and is used in rockets as a fuel. Heat of evaporation of LH2 is about 445 J/g, and 1 Watt of heat input evaporates about 115 cm^3 of liquid per hour. One litre of liquid, on evaporation, produces about 780 litres of gas at NTP.

Main application of hydrogen is as a rocket fuel. Also, it is used in high energy physics, hydrogen bubble chambers, nuclear applications, industry, chemistry etc.

Hydrogen exists in two molecular states: ortho and para. In ortho-hydrogen (o-H2), spin vectors are in the same direction and in para-hydrogen (p-H2), the spin vectors are in parallel direction. Equilibrium percentage of o_h2 and p-H2 varies with temp as follows:

T (K)	20.39	30	40	70	120	200	250	300
% p-H2 in equilib. hydrogen	99.8	97.02	88.73	55.88	32.96	25.97	25.26	25.07

Note that at room temp hydrogen is a mixture of 75% ortho and 25% parahydrogen. This is known as normal-hydrogen. As temp comes down, % of parahydrogen increases. At equilibrium, liquid hydrogen contains 99.8% parahydrogen and 0.2% orthohydrogen, and may be treated as parahydrogen for all practical purposes.

Ortho-para conversion is an exothermic process. And, this conversion process is very slow in liquid state and can occur in gaseous state only in the presence of a catalyst.In liquid staste, heat of conversion is about 706 J/g, which is more than the heat of evaporation of LH2 (i.e. 447 J/g). Therefore, if LH2 is stored in a dewar without converting it from ortho to para during the liquefaction, there will be very high evaporation losses! And, it is customary to adopt ortho-para conversion using a catalyst during the liquefaction process itself. Solid catalysts used are: activated carbon, metal oxides, hydroxides of iron, nickel, chromium or manganese.

Hydrogen burns in the presence of oxygen or air and the flame propagates at a very high speed of about 2.7 m/s. Further, hydrogen ignites in air at atmospheric pressure over a wide range of concentrations, i.e. in the range 4% to 75% of hydrogen (by volume). Therefore, while handling hydrogen, attention should be given to both the fire and explosion hazards.

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Main applications of hydrogen from Ref.[11]:

Industries	Applications
Food and Beverage	Pure hydrogen is used for the production of plastics, polyester and nylon. H_2 gas is also used in the hydrogenation of amines and fatty acids (food oils).
Glass, Cement and Lime	Hydrogen is an active gas used in combination with nitrogen to create a reductive atmosphere over the tin bath in the FLOAT glass process. Hydrogen is used for heat treatment (oxy-hydrogen flame) of the hollow glass and the optic fibers pre-forms.
Metals industry	Reductive atmosphere for various processes of heat treatment.

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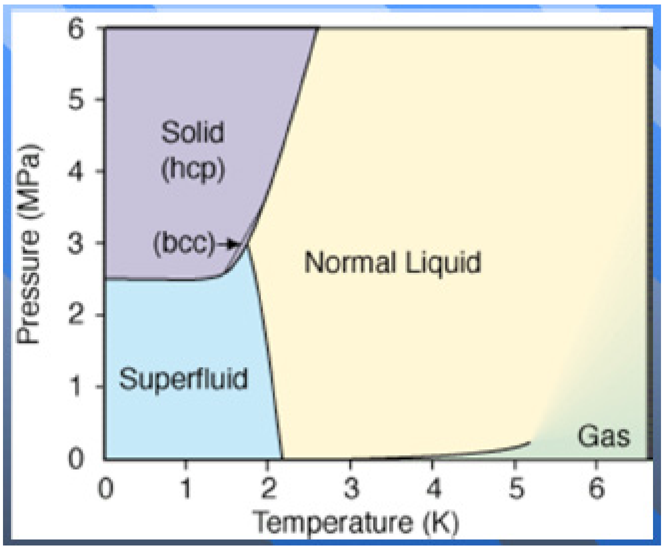
Laboratories & analysis	Hydrogen is used as a carrier gas in gas chromatography and in various analytical instrument applications, most commonly as a fuel component of combustion gases for Flame Ionization (FID) and Flame Photometric (FPD) detectors. Spark discharge analyzers, total hydrocarbons measurements use also hydrogen mixtures.
Welding, Cutting & Coating	Heat treatment of various metals
Oil and Gas	Desulfurization of fuel-oil and gasoline
Electronics	Hydrogen is used as carrier gas in semiconductor processes, especially for silicon deposition or crystal growing and as a scavenger gas in atmosphere soldering as well as for annealing copper films. The use of forming gases (that is H_2 diluted in nitrogen) allows virtually a complete elimination of oxygen and its inconveniences in medium to high temperature processes.
Space and Aeronautics	Hydrogen is used in their liquid states as ergols for the propulsion of the cryogenic stages of the Ariane rocket.
Automotive & transportation	Hydrogen is a carbon-free energy source used in the fuel cells.

Liquid Helium [1,7,10]: Helium is a very special fluid. It does not freeze under its own vapor pressure. To freeze liquid helium, at absolute zero temp, we have to apply a pressure of about 2.5 MPa over the liquid! See the phase diagram below:



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Helium has two stable isotopes: He4 and He3. He4 is more abundant and He3 is rare, and therefore more expensive. He4 is generally separated from Natural gas where the concentration of He4 may be 0.1 to 0.5%. Helium is mainly obtained from Natural gas wells located in USA, Poland, Russia and Algeria. World consumption of He4 is about 35 million m^3/year. Main applications are in: balloons, diving, inert atmosphere, welding, leak detection, pressurization in rockets, nuclear engineering etc.

Liquid helium boils at 4.216 K at atmospheric pressure. By varying pressure over liquid helium temperature range obtainable is: 0.1 K (at 0.1 mbar) to 5.2 K (at 2.26 bar). It is a very light liquid, density being about 125 g/litre at 4.2 K, i.e. about one-eighth that of water. It has very low latent heat of evaporation (= 20.9 J/g). One Watt of heat input results in an evaporation of 1.4 lit/hour of liquid. And, evaporation of 1 litre of liquid results in 750 litres of gas at NTP.

Helium-4 vapors are quite dense; vapor at 4.2 K weighs 17 g/litre. As a consequence, 100 litres of vapor at 4.2 K is equivalent to 10 m^3 of gas at NTP.

Also, enthalpy of vapor is quite large: as an example, to cool 1 kg of copper from 300 K to 4.2 K, we need 30 litres of helium without using the enthalpy of vapor, whereas if we use the vapor enthalpy also, we will need only 0.4 litres of helium.

If we pre-cool the copper with liquid nitrogen to 77 K, then to cool 1 kg of copper from 77 K to 4.2 K we will need about 0.5 litres of liquid helium without using the enthalpy of vapor, and 0.2 litres of liquid helium using the vapor enthalpy.

Main applications of helium are [11]:

Industries	Applications
Laboratories & analysis	Helium is the most commonly gas used as carrier in gas chromatography. Under liquid state, at -269 °C, helium is the cooling fluid for the MRI, NMR or EPR magnets.
Space and Aeronautics	The oxygen tank of new-generation Ariane 5 launch vehicle is pressurized by a liquid helium subsystem.
Other industries	- Balloon inflation - leak detection - because the boiling point of helium is close (-269 °C or -452 °F) to the absolute zero (-273 °C) He is used for cooling of superconducting magnets - used in helium neon lasers, helium is a component of the special mixtures used in CO_2 lasers (§ LASAL™). - blanket gas to exclude air from certain fabrication processes. - helium is used as a heat transfer material.

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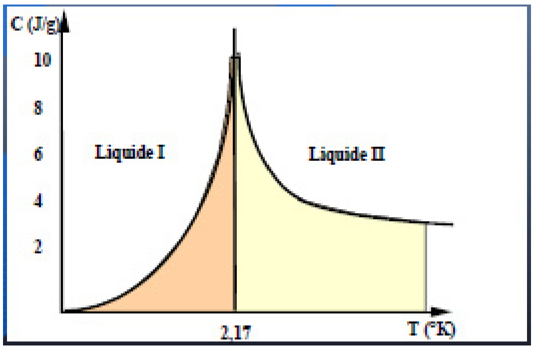
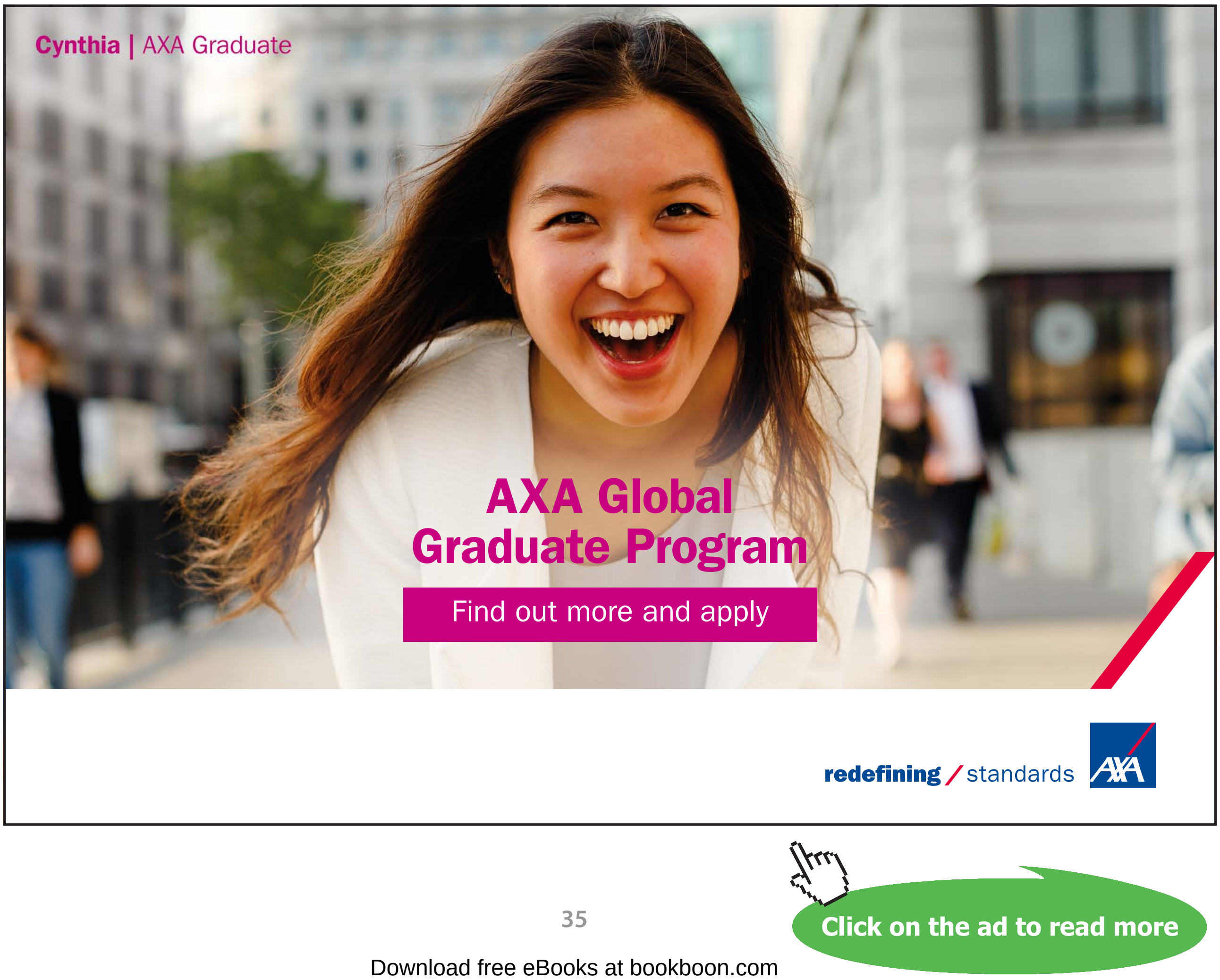
Helium, which is a rare gas, is the most difficult gas to liquefy. See from the phase diagram above that there is no triple point for helium as for other fluids. Instead, **there are two different liquid phases**: Helium-I (i.e. *normal* liquid) and Helium-II, i.e. the *superfluid*. The two liquid phases are separated by the Lambda line, which occurs at 'Lambda point' temperature of 2.17 K and a pressure of 50 mbar.

Several properties undergo drastic changes at lambda point temp:

Specific heat: At 4.2 K the sp. heat value is about 4.18 J/g.K, and as the temp is decreased from 4.2 K, the sp. heat goes on increasing up to the lambda point and reaches a value of about 8 J/g.K, and then decreases, as shown below:





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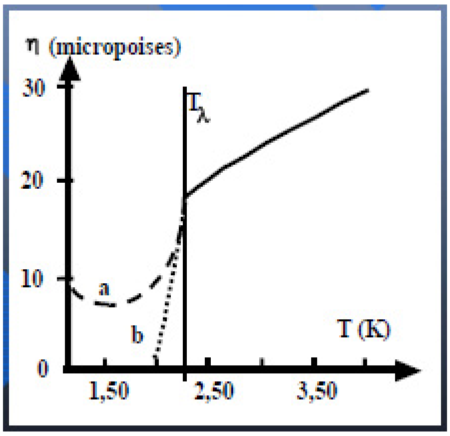
Note that the sp. heat curve resembles the shape of greek letter lambda.

Thermal conductivity: LHe-I is like an insulator! Its thermal conductivity is about 0.27 mW/cm.K whereas the thermal conductivity of LHe-II is very large, i.e. about 8000 W/cm.K at 1.9 K, i.e about 1000 times better than that of copper! As a result, there is no temperature stratification or presence of bubbles in a superfluid helium bath.

Large thermal conductivity and specific heats of Helium-II find applications in cooling of superconducting magnets.

Viscosity: Helium-II or superfluid helium behaves as if it has zero viscosity! Helium-I (i.e. above lambda point temperature of 2.17 K) has a small viscosity of about 30 micropoises. Helium-II, i.e. below the lambda point temperature, the viscosity of He-II depends on the method used for measurement of viscosity: (a) by damping of disc oscillations in the liquid, the viscosity is above 5 micropoises, and (b) by measurement of flow in narrow slits (10^{-3} Angstroms to 10^{-4} mm), the viscosity is lower than 0.001 micropoises. This is shown below:



This behavior is explained by the two-fluid model of Tisza:

As per the two fluid model, the liquid He-II is imagined to be a mixture of two fluids: the normal fluid and the superfluid; and, the superfluid possesses zero entropy and can move past other fluids and solid boundaries with zero friction. With this model, liquid He-II has a composition of normal and superfluid that varies with temperature, the liquid composition being 100% superfluid at absolute zero temp and at the lambda point the liquid composition is 100% normal fluid.

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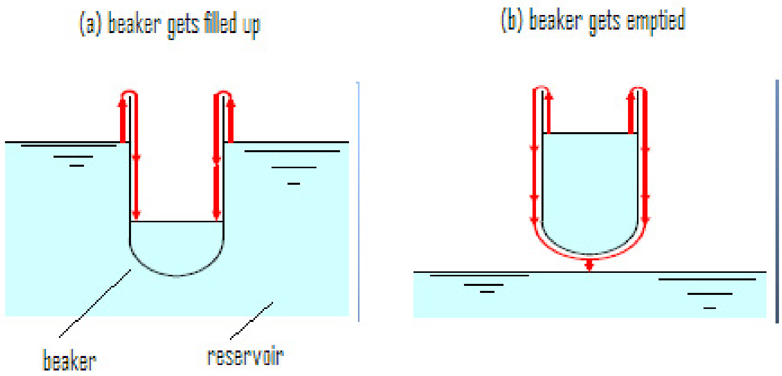
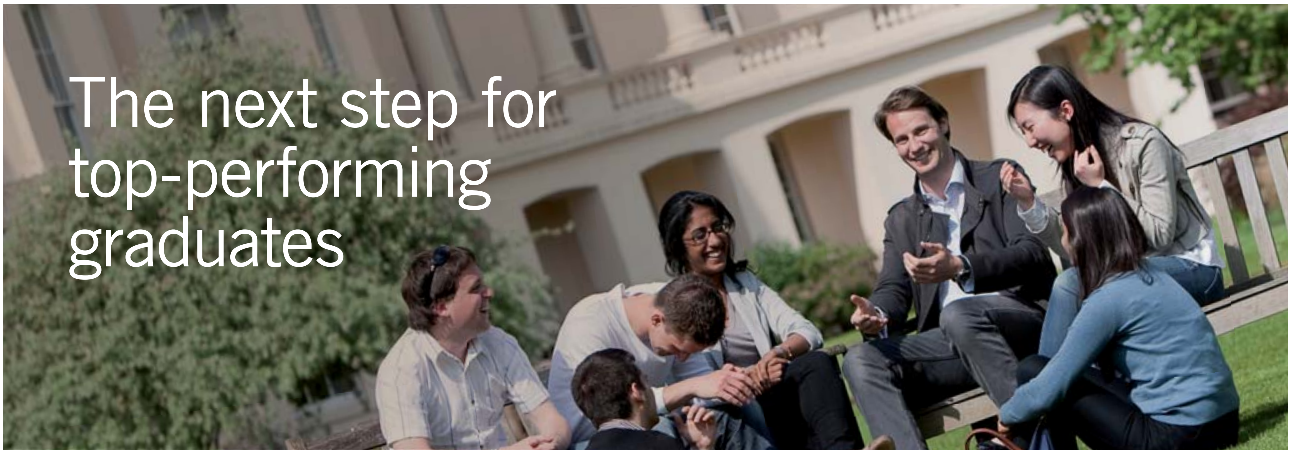
Two interesting phenomena observed with liquid He-II are:

a) **Rollin film:**

Here, levels of superfluids in two reservoirs, separated by a solid boundary, tend to equalize with the superfluid creeping in a thin film (30 nm) along the solid boundary. This effect, known as 'mechano-caloric effect' is shown below:



Displacement velocity may be 25 cm/s. The film flows from cold to hot places, and evaporates at the lambda temp. Thus, the creeping film climbs along the neck of cryostats and along the pumping lines! So, it is essential to have film-burners or diaphragms at temperatures less than 1 K.



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* Figures taken from London Business School's Masters in Management 2010 employment report

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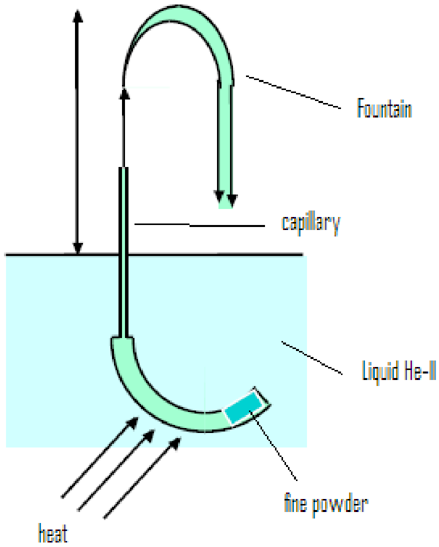
b) **Fountain effect or thermo-mechanical effect:**

As shown below, a U-tube is filled with a fine powder (alumina) and when heat is applied to the U-tube, *superfluid flows towards the hot point* and the normal fluid is pushed out through the capillary in a fountain. Height of the fountain may reach even one metre!

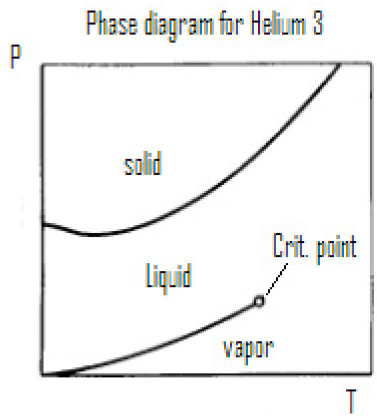


Helium-3 [1,7,10]:

Helium -3 is generally produced in nuclear reactions and is therefore very expensive. Normal boiling point of He-3 is 3.2 K and density of liquid at the normal boiling point is 0.05895 g/cm^3. Heat of vaporization at the normal boiling point is 8.49 J/g. Range of temp available by varying the pressure over He-3 is 0.3 K at 0.001 mbar to 3.33 K at 1.16 bar.

One Watt of heat input evaporates about 3 litres/hour of liquid helium 3. And, one litre of liquid produces about 460 litres of gas at NTP. Density of He-3 at 300 K is about 59 g/lit.

As in the case of liquid He-4, liquid He-3 remains in the liquid state under its own vapor pressure down to absolute zero temp. He-3 must be compressed to 29.3 atm at 0.32 K (the min. point in the freezing curve, see the fig. below) before it will solidify.



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Some properties of He-3 are summarized below [6]:

Normal boiling point (K)	3.191
Critical constants	
T_c (K)	3.324
p_c (MPa)	0.115
ρ_c (kg/m^3)	41.3
Density at 0 K (kg/m^3)	82.3
Compressibility at 0 K (mm^3/J)	361
Heat of vaporization at 0 K (J/mol)	20.56
Surface tension at 0 K (mJ/m^2)	0.16
Velocity of sound at 0 K (m/s)	183
Thermal conductivity at 3.2 K (W/mK)	0.020
Viscosity at 3.2 K (μPa s)	1.9
Magnetic moment (nuclear magnetons)	−2.127
Vapor pressure at 1.7 K (kPa)	10.9
Specific heat at 1.0 K(J/mol · K)	4.222
Superfluid transition (mK)	2.6

An important application of He3 is to *continuously* produce a temp of a few milli-Kelvin in **'dilution refrigerators'** where a mixture of He4 and He3 is used. This topic will be discussed further in the chapter on Cryogenic Refrigeration.

Other applications of He3 are in medical imaging and in neutron detectors.

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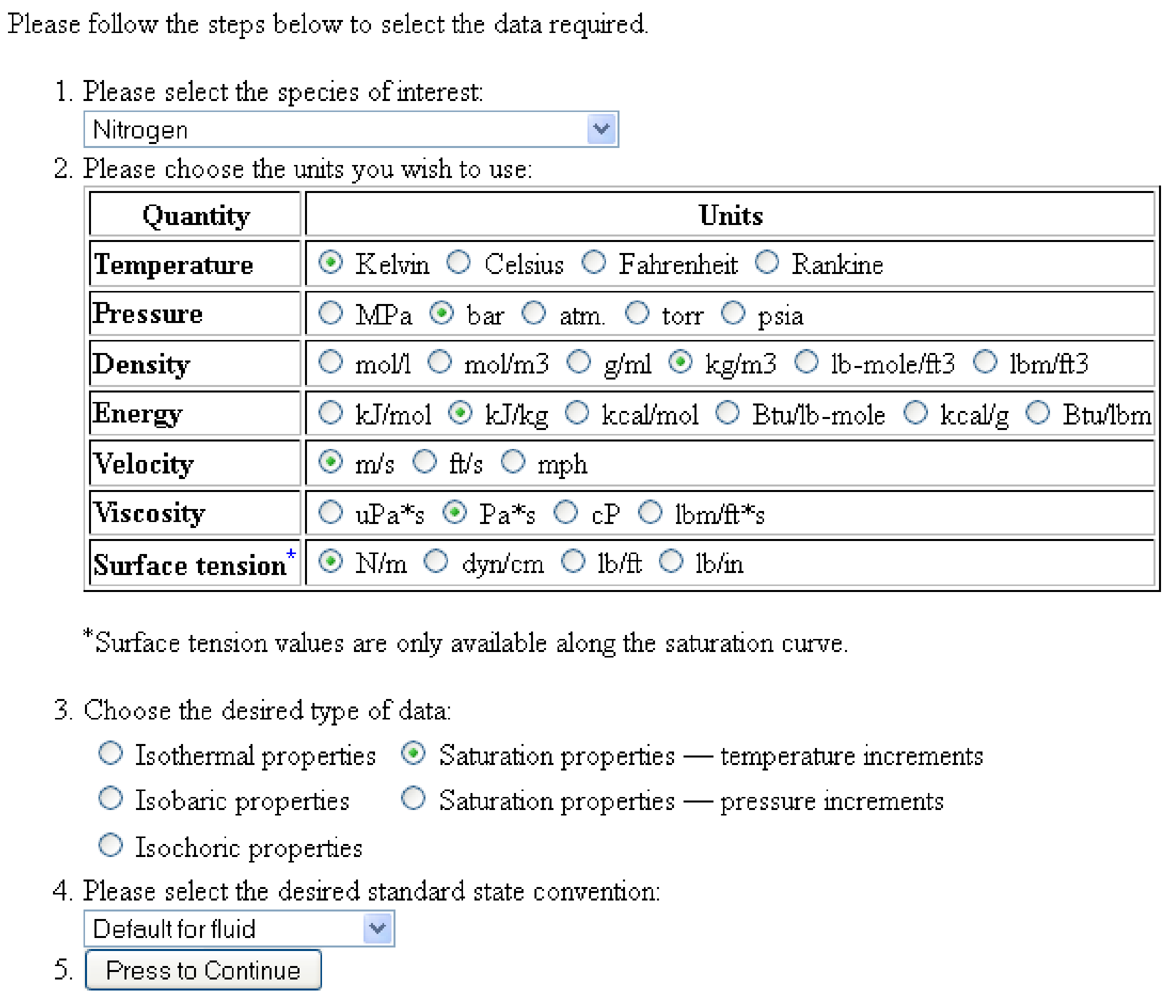
1.3 Data for Cryogenic Fluids – Saturation properties [9]:

1.3.1 Data for Nitrogen:

As you go to Ref.[9], i.e. http://webbook.nist.gov/chemistry/fluid/, you get:



Please follow the steps below to select the data required.

1. Please select the species of interest:
   Nitrogen
2. Please choose the units you wish to use:

Quantity	Units
Temperature	Kelvin / Celsius / Fahrenheit / Rankine
Pressure	MPa / bar / atm. / torr / psia
Density	mol/l / mol/m3 / g/ml / kg/m3 / lb-mole/ft3 / lbm/ft3
Energy	kJ/mol / kJ/kg / kcal/mol / Btu/lb-mole / kcal/g / Btu/lbm
Velocity	m/s / ft/s / mph
Viscosity	uPa*s / Pa*s / cP / lbm/ft*s
Surface tension*	N/m / dyn/cm / lb/ft / lb/in

*Surface tension values are only available along the saturation curve.

3. Choose the desired type of data:
   Isothermal properties / Saturation properties — temperature increments
   Isobaric properties / Saturation properties — pressure increments
   Isochoric properties
4. Please select the desired standard state convention:
   Default for fluid
5. Press to Continue

In the above, note that:

i. Under item 1, you can choose the desired species
ii. Under item 2, you select the Units in which you want the data
iii. Under item 3, choose the desired type of data

Now, observe that we have chosen Nitrogen for the fluid, and we have also chosen Units for various quantities by selecting the appropriate radio buttons, and under item 3, note that we have chosen 'Saturation properties – temp increments'.

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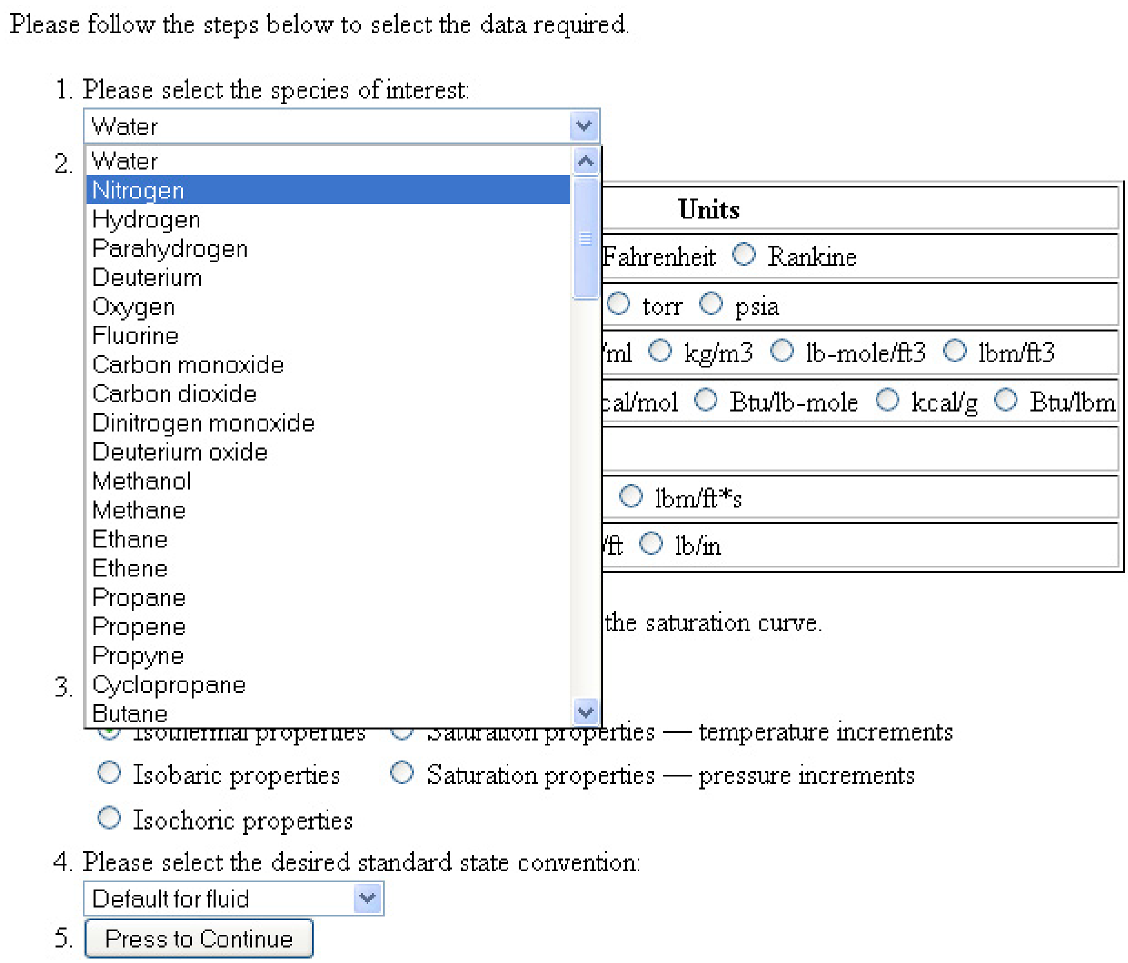
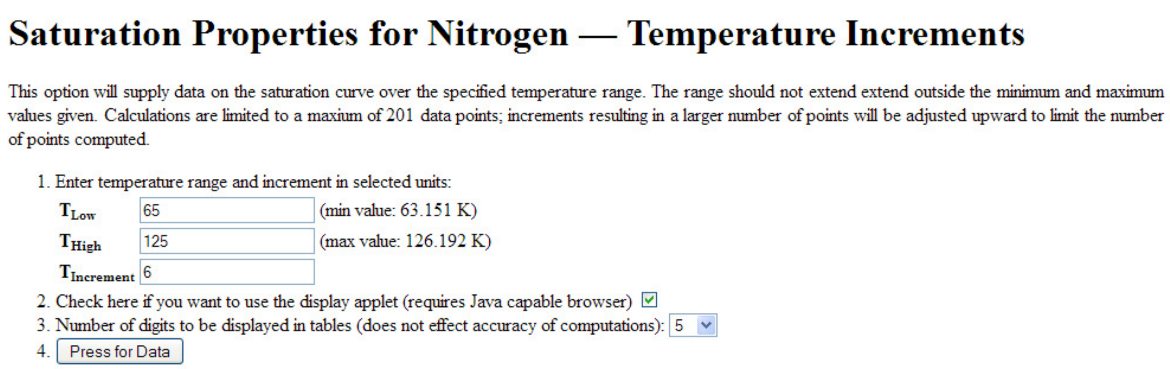
There is a large selection of fluids possible under item 1, as shown below:



Now, click on 'Press to continue' and we get:



In the above, we have chosen the low and high temp limits and the temp increment.

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Now, click 'Press for Data'. We get:

Saturation Properties for Nitrogen — Temperature Increments

- Fluid Data
- Auxiliary Data
- References
- Additional Information
- Important Information About This Data
- Notes
- **Other Data Available:**
  - View data in HTML table.
  - Download data as a tab-delimited text file.
  - Main NIST Chemistry WebBook page for this species.
  - Recommended citation for data from this page.
  - Fluid data for other species

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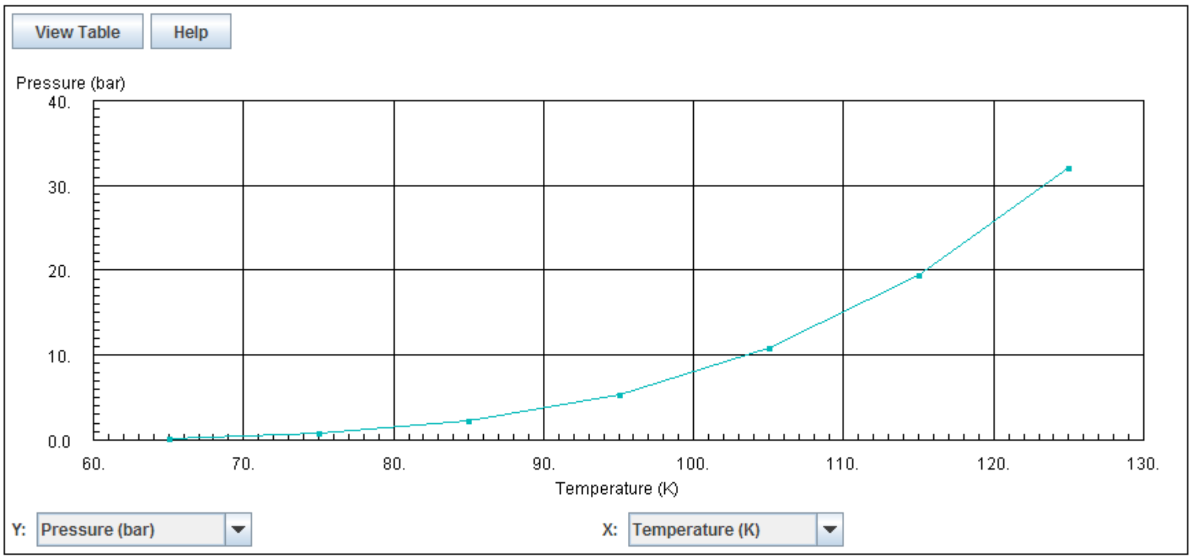

If we click on **'View Data in HTML Table'**, we get:

Vapor Phase Data							
Data on Saturation Curve							
Temperature (K)	**Pressure (bar)**	**Density (kg/m3)**	**Volume (m3/kg)**	**Internal Energy (kJ/kg)**	**Enthalpy (kJ/kg**	**Entropy (J/g*K)**	**Cv (J/g*K)**
65	0.17404	0.91308	1.0952	47.474	66.536	5.769	0.75174
71	0.44527	2.1647	0.46196	51.402	71.972	5.5751	0.75956
77	0.97152	4.4367	0.22539	54.989	76.887	5.4174	0.77052
83	1.878	8.168	0.12243	58.129	81.121	5.2853	0.78513
89	3.3055	13.888	0.072005	60.702	84.503	5.1706	0.80417
95	5.4052	22.272	0.0449	62.559	86.828	5.0672	0.82877
101	8.3358	34.264	0.029186	63.497	87.825	4.9698	0.86077
107	12.264	51.351	0.019474	63.196	87.079	4.8729	0.90257
113	17.371	76.307	0.013105	61.049	83.813	4.7692	0.96113
119	23.869	115.89	0.0086288	55.586	76.182	4.6439	1.0708
125	32.069	205.18	0.0048737	39.404	55.034	4.4263	1.4021

Cp (J/g*K)	**Sound Spd. (m/s)**	**Joule-Thomson (K/bar**	**Viscosity (Pa*s)**	**Therm. Cond. (W/m*K)**	**Phase**	**Temperature (K)**
1.0633	163.2	3.8268	4.51E-06	0.0063374	vapor	65
1.0862	169.39	3.1922	4.95E-06	0.0068898	vapor	71
1.1214	174.55	2.7328	5.41E-06	0.0074688	vapor	77
1.1735	178.6	2.3884	5.88E-06	0.0081137	vapor	83
1.2497	181.43	2.1212	6.37E-06	0.0088772	vapor	89
1.3628	182.99	1.9057	6.91E-06	0.0098408	vapor	95
1.5379	183.18	1.7236	7.50E-06	0.011142	vapor	101
1.8304	181.93	1.56	8.18E-06	0.013035	vapor	107
2.4073	179.15	1.3996	9.04E-06	0.016066	vapor	113
4.0381	173.87	1.2045	1.03E-05	0.0219	vapor	119
23.743	160.26	0.8603	1.35E-05	0.04504	vapor	125

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Liquid Phase Data							
Data on Saturation Curve							
Temperature (K)	Pressure (bar)	Density (kg/m3)	Volume (m3/kg)	Internal Energy (kJ/kg)	Enthalpy (kJ/kg	Entropy (J/g*K)	Cv (J/g*K)
65	0.17404	859.6	0.0011633	-147.05	-147.03	2.4834	1.1634
71	0.44527	834.21	0.0011987	-135	-134.95	2.6607	1.1231
77	0.97152	807.69	0.0012381	-122.87	-122.75	2.8248	1.0861
83	1.878	779.8	0.0012824	-110.59	-110.35	2.9784	1.053
89	3.3055	750.16	0.001333	-98.107	-97.667	3.1237	1.024
95	5.4052	718.26	0.0013922	-85.324	-84.571	3.263	0.99956
101	8.3358	683.25	0.0014636	-72.094	-70.874	3.3985	0.98039
107	12.264	643.7	0.0015535	-58.181	-56.276	3.5332	0.96856
113	17.371	596.85	0.0016755	-43.143	-40.232	3.6715	0.96914
119	23.869	536.02	0.0018656	-25.929	-21.476	3.8232	0.99885
125	32.069	426.08	0.002347	-1.1236	6.4029	4.0373	1.238

Cp (J/g*K)	Sound Spd. (m/s)	Joule-Thomson (K/bar	Viscosity (Pa*s)	Therm. Cond. (W/m*K)	Surf. Tension (N/m)	Phase	Temperature (K)
2.0034	976.36	-0.039833	0.00028011	0.17315	0.011789	liquid	65
2.0173	915.66	-0.037508	0.00021011	0.15962	0.010353	liquid	71
2.0398	855	-0.034334	0.00016294	0.14657	0.0089561	liquid	77
2.0751	793.36	-0.029951	0.00012993	0.13402	0.0076032	liquid	83
2.1292	729.84	-0.023813	0.0001059	0.12188	0.0062983	liquid	89
2.2126	663.5	-0.015025	8.77E-05	0.11009	0.0050469	liquid	95
2.3447	593.17	-0.00201	7.32E-05	0.098609	0.0038567	liquid	101
2.5679	517.24	0.018288	6.10E-05	0.087361	0.0027383	liquid	107
2.9973	433.19	0.052741	5.03E-05	0.076225	0.001708	liquid	113
4.1164	335.85	0.12154	4.00E-05	0.065124	0.00079579	liquid	119
16.717	195.48	0.35308	2.73E-05	0.059228	8.28E-05	liquid	125

Also, in the above plot, if we click on 'View Table', we get:

View Table:

View XY Plot

Temperature (K)	Pressure (bar)	Density (kg/m3)	Volume (m3/kg)	Phase
65.000	0.17404	undefined	undefined	liquid and vapor
65.000	0.17404	859.60	0.0011633	liquid
65.000	0.17404	0.91308	1.0952	vapor
75.000	0.76043	undefined	undefined	liquid and vapor
75.000	0.76043	816.67	0.0012245	liquid
75.000	0.76043	3.5404	0.28245	vapor
85.000	2.2886	undefined	undefined	liquid and vapor
85.000	2.2886	770.13	0.0012985	liquid
85.000	2.2886	9.8241	0.10179	vapor
95.000	5.4052	undefined	undefined	liquid and vapor
95.000	5.4052	718.26	0.0013922	liquid
95.000	5.4052	22.272	0.044900	vapor
105.00	10.833	undefined	undefined	liquid and vapor
105.00	10.833	657.52	0.0015209	liquid
105.00	10.833	44.959	0.022243	vapor
115.00	19.370	undefined	undefined	liquid and vapor
115.00	19.370	578.70	0.0017280	liquid
115.00	19.370	87.294	0.011456	vapor
125.00	32.069	undefined	undefined	liquid and vapor
125.00	32.069	426.08	0.0023470	liquid
125.00	32.069	205.18	0.0048737	vapor

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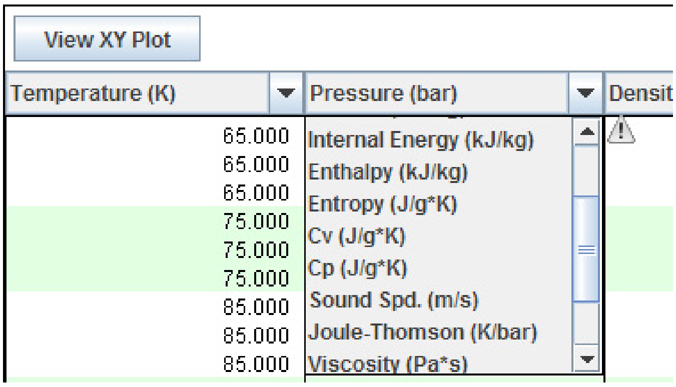
Other parameters can be obtained from the pull down menu as shown below:



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View XY Plot

Temperature (K)	Internal Energy (kJ/kg)	Enthalpy (kJ/kg)	Entropy (J/g*K)	Phase
65.000	undefined	undefined	undefined	liquid and vapor
65.000	-147.05	-147.03	2.4834	liquid
65.000	47.474	66.536	5.7690	vapor
75.000	undefined	undefined	undefined	liquid and vapor
75.000	-126.92	-126.83	2.7714	liquid
75.000	53.838	75.316	5.4667	vapor
85.000	undefined	undefined	undefined	liquid and vapor
85.000	-106.46	-106.16	3.0277	liquid
85.000	59.056	82.352	5.2454	vapor
95.000	undefined	undefined	undefined	liquid and vapor
95.000	-85.324	-84.571	3.2630	liquid
95.000	62.559	86.828	5.0672	vapor
105.00	undefined	undefined	undefined	liquid and vapor
105.00	-62.915	-61.268	3.4882	liquid
105.00	63.462	87.557	4.9055	vapor
115.00	undefined	undefined	undefined	liquid and vapor
115.00	-37.736	-34.389	3.7198	liquid
115.00	59.721	81.911	4.7311	vapor
125.00	undefined	undefined	undefined	liquid and vapor
125.00	-1.1236	6.4029	4.0373	liquid
125.00	39.404	55.034	4.4263	vapor

View XY Plot

Temperature (K)	Cv (J/g*K)	Cp (J/g*K)	Sound Spd. (m/s)	Phase
65.000	undefined	undefined	undefined	liquid and vapor
65.000	1.1634	2.0034	976.36	liquid
65.000	0.75174	1.0633	163.20	vapor
75.000	undefined	undefined	undefined	liquid and vapor
75.000	1.0981	2.0311	875.28	liquid
75.000	0.76649	1.1080	172.95	vapor
85.000	undefined	undefined	undefined	liquid and vapor
85.000	1.0429	2.0906	772.44	liquid
85.000	0.79094	1.1957	179.68	vapor
95.000	undefined	undefined	undefined	liquid and vapor
95.000	0.99956	2.2126	663.50	liquid
95.000	0.82877	1.3628	182.99	vapor
105.00	undefined	undefined	undefined	liquid and vapor
105.00	0.97148	2.4789	543.30	liquid
105.00	0.88744	1.7139	182.51	vapor
115.00	undefined	undefined	undefined	liquid and vapor
115.00	0.97416	3.2403	402.67	liquid
115.00	0.98957	2.7490	177.75	vapor
125.00	undefined	undefined	undefined	liquid and vapor
125.00	1.2380	16.717	195.48	liquid
125.00	1.4021	23.743	160.26	vapor

View XY Plot

Temperature (K)	Joule-Thomson (K/bar)	Viscosity (Pa*s)	Therm. Cond. (W/m*K)	Phase
65.000	undefined	undefined	undefined	liquid and vapor
65.000	-0.039833	0.00028011	0.17315	liquid
65.000	3.8268	4.5084e-06	0.0063374	vapor
75.000	undefined	undefined	undefined	liquid and vapor
75.000	-0.035506	0.00017675	0.15087	liquid
75.000	2.8707	5.2557e-06	0.0072706	vapor
85.000	undefined	undefined	undefined	liquid and vapor
85.000	-0.028135	0.00012111	0.12993	liquid
85.000	2.2923	6.0405e-06	0.0083518	vapor
95.000	undefined	undefined	undefined	liquid and vapor
95.000	-0.015025	8.7656e-05	0.11009	liquid
95.000	1.9057	6.9056e-06	0.0098408	vapor
105.00	undefined	undefined	undefined	liquid and vapor
105.00	0.010414	6.4882e-05	0.091091	liquid
105.00	1.6132	7.9386e-06	0.012314	vapor
115.00	undefined	undefined	undefined	liquid and vapor
115.00	0.069974	4.6895e-05	0.072515	liquid
115.00	1.3409	9.4010e-06	0.017541	vapor
125.00	undefined	undefined	undefined	liquid and vapor
125.00	0.35308	2.7250e-05	0.059228	liquid
125.00	0.86030	1.3460e-05	0.045040	vapor

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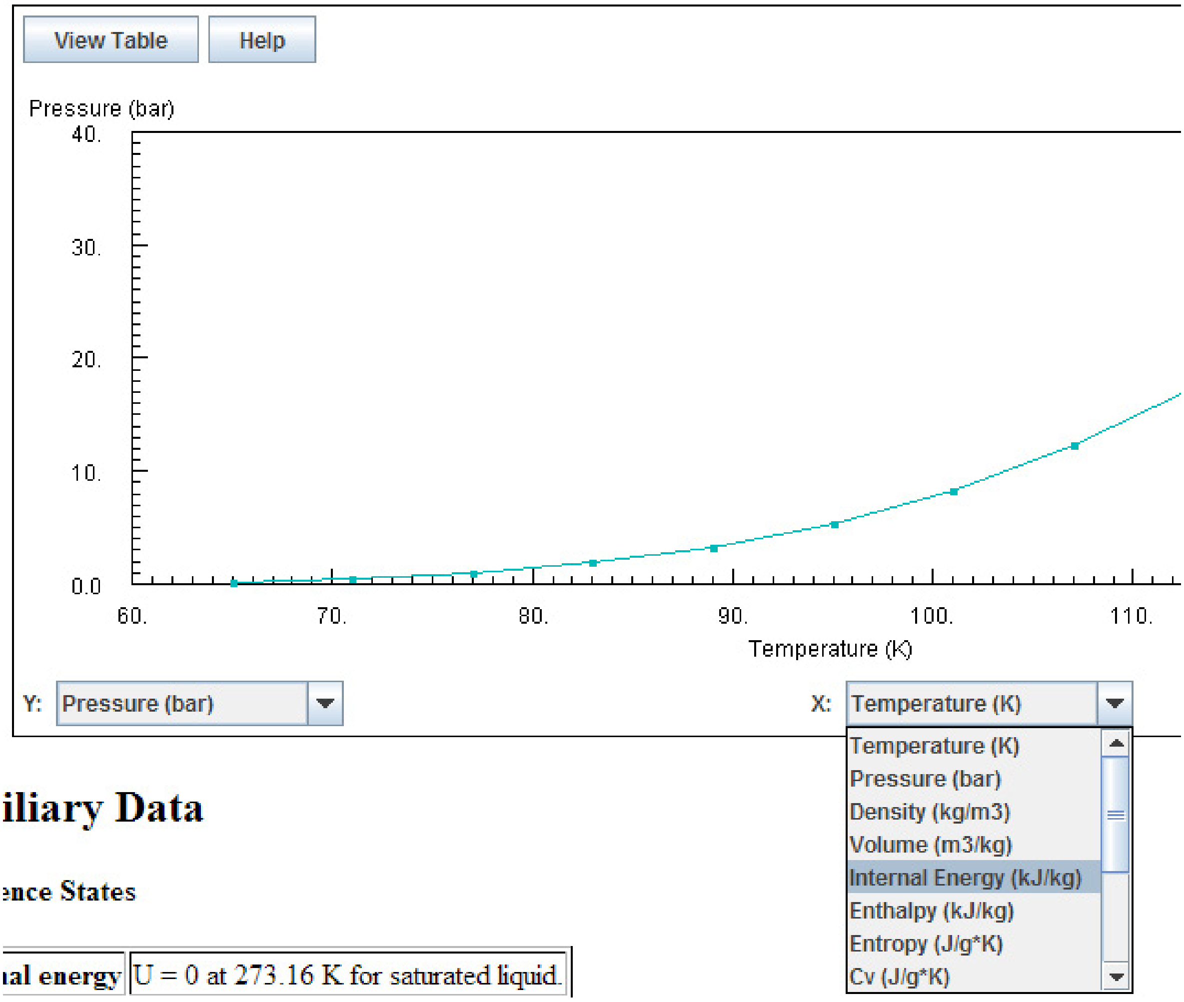
View XY Plot

Temperature (K)	Joule-Thomson (K/bar)	Viscosity (Pa*s)	Surf. Tension (N/m)	Phase
65.000	undefined	undefined	undefined	liquid and vapor
65.000	-0.039833	0.00028011	0.011789	liquid
65.000	3.8268	4.5084e-06	undefined	vapor
75.000	undefined	undefined	undefined	liquid and vapor
75.000	-0.035506	0.00017675	0.0094170	liquid
75.000	2.8707	5.2557e-06	undefined	vapor
85.000	undefined	undefined	undefined	liquid and vapor
85.000	-0.028135	0.00012111	0.0071627	liquid
85.000	2.2923	6.0405e-06	undefined	vapor
95.000	undefined	undefined	undefined	liquid and vapor
95.000	-0.015025	8.7656e-05	0.0050469	liquid
95.000	1.9057	6.9056e-06	undefined	vapor
105.00	undefined	undefined	undefined	liquid and vapor
105.00	0.010414	6.4882e-05	0.0031022	liquid
105.00	1.6132	7.9386e-06	undefined	vapor
115.00	undefined	undefined	undefined	liquid and vapor
115.00	0.069974	4.6895e-05	0.0013887	liquid
115.00	1.3409	9.4010e-06	undefined	vapor
125.00	undefined	undefined	undefined	liquid and vapor
125.00	0.35308	2.7250e-05	8.2805e-05	liquid
125.00	0.86030	1.3460e-05	undefined	vapor

Similarly other plots are possible by selecting different X-axis and Y-axis parameters:



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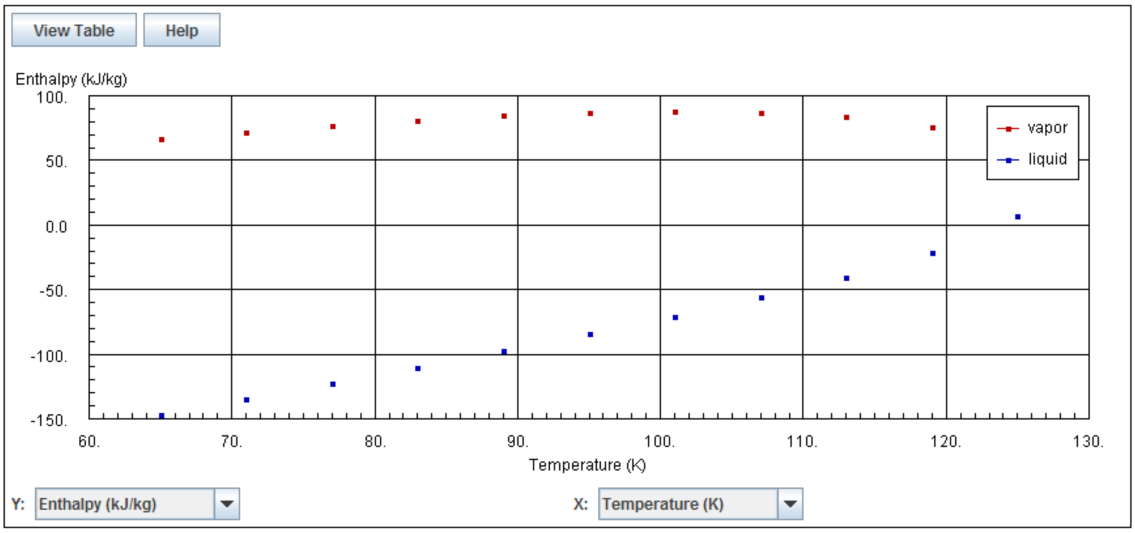
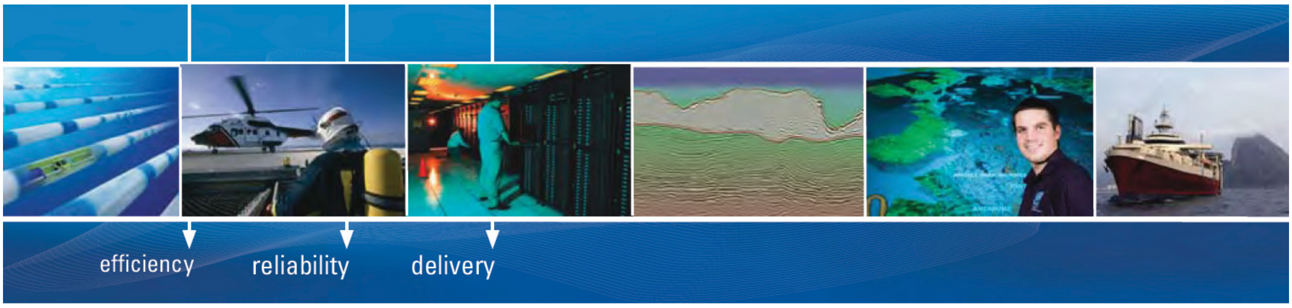
For example, if we select Temp for X-axis and Enthalpy for Y-axis, we get:



Proceeding along the lines described above, we get data/plots for other cryogenic fluids from this versatile NIST Chemistry website:



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1.3.2 Data for Oxygen:

Liquid Phase Data							
Data on Saturation Curve							
Temperature (K)	Pressure (bar)	Density (kg/m3)	Volume (m3/kg)	Internal Energy (kJ/kg)	Enthalpy (kJ/kg	Entropy (J/g*K)	Cv (J/g*K)
55	0.0017857	1303.5	0.00076719	-192.55	-192.55	2.1117	1.1766
64	0.018781	1264.2	0.00079102	-177.49	-177.49	2.3652	1.0529
73	0.10543	1223.2	0.00081756	-162.39	-162.38	2.586	1.0016
82	0.39226	1181	0.00084676	-147.28	-147.24	2.7812	0.96123
91	1.1022	1137.1	0.00087941	-132.08	-131.98	2.9571	0.92586
100	2.54	1090.9	0.00091668	-116.68	-116.45	3.1184	0.89489
109	5.0687	1041.3	0.00096038	-100.94	-100.46	3.2693	0.86841
118	9.0859	986.81	0.0010134	-84.669	-83.749	3.413	0.84699
127	15.014	925.25	0.0010808	-67.567	-65.944	3.5533	0.8322
136	23.303	852.02	0.0011737	-49.082	-46.347	3.6952	0.82802
145	34.477	755.13	0.0013243	-27.785	-23.219	3.8498	0.84969
154	49.307	547.04	0.001828	6.549	15.562	4.093	1.1293

Cp (J/g*K)	Sound Spd. (m/s)	Joule-Thomson (K/bar	Viscosity (Pa*s)	Therm. Cond. (W/m*K)	Surf. Tension (N/m)	Phase	Temperature (K)
1.6716	1126.9	-0.037886	0.00087313	0.20006	0.022501	liquid	55
1.6767	1108	-0.03644	0.00052457	0.18875	0.02003	liquid	64
1.6784	1043.2	-0.035277	0.00034894	0.17628	0.017615	liquid	73
1.6836	971.26	-0.033614	0.00025106	0.16346	0.015259	liquid	82
1.7016	897.64	-0.030942	0.00019146	0.15043	0.01297	liquid	91
1.7375	822.19	-0.026804	0.00015243	0.13731	0.010753	liquid	100
1.7981	743.73	-0.020516	0.00012524	0.12399	0.0086185	liquid	109
1.8972	660.76	-0.010823	0.00010516	0.11045	0.0065785	liquid	118
2.0679	571.27	0.004867	8.93E-05	0.096719	0.0046507	liquid	127
2.4071	472.01	0.032862	7.57E-05	0.082988	0.0028633	liquid	136
3.3684	355.2	0.093865	6.21E-05	0.07018	0.0012695	liquid	145
37.253	178.08	0.36839	4.04E-05	0.066785	4.06E-05	liquid	154

Vapor Phase Data							
Data on Saturation Curve							
Temperature (K)	Pressure (bar)	Density (kg/m3)	Volume (m3/kg)	Internal Energy (kJ/kg)	Enthalpy (kJ/kg	Entropy (J/g*K)	Cv (J/g*K)
55	0.0017857	0.012499	80.009	35.397	49.685	6.5159	0.66556
64	0.018781	0.11313	8.8392	41.167	57.768	6.0411	0.69455
73	0.10543	0.55924	1.7882	46.867	65.721	5.7106	0.70528
82	0.39226	1.8709	0.5345	52.376	73.342	5.4713	0.69069
91	1.1022	4.8258	0.20722	57.437	80.276	5.2896	0.67463
100	2.54	10.425	0.095925	61.79	86.155	5.1445	0.67518
109	5.0687	19.919	0.050203	65.208	90.654	5.0226	0.69549
118	9.0859	34.978	0.028589	67.444	93.421	4.9145	0.73166
127	15.014	58.145	0.017198	68.117	93.938	4.8122	0.78071
136	23.303	94.137	0.010623	66.477	91.232	4.7068	0.8457
145	34.477	154.91	0.0064553	60.574	82.83	4.5812	0.94615
154	49.307	326.8	0.0030599	36.694	51.781	4.3282	1.2597

Cp (J/g*K)	Sound Spd. (m/s)	Joule-Thomson (K/bar	Viscosity (Pa*s)	Therm. Cond. (W/m*K)	Phase	Temperature (K)
0.92809	141.11	48.026	4.07E-06	0.0047713	vapor	55
0.96333	151.54	17.684	4.80E-06	0.005672	vapor	64
0.97982	161.25	6.3548	5.54E-06	0.0065787	vapor	73
0.97196	170.29	3.1877	6.30E-06	0.0075007	vapor	82
0.97181	178.09	2.3091	7.09E-06	0.0084577	vapor	91
1.0064	184.06	1.9753	7.94E-06	0.0094862	vapor	100
1.0889	187.86	1.7484	8.89E-06	0.010653	vapor	109
1.2329	189.38	1.5467	9.98E-06	0.012078	vapor	118
1.4784	188.57	1.3637	1.13E-05	0.013991	vapor	127
1.9617	185.23	1.1931	1.30E-05	0.016876	vapor	136
3.3693	178.78	1.0071	1.57E-05	0.02219	vapor	145
51.062	161.95	0.64644	2.42E-05	0.0508	vapor	154

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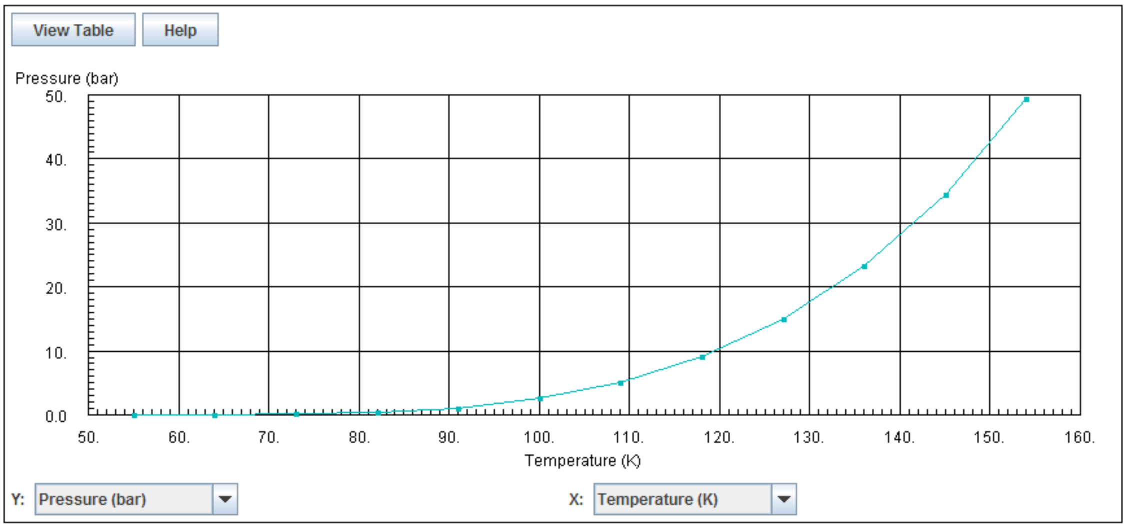

1.3.3 Data for Helium-4:

Liquid Phase Data							
Data on Saturation Curve							
Temperature (K)	**Pressure (bar)**	**Density (kg/m3)**	**Volume (m3/kg)**	**Internal Energy (kJ/kg)**	**Enthalpy (kJ/kg**	**Entropy (J/g*K)**	**Cv (J/g*K)**
2.2	0.051477	146.18	0.0068406	-7.3943	-7.3591	-2.1124	5.7617
2.4	0.081428	145.46	0.0068746	-6.5402	-6.4843	-1.7392	3.0918
2.6	0.12127	144.38	0.0069261	-5.9946	-5.9106	-1.5202	2.2136
2.8	0.1727	143	0.0069931	-5.5229	-5.4022	-1.345	2.0173
3	0.2373	141.35	0.0070749	-5.0365	-4.8686	-1.1767	2.0609
3.2	0.31661	139.43	0.007172	-4.5041	-4.277	-1.0041	2.1706
3.4	0.41209	137.25	0.0072858	-3.9161	-3.6159	-0.82472	2.2822
3.6	0.52519	134.8	0.0074186	-3.2701	-2.8804	-0.63839	2.3758
3.8	0.65733	132.03	0.0075742	-2.5638	-2.0659	-0.44504	2.4488
4	0.80998	128.9	0.0077582	-1.7927	-1.1643	-0.24391	2.5045
4.2	0.9847	125.32	0.0079794	-0.94792	-0.1622	-0.033061	2.5479
4.4	1.1832	121.17	0.0082527	-0.012504	0.96394	0.19132	2.5843
4.6	1.4075	116.2	0.0086057	1.0454	2.2566	0.43649	2.6185
4.8	1.6602	109.9	0.009099	2.2934	3.804	0.71802	2.6565
5	1.9453	100.83	0.0099181	3.9251	5.8545	1.0809	2.7093

Cp (J/g*K)	Sound Spd. (m/s)	Joule-Thomson (K/bar	Viscosity (Pa*s)	Therm. Cond. (W/m*K)	Surf. Tension (N/m)	Phase	Temperature (K)
5.8003	216.59	-0.1129	3.62E-06	0.013631	0.00028652	liquid	2.2
3.2166	215.68	-0.19623	3.72E-06	0.0145	0.00026997	liquid	2.4
2.4528	216.56	-0.24815	3.75E-06	0.015265	0.0002522	liquid	2.6
2.3935	216.57	-0.24447	3.74E-06	0.015946	0.00023339	liquid	2.8
2.5978	214.33	-0.21509	3.69E-06	0.016553	0.00021376	liquid	3
2.8966	210.33	-0.18205	3.63E-06	0.017087	0.00019349	liquid	3.2
3.234	205.24	-0.15095	3.55E-06	0.017548	0.00017278	liquid	3.4
3.6026	199.38	-0.12141	3.47E-06	0.017934	0.00015184	liquid	3.6
4.0198	192.87	-0.09171	3.38E-06	0.018243	0.00013087	liquid	3.8
4.523	185.7	-0.059987	3.28E-06	0.018476	0.00011005	liquid	4
5.1788	177.75	-0.024173	3.18E-06	0.018637	8.96E-05	liquid	4.2
6.1181	168.87	0.018366	3.07E-06	0.018743	6.97E-05	liquid	4.4
7.646	158.8	0.071637	2.95E-06	0.018828	5.06E-05	liquid	4.6
10.7	147.11	0.14292	2.81E-06	0.018956	3.24E-05	liquid	4.8
20.24	132.96	0.24923	2.63E-06	0.019301	1.53E-05	liquid	5

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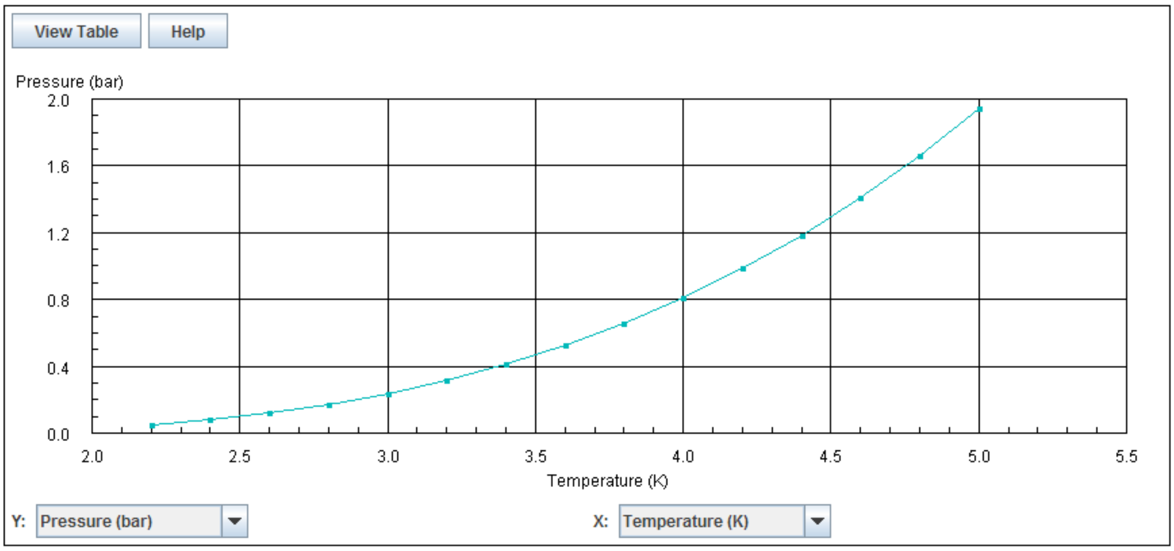
Vapor Phase Data							
Data on Saturation Curve							
Temperature (K)	Pressure (bar)	Density (kg/m3)	Volume (m3/kg)	Internal Energy (kJ/kg)	Enthalpy (kJ/kg	Entropy (J/g*K)	Cv (J/g*K)
2.2	0.051477	1.2038	0.83068	11.543	15.819	8.4229	3.4728
2.4	0.081428	1.7776	0.56257	12.016	16.597	7.878	3.4856
2.6	0.12127	2.493	0.40113	12.471	17.335	7.4205	3.4841
2.8	0.1727	3.3699	0.29675	12.9	18.025	7.0219	3.4721
3	0.2373	4.4284	0.22582	13.3	18.659	6.6658	3.452
3.2	0.31661	5.6903	0.17574	13.665	19.229	6.3416	3.4258
3.4	0.41209	7.1811	0.13925	13.989	19.728	6.0411	3.3948
3.6	0.52519	8.933	0.11194	14.265	20.145	5.7575	3.3602
3.8	0.65733	10.988	0.091006	14.485	20.467	5.4848	3.323
4	0.80998	13.406	0.074592	14.637	20.679	5.2169	3.2839
4.2	0.9847	16.275	0.061444	14.704	20.755	4.9472	3.2432
4.4	1.1832	19.734	0.050673	14.662	20.657	4.667	3.2011
4.6	1.4075	24.034	0.041607	14.465	20.321	4.3635	3.1572
4.8	1.6602	29.696	0.033674	14.024	19.614	4.0118	3.1097
5	1.9453	38.213	0.026169	13.093	18.183	3.5467	3.0526

Cp (J/g*K)	Sound Spd. (m/s)	Joule-Thomson (K/bar	Viscosity (Pa*s)	Therm. Cond. (W/m*K)	Phase	Temperature (K)
6.0759	83.564	2.7045	5.45E-07	0.0040381	vapor	2.2
6.1988	86.335	2.2367	6.07E-07	0.0045326	vapor	2.4
6.3183	88.833	1.913	6.69E-07	0.0049927	vapor	2.6
6.4459	91.063	1.6819	7.32E-07	0.0054423	vapor	2.8
6.5921	93.038	1.5127	7.96E-07	0.0058927	vapor	3
6.7682	94.77	1.3862	8.62E-07	0.00635	vapor	3.2
6.9887	96.271	1.2902	9.29E-07	0.006818	vapor	3.4
7.2737	97.549	1.2162	1.00E-06	0.0073054	vapor	3.6
7.6537	98.614	1.1584	1.07E-06	0.0078134	vapor	3.8
8.1786	99.469	1.1127	1.15E-06	0.0083555	vapor	4
8.9377	100.12	1.0753	1.23E-06	0.0089516	vapor	4.2
10.11	100.58	1.0428	1.32E-06	0.0096385	vapor	4.4
12.117	100.88	1.0104	1.42E-06	0.010487	vapor	4.6
16.244	101.11	0.96925	1.54E-06	0.011648	vapor	4.8
29.094	101.63	0.89603	1.69E-06	0.013587	vapor	5



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1.3.4 Data for Hydrogen:

Liquid Phase Data							
Data on Saturation Curve							
Temperature (K)	Pressure (bar)	Density (kg/m3)	Volume (m3/kg)	Internal Energy (kJ/kg)	Enthalpy (kJ/kg	Entropy (J/g*K)	Cv (J/g*K)
14	0.075414	76.971	0.012992	-53.717	-53.619	-3.0506	5.1623
17	0.31759	74.347	0.01345	-31.158	-30.731	-1.5935	5.4191
20	0.90717	71.267	0.014032	-4.939	-3.6661	-0.17424	5.6367
23	2.0438	67.594	0.014794	25.701	28.724	1.2556	5.8274
26	3.9399	63.081	0.015853	62.099	68.345	2.753	6.0154
29	6.8205	57.121	0.017507	107.26	119.2	4.4252	6.2414
32	10.957	47.086	0.021238	173.46	196.73	6.6981	6.8108

Cp (J/g*K)	Sound Spd. (m/s)	Joule-Thomson (K/bar	Viscosity (Pa*s)	Therm. Cond. (W/m*K)	Surf. Tension (N/m)	Phase	Temperature (K)
7.031	1268.3	-0.15728	2.55E-05	0.076669	0.0029925	liquid	14
8.1366	1203.3	-0.12913	1.80E-05	0.094986	0.0024958	liquid	17
9.5694	1129.1	-0.099177	1.37E-05	0.10329	0.0020051	liquid	20
11.489	1037.5	-0.065873	1.09E-05	0.10533	0.0015216	liquid	23
14.486	923.09	-0.023094	8.81E-06	0.10306	0.0010475	liquid	26
20.807	774.75	0.044733	7.07E-06	0.096891	0.00058656	liquid	29
57.285	552.87	0.21008	5.25E-06	0.084264	0.00014903	liquid	32

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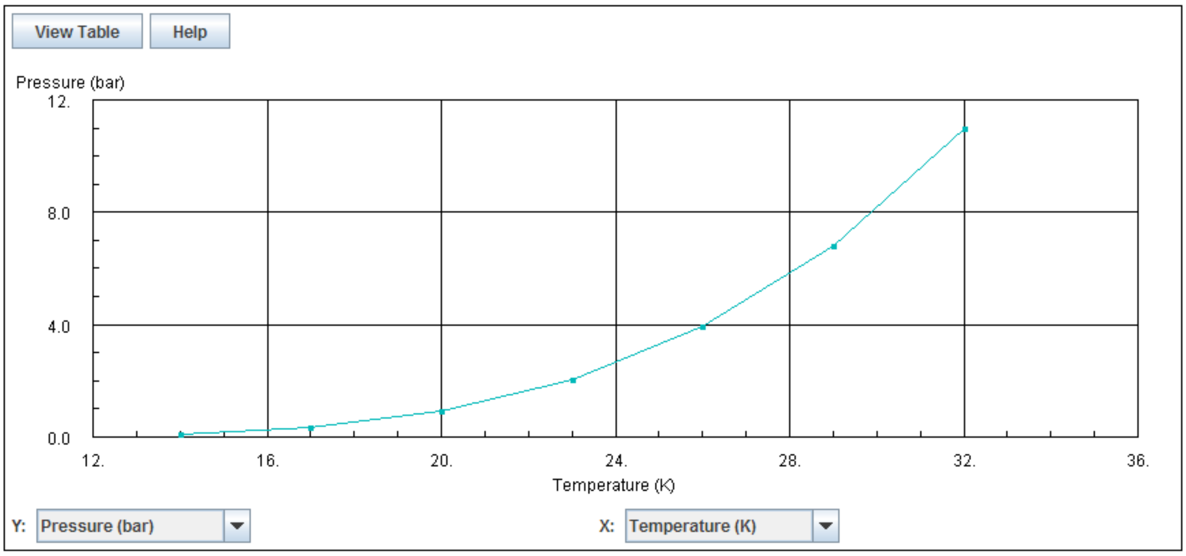
Vapor Phase Data							
Data on Saturation Curve							
Temperature (K)	Pressure (bar)	Density (kg/m3)	Volume (m3/kg)	Internal Energy (kJ/kg)	Enthalpy (kJ/kg	Entropy (J/g*K)	Cv (J/g*K)
14	0.075414	0.13273	7.5343	343.39	400.21	29.366	6.2447
17	0.31759	0.47357	2.1116	358.97	426.03	25.275	6.3425
20	0.90717	1.2059	0.82926	371.4	446.63	22.341	6.4341
23	2.0438	2.5335	0.39472	379.2	459.87	20.001	6.5925
26	3.9399	4.7675	0.20975	380.44	463.08	17.935	6.8618
29	6.8205	8.5604	0.11682	371.24	450.91	15.864	7.292
32	10.957	16.496	0.060621	335.87	402.29	13.122	8.0823

Cp (J/g*K)	Sound Spd. (m/s)	Joule-Thomson (K/bar	Viscosity (Pa*s)	Therm. Cond. (W/m*K)	Phase	Temperature (K)
10.569	307.56	2.9101	6.67E-07	0.010426	vapor	14
11.047	333.81	2.2575	8.74E-07	0.01367	vapor	17
11.891	354.3	1.8665	1.06E-06	0.016692	vapor	20
13.471	368.87	1.5864	1.25E-06	0.02013	vapor	23
16.603	377.32	1.3577	1.46E-06	0.024369	vapor	26
24.444	379.64	1.1476	1.73E-06	0.030269	vapor	29
74.634	375.77	0.87733	2.27E-06	0.041855	vapor	32



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1.3.5 Data for Neon:

Liquid Phase Data							
Data on Saturation Curve							
Temperature (K)	Pressure (bar)	Density (kg/m3)	Volume (m3/kg)	Internal Energy (kJ/kg)	Enthalpy (kJ/kg	Entropy (J/g*K)	Cv (J/g*K)
25	0.5092	1243.9	0.0008039	-4.0487	-4.0077	-0.15241	0.91376
26	0.71611	1226.1	0.0008156	-2.1306	-2.0721	-0.077133	0.90158
27	0.98173	1208.8	0.00082728	-0.27762	-0.1964	-0.0071635	0.89232
28	1.3159	1191.2	0.00083949	1.5837	1.6942	0.060576	0.88225
29	1.7287	1173	0.00085252	3.4853	3.6327	0.12737	0.87163
30	2.2307	1154	0.00086658	5.4406	5.6339	0.19374	0.86084
31	2.8324	1134	0.00088182	7.4533	7.7031	0.25986	0.85019
32	3.5446	1113.1	0.00089838	9.5232	9.8416	0.32574	0.84007
33	4.3782	1091.2	0.0009164	11.649	12.05	0.39136	0.83096
34	5.3443	1068.3	0.00093607	13.83	14.33	0.45675	0.82332
35	6.4543	1044.2	0.00095764	16.069	16.687	0.52201	0.81757
36	7.7202	1018.9	0.00098146	18.372	19.129	0.58737	0.81402
37	9.1543	992.03	0.001008	20.751	21.674	0.65317	0.81295
38	10.77	963.27	0.0010381	23.226	24.344	0.71997	0.81461
39	12.581	932	0.001073	25.828	27.178	0.78861	0.81945
40	14.603	897.21	0.0011146	28.608	30.236	0.86041	0.82833
41	16.855	857.03	0.0011668	31.656	33.623	0.93768	0.84313
42	19.355	807.59	0.0012382	35.155	37.552	1.0251	0.86831
43	22.121	739.37	0.0013525	39.548	42.54	1.134	0.91534
44	25.168	632.15	0.0015819	45.791	49.772	1.29	1.0016

Cp (J/g*K)	Sound Spd. (m/s)	Joule-Thomson (K/bar	Viscosity (Pa*s)	Therm. Cond. (W/m*K)	Surf. Tension (N/m)	Phase	Temperature (K)
2.0029	652.08	-0.025101	0.00014536	0.16829	0.00547	liquid	25
1.8756	617.51	-0.027322	0.00013015	0.16188	0.005009	liquid	26
1.8603	596	-0.027053	0.00011733	0.15565	0.004567	liquid	27
1.8931	579.65	-0.025492	0.00010636	0.14953	0.0041439	liquid	28
1.9477	564.56	-0.023297	9.69E-05	0.14347	0.0037399	liquid	29
2.0117	548.99	-0.020788	8.86E-05	0.13745	0.0033549	liquid	30
2.0792	532.26	-0.01809	8.13E-05	0.13148	0.0029892	liquid	31
2.1481	514.19	-0.015212	7.47E-05	0.12554	0.0026426	liquid	32
2.2196	494.83	-0.012096	6.89E-05	0.11965	0.0023152	liquid	33
2.2966	474.28	-0.0086349	6.36E-05	0.11381	0.0020072	liquid	34
2.3844	452.65	-0.0046782	5.88E-05	0.10802	0.0017185	liquid	35
2.4903	429.96	-2.74E-05	5.43E-05	0.10227	0.0014492	liquid	36
2.6249	406.17	0.0055871	5.01E-05	0.096555	0.0011995	liquid	37
2.8047	381.08	0.012549	4.62E-05	0.090861	0.00096946	liquid	38
3.0586	354.35	0.021441	4.24E-05	0.085162	0.00075925	liquid	39
3.4429	325.39	0.033222	3.87E-05	0.079415	0.00056919	liquid	40
4.0889	293.27	0.049632	3.50E-05	0.073552	0.00039975	liquid	41
5.3776	256.54	0.07418	3.11E-05	0.067487	0.00025181	liquid	42
8.7614	213.78	0.11433	2.67E-05	0.061291	0.0001271	liquid	43
22.206	170.57	0.18283	2.10E-05	0.0567	3.04E-05	liquid	44

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Vapor Phase Data							
Data on Saturation Curve							
Temperature (K)	Pressure (bar)	Density (kg/m3)	Volume (m3/kg)	Internal Energy (kJ/kg)	Enthalpy (kJ/kg	Entropy (J/g*K)	Cv (J/g*K)
25	0.5092	5.1267	0.19506	73.828	83.76	3.3583	1.4777
26	0.71611	6.9815	0.14323	74.563	84.82	3.2649	1.0924
27	0.98173	9.3048	0.10747	75.121	85.672	3.1732	0.89354
28	1.3159	12.168	0.082184	75.56	86.375	3.0849	0.79294
29	1.7287	15.647	0.063908	75.908	86.956	3.0006	0.74439
30	2.2307	19.828	0.050434	76.178	87.428	2.9202	0.72373
31	2.8324	24.803	0.040317	76.373	87.792	2.8434	0.7184
32	3.5446	30.68	0.032594	76.492	88.045	2.7696	0.72184
33	4.3782	37.584	0.026607	76.529	88.178	2.6983	0.73072
34	5.3443	45.664	0.021899	76.477	88.18	2.6288	0.74336
35	6.4543	55.106	0.018147	76.324	88.037	2.5606	0.759
36	7.7202	66.143	0.015119	76.055	87.726	2.4928	0.77743
37	9.1543	79.087	0.012644	75.649	87.224	2.4248	0.79875
38	10.77	94.361	0.010598	75.078	86.492	2.3554	0.82334
39	12.581	112.58	0.0088829	74.303	85.479	2.2835	0.85184
40	14.603	134.66	0.007426	73.263	84.107	2.2072	0.88522
41	16.855	162.17	0.0061666	71.857	82.251	2.1237	0.92493
42	19.355	197.94	0.0050521	69.91	79.688	2.0283	0.973
43	22.121	248.26	0.004028	67.048	75.959	1.9112	1.0319
44	25.168	333.79	0.0029959	62.126	69.666	1.7421	1.1005

Cp (J/g*K)	Sound Spd. (m/s)	Joule-Thomson (K/bar	Viscosity (Pa*s)	Therm. Cond. (W/m*K)	Phase	Temperature (K)
2.071	115.48	2.3404	4.14E-06	0.0060862	vapor	25
1.6402	121.12	1.8114	4.32E-06	0.0063535	vapor	26
1.4292	126.17	1.5446	4.51E-06	0.0066394	vapor	27
1.3352	130.23	1.4023	4.70E-06	0.0069474	vapor	28
1.3057	133.28	1.311	4.90E-06	0.0072816	vapor	29
1.3141	135.55	1.2393	5.10E-06	0.0076474	vapor	30
1.3471	137.25	1.1758	5.31E-06	0.0080515	vapor	31
1.399	138.54	1.1166	5.53E-06	0.0085022	vapor	32
1.4685	139.52	1.0606	5.75E-06	0.0090106	vapor	33
1.557	140.26	1.0073	5.99E-06	0.0095905	vapor	34
1.6685	140.78	0.95602	6.24E-06	0.01026	vapor	35
1.8104	141.11	0.90641	6.48E-06	0.011057	vapor	36
1.9943	141.24	0.8578	6.76E-06	0.01194	vapor	37
2.2403	141.18	0.80944	7.06E-06	0.013022	vapor	38
2.5837	140.93	0.76033	7.41E-06	0.014368	vapor	39
3.0926	140.49	0.70917	7.80E-06	0.016087	vapor	40
3.9164	139.83	0.65404	8.28E-06	0.01838	vapor	41
5.4496	138.95	0.59193	8.90E-06	0.021663	vapor	42
9.1322	137.87	0.5176	9.80E-06	0.026952	vapor	43
27.296	136.83	0.41789	1.15E-05	0.038728	vapor	44

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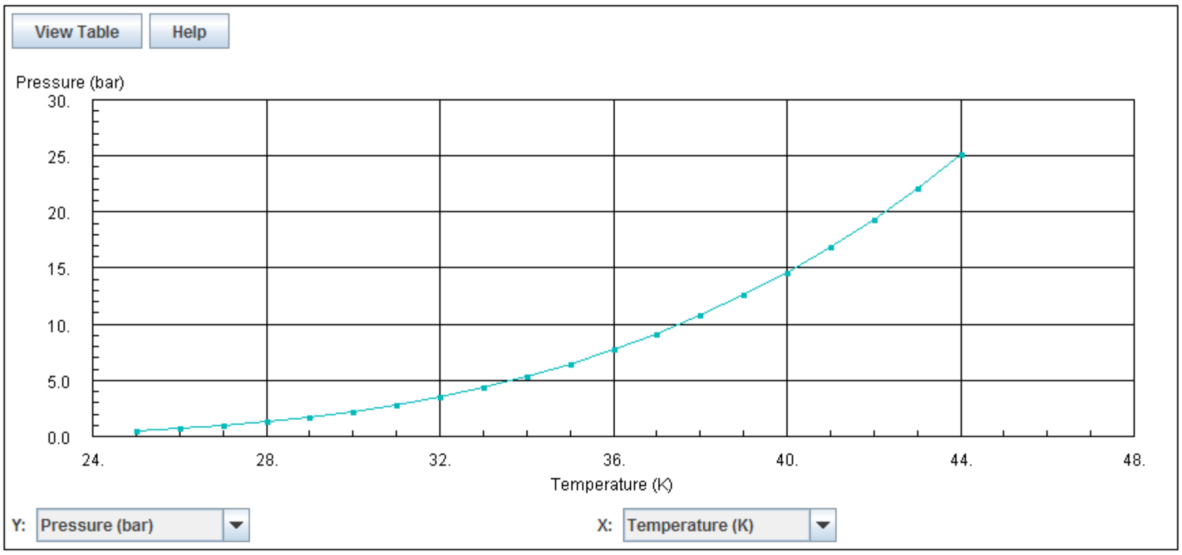

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1.3.6 Data for Fluorine:

Liquid Phase Data							
Data on Saturation Curve							
Temperature (K)	Pressure (bar)	Density (kg/m3)	Volume (m3/kg)	Internal Energy (kJ/kg)	Enthalpy (kJ/kg	Entropy (J/g*K)	Cv (J/g*K)
54	0.0028119	1703.3	0.0005871	-46.018	-46.018	-0.6716	0.94762
63	0.030036	1646.6	0.0006073	-32.833	-32.832	-0.44579	0.8873
72	0.16849	1589.4	0.00062917	-19.528	-19.517	-0.24839	0.85633
81	0.62208	1529.7	0.00065372	-6.13	-6.0893	-0.07305	0.83248
90	1.7296	1466.3	0.00068198	7.4521	7.57	0.085963	0.80622
99	3.9396	1398	0.00071533	21.334	21.616	0.23304	0.78002
108	7.7664	1323	0.00075585	35.651	36.238	0.37165	0.75639
117	13.761	1238.6	0.00080737	50.625	51.736	0.50525	0.73746
126	22.519	1138.3	0.00087854	66.725	68.703	0.63881	0.72835
135	34.739	1003.7	0.00099628	85.263	88.724	0.78335	0.75037
144	51.458	699.44	0.0014297	115.82	123.17	1.0152	1.0263

Cp (J/g*K)	Sound Spd. (m/s)	Joule-Thomson (K/bar	Viscosity (Pa*s)	Therm. Cond. (W/m*K)	Surf. Tension (N/m)	Phase	Temperature (K)
1.4965	1041.2	-0.03108	undefined	undefined	0.022671	liquid	54
1.4734	1032.6	-0.031333	undefined	undefined	0.019865	liquid	63
1.483	952.55	-0.029975	undefined	undefined	0.017139	liquid	72
1.4989	861.47	-0.027831	undefined	undefined	0.0145	liquid	81
1.5295	779.02	-0.024474	undefined	undefined	0.011957	liquid	90
1.5786	700.92	-0.019456	undefined	undefined	0.0095208	liquid	99
1.6557	621.85	-0.011801	undefined	undefined	0.007208	liquid	108
1.7889	537.04	0.00077695	undefined	undefined	0.0050404	liquid	117
2.0653	440.49	0.024205	undefined	undefined	0.0030528	liquid	126
2.8936	321.84	0.078572	undefined	undefined	0.0013109	liquid	135
46.003	152.29	0.34462	undefined	undefined	2.56E-05	liquid	144

Vapor Phase Data							
Data on Saturation Curve							
Temperature (K)	Pressure (bar)	Density (kg/m3)	Volume (m3/kg)	Internal Energy (kJ/kg)	Enthalpy (kJ/kg	Entropy (J/g*K)	Cv (J/g*K)
54	0.0028119	0.023807	42.005	140.85	152.66	3.0077	0.54746
63	0.030036	0.21846	4.5774	145.7	159.45	2.6063	0.54898
72	0.16849	1.08	0.92597	150.37	165.97	2.3278	0.55368
81	0.62208	3.599	0.27786	154.65	171.94	2.1248	0.56356
90	1.7296	9.2442	0.10818	158.38	177.09	1.9696	0.57934
99	3.9396	19.903	0.050244	161.41	181.2	1.845	0.60013
108	7.7664	37.991	0.026322	163.56	184	1.7398	0.62448
117	13.761	67.058	0.014913	164.55	185.07	1.6448	0.65289
126	22.519	113.74	0.0087922	163.67	183.47	1.5497	0.6922
135	34.739	195.17	0.0051239	159.04	176.84	1.4361	0.76968
144	51.458	461.53	0.0021667	135.58	146.73	1.1788	1.1162

Cp (J/g*K)	Sound Spd. (m/s)	Joule-Thomson (K/bar	Viscosity (Pa*s)	Therm. Cond. (W/m*K)	Phase	Temperature (K)
0.76669	128.59	7.4475	undefined	undefined	vapor	54
0.77048	138.72	5.2244	undefined	undefined	vapor	63
0.78235	147.74	3.8294	undefined	undefined	vapor	72
0.80801	155.43	2.8905	undefined	undefined	vapor	81
0.85186	161.52	2.2322	undefined	undefined	vapor	90
0.9179	165.77	1.7695	undefined	undefined	vapor	99
1.0156	167.94	1.4533	undefined	undefined	vapor	108
1.1769	167.82	1.2429	undefined	undefined	vapor	117
1.5156	165.45	1.091	undefined	undefined	vapor	126
2.6291	161.03	0.92577	undefined	undefined	vapor	135
84.654	143.81	0.53502	undefined	undefined	vapor	144

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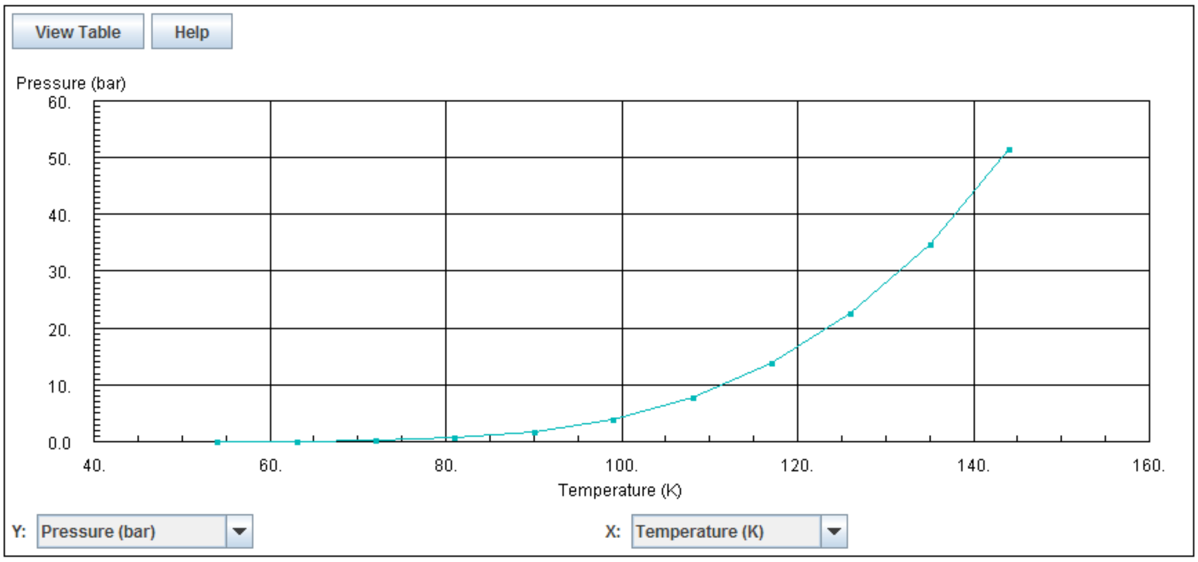

1.3.7 Data for Argon:

Liquid Phase Data							
Data on Saturation Curve							
Temperature (K)	Pressure (bar)	Density (kg/m3)	Volume (m3/kg)	Internal Energy (kJ/kg)	Enthalpy (kJ/kg	Entropy (J/g*K)	Cv (J/g*K)
84	0.70447	1415.6	0.00070642	-121.27	-121.22	1.3321	0.54881
90	1.3351	1378.6	0.00072536	-114.58	-114.49	1.409	0.52677
96	2.3249	1340.3	0.00074612	-107.85	-107.68	1.4814	0.5084
102	3.7825	1300.1	0.00076919	-101.01	-100.72	1.5505	0.49257
108	5.8226	1257.6	0.00079519	-94.033	-93.57	1.6172	0.47882
114	8.5644	1212.1	0.00082501	-86.85	-86.144	1.6821	0.46708
120	12.13	1162.8	0.00085998	-79.396	-78.353	1.7461	0.45763
126	16.648	1108.4	0.00090223	-71.566	-70.064	1.8102	0.45116
132	22.252	1046.5	0.0009556	-63.188	-61.062	1.876	0.44921
138	29.096	972.57	0.0010282	-53.921	-50.93	1.946	0.45504
144	37.363	874.98	0.0011429	-42.905	-38.635	2.0268	0.47972
150	47.346	680.43	0.0014697	-24.838	-17.88	2.1589	0.70603

Cp (J/g*K)	Sound Spd. (m/s)	Joule-Thomson (K/bar	Viscosity (Pa*s)	Therm. Cond. (W/m*K)	Surf. Tension (N/m)	Phase	Temperature (K)
1.1157	861.1	-0.040441	0.00030406	0.13001	0.013371	liquid	84
1.1212	819.45	-0.038056	0.00024764	0.12207	0.011853	liquid	90
1.1374	776.45	-0.034548	0.00020616	0.1141	0.010377	liquid	96
1.1637	731.83	-0.029777	0.00017415	0.10626	0.0089444	liquid	102
1.2017	685.24	-0.023427	0.00014844	0.098464	0.0075606	liquid	108
1.2553	636.24	-0.014957	0.0001271	0.090774	0.0062299	liquid	114
1.3324	584.19	-0.0034666	0.00010889	0.083208	0.0049587	liquid	120
1.4485	528.16	0.012622	9.30E-05	0.075775	0.003755	liquid	126
1.64	466.63	0.036324	7.87E-05	0.068468	0.0026307	liquid	132
2.0106	397.21	0.074246	6.55E-05	0.061263	0.0016037	liquid	138
3.0262	313.8	0.14528	5.24E-05	0.054216	0.00070743	liquid	144
23.582	174.74	0.37559	3.53E-05	0.050932	3.86E-05	liquid	150

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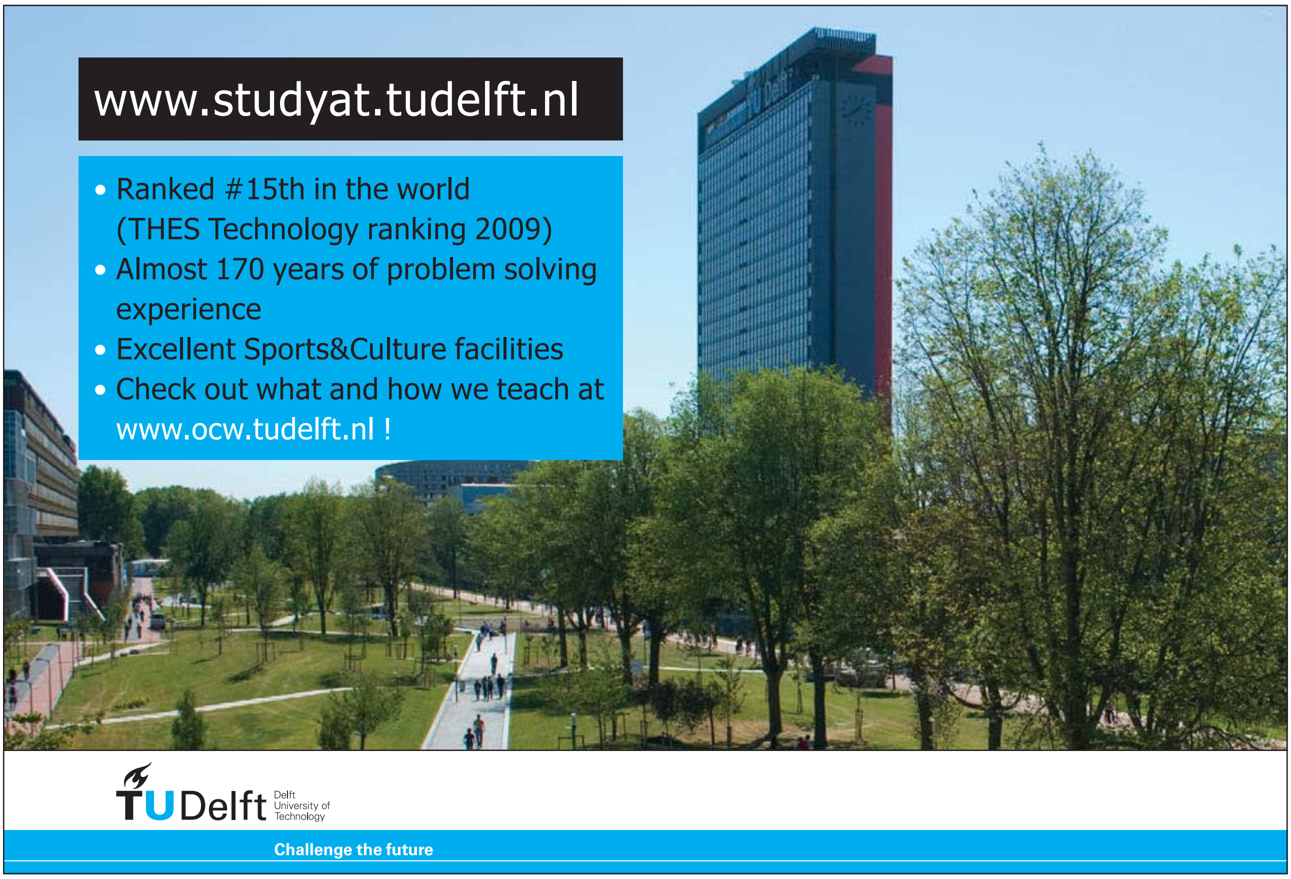
Vapor Phase Data

Data on Saturation Curve

Temperature (K)	Pressure (bar)	Density (kg/m3)	Volume (m3/kg)	Internal Energy (kJ/kg)	Enthalpy (kJ/kg	Entropy (J/g*K)	Cv (J/g*K)
84	0.70447	4.1384	0.24164	25.335	42.358	3.2794	0.32489
90	1.3351	7.4362	0.13448	26.619	44.572	3.1763	0.33094
96	2.3249	12.397	0.080668	27.661	46.415	3.0865	0.33853
102	3.7825	19.495	0.051294	28.411	47.813	3.0068	0.34781
108	5.8226	29.3	0.03413	28.811	48.684	2.9343	0.35906
114	8.5644	42.526	0.023515	28.788	48.927	2.8669	0.37267
120	12.13	60.144	0.016627	28.244	48.413	2.8025	0.38934
126	16.648	83.59	0.011963	27.031	46.947	2.7389	0.41024
132	22.252	115.23	0.0086782	24.906	44.217	2.6736	0.43734
138	29.096	159.65	0.0062637	21.396	39.621	2.6022	0.47581
144	37.363	228.48	0.0043767	15.319	31.672	2.515	0.54719
150	47.346	394.5	0.0025348	-0.47956	11.522	2.355	0.82182

Cp (J/g*K)	Sound Spd. (m/s)	Joule-Thomson (K/bar	Viscosity (Pa*s)	Therm. Cond. (W/m*K)	Phase	Temperature (K)
0.55557	168.28	3.5545	6.83E-06	0.0052709	vapor	84
0.57569	172.83	3.0979	7.39E-06	0.0057436	vapor	90
0.60327	176.71	2.7325	7.96E-06	0.0062742	vapor	96
0.64062	179.89	2.4323	8.55E-06	0.0068815	vapor	102
0.69138	182.37	2.1795	9.19E-06	0.0075919	vapor	108
0.76168	184.11	1.961	9.87E-06	0.0084449	vapor	114
0.86265	185.09	1.7668	1.06E-05	0.0095027	vapor	120
1.0166	185.24	1.5875	1.15E-05	0.010867	vapor	126
1.2751	184.49	1.4141	1.25E-05	0.012721	vapor	132
1.7932	182.6	1.2341	1.39E-05	0.015451	vapor	138
3.3149	177.93	1.021	1.59E-05	0.020253	vapor	144
35.468	157.01	0.67455	2.13E-05	0.040853	vapor	150



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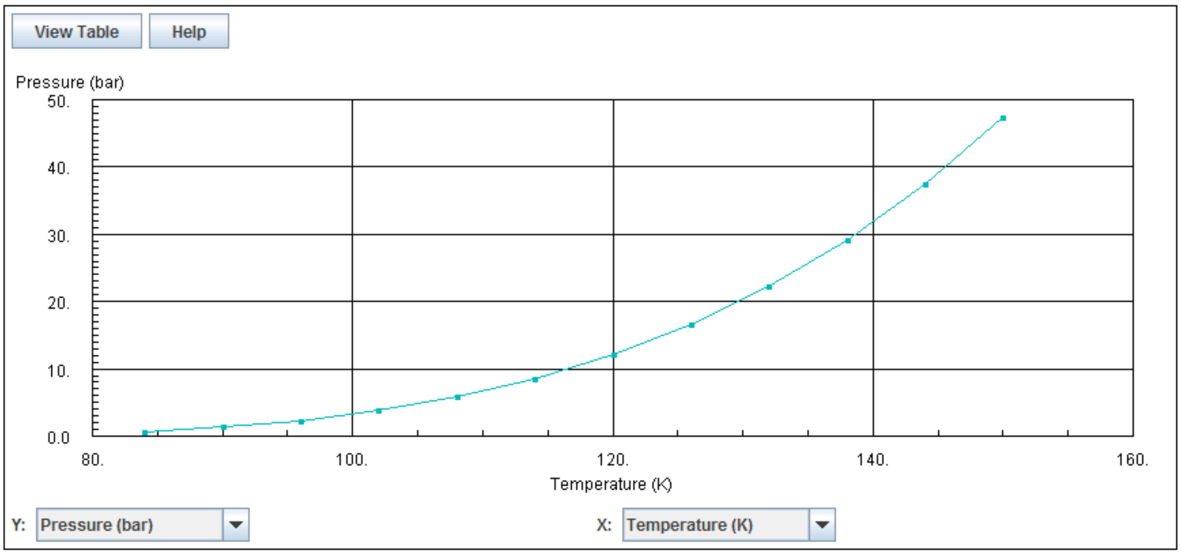

1.4 Data for Cryogenic Fluids – Properties of gases at 1 atm [9]:

1.4.1 For Helium at 1 atm.:

From the NIST website, viz. http://webbook.nist.gov/chemistry/fluid/

Select Helium for the gas, and 'Isobaric properties':

Please follow the steps below to select the data required.

1. Please select the species of interest:
   Helium
2. Please choose the units you wish to use:

Quantity	Units
Temperature	◉ Kelvin ○ Celsius ○ Fahrenheit ○ Rankine
Pressure	○ MPa ○ bar ◉ atm. ○ torr ○ psia
Density	○ mol/l ○ mol/m3 ○ g/ml ◉ kg/m3 ○ lb-mole/ft3 ○ lbm/ft3
Energy	○ kJ/mol ◉ kJ/kg ○ kcal/mol ○ Btu/lb-mole ○ kcal/g ○ Btu/lbm
Velocity	◉ m/s ○ ft/s ○ mph
Viscosity	○ uPa*s ◉ Pa*s ○ cP ○ lbm/ft*s
Surface tension*	◉ N/m ○ dyn/cm ○ lb/ft ○ lb/in

*Surface tension values are only available along the saturation curve.

3. Choose the desired type of data:
   ○ Isothermal properties ○ Saturation properties — temperature increments
   ◉ Isobaric properties ○ Saturation properties — pressure increments
   ○ Isochoric properties
4. Please select the desired standard state convention:
   Default for fluid
5. Press to Continue

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Click on 'Press to continue':

Isobaric properties for Helium

This option will supply data on a constant pressure curve over the specified temperature range. Values should not extend extend outside the minimum and maximum values given. Calculations are limited to a maxium of 201 data points; increments resulting in a larger number of points will be adjusted upward to limit the number of points computed.

1. Enter pressure in selected units:
   1 (Acceptable range: 0.0 to 986.9233 atm)
2. Enter temperature range and increment in selected units:
   T_{Low}* 5
   T_{High} 305 (max value: 1500.0 K)
   $T_{Increment}$ 10

   * The minimum temperature limit is the highest of the following values:
     - 2.1768 K
     - The temperature at which a density of 146.24 kg/m3 is reached.
3. Check here if you want to use the display applet (requires Java capable browser) ☑
4. Number of digits to be displayed in tables (does not effect accuracy of computations): 5
5. Press for Data

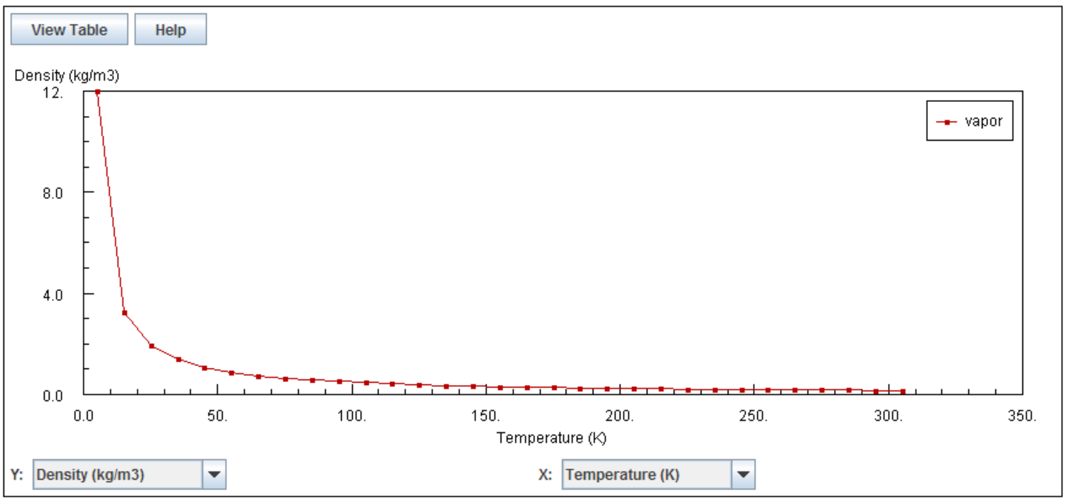
In the above, we have given 5 K as T_{Low} and 305 K as T_{High}, with a temp increment of 10 deg. Click on 'Press for Data', and we get:

Isobaric Properties for Helium

- Fluid Data
- Auxiliary Data
- References
- Additional Information
- Important Information About This Data
- Notes
- **Other Data Available:**
  - View data in HTML table.
  - Download data as a tab-delimited text file.
  - Main NIST Chemistry WebBook page for this species.
  - Recommended citation for data from this page.
  - Fluid data for other species

Fluid Data

Isobaric Data for P = 1.0000 atm



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In the above, click on 'View Data in HTML Table' and we get:

Isobaric Data for P = 1.0000 atm

Temperature (K)	Pressure (atm)	Density (kg/m3)	Volume (m3/kg)	Internal Energy (kJ/kg)	Enthalpy (kJ/kg)	Entropy (J/g*K)	Cv (J/g*K)
5	1	11.978	0.083484	18.146	26.605	6.1816	3.1588
15	1	3.2727	0.30556	51.215	82.176	12.393	3.1202
25	1	1.9481	0.51333	82.708	134.72	15.079	3.1204
35	1	1.3901	0.7194	114.01	186.91	16.835	3.1193
45	1	1.0812	0.92492	145.25	238.97	18.143	3.1184
55	1	0.88479	1.1302	176.46	290.98	19.187	3.1179
65	1	0.74885	1.3354	207.66	342.96	20.056	3.1175
75	1	0.64915	1.5405	238.84	394.93	20.799	3.1172
85	1	0.57289	1.7455	270.02	446.89	21.45	3.117
95	1	0.51267	1.9506	301.19	498.83	22.027	3.1168
105	1	0.4639	2.1556	332.36	550.78	22.547	3.1167
115	1	0.42362	2.3606	363.53	602.72	23.02	3.1166
125	1	0.38977	2.5656	394.69	654.66	23.453	3.1165
135	1	0.36093	2.7706	425.86	706.59	23.852	3.1164
145	1	0.33606	2.9756	457.02	758.53	24.224	3.1164
155	1	0.3144	3.1806	488.18	810.46	24.57	3.1163
165	1	0.29537	3.3856	519.34	862.39	24.895	3.1163
175	1	0.2785	3.5906	550.51	914.33	25.2	3.1162

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185	1	0.26346	3.7956	581.67	966.26	25.489	3.1162
195	1	0.24996	4.0006	612.83	1018.2	25.762	3.1162
205	1	0.23778	4.2056	643.99	1070.1	26.022	3.1162
215	1	0.22673	4.4106	675.15	1122.1	26.269	3.1161
225	1	0.21666	4.6156	706.31	1174	26.505	3.1161
235	1	0.20744	4.8206	737.47	1225.9	26.731	3.1161
245	1	0.19898	5.0256	768.63	1277.8	26.948	3.1161
255	1	0.19118	5.2306	799.79	1329.8	27.155	3.1161
265	1	0.18397	5.4356	830.95	1381.7	27.355	3.1161
275	1	0.17729	5.6406	862.1	1433.6	27.547	3.116
285	1	0.17107	5.8455	893.26	1485.6	27.733	3.116
295	1	0.16527	6.0505	924.42	1537.5	27.912	3.116

Cp (J/g*K)	Sound Spd. (m/s)	Joule-Thomson (F/atm)	Viscosity (Pa*s)	Therm. Cond. (W/m*K)	Phase	Temperature (K)
6.7704	119.51	1.4531	1.39E-06	0.01023	vapor	5
5.2961	228.53	0.31512	2.97E-06	0.021914	vapor	15
5.2295	295.48	0.10776	4.13E-06	0.030089	vapor	25
5.2108	349.41	0.020573	5.10E-06	0.037156	vapor	35
5.2031	395.95	-0.025542	5.96E-06	0.043614	vapor	45
5.1994	437.52	-0.053088	6.75E-06	0.049655	vapor	55
5.1972	475.45	-0.070842	7.48E-06	0.055383	vapor	65
5.196	510.57	-0.08289	8.17E-06	0.06086	vapor	75
5.1951	543.41	-0.091371	8.83E-06	0.066131	vapor	85
5.1946	574.38	-0.097501	9.47E-06	0.071225	vapor	95
5.1942	603.76	-0.10202	9.99E-06	0.076167	vapor	105
5.1939	631.77	-0.10539	1.05E-05	0.080975	vapor	115
5.1937	658.6	-0.10794	1.11E-05	0.085664	vapor	125
5.1935	684.37	-0.10986	1.17E-05	0.090245	vapor	135
5.1934	709.21	-0.11132	1.22E-05	0.09473	vapor	145
5.1933	733.2	-0.11241	1.28E-05	0.099126	vapor	155
5.1933	756.44	-0.11323	1.33E-05	0.10344	vapor	165
5.1932	778.98	-0.11383	1.38E-05	0.10768	vapor	175
5.1932	800.89	-0.11425	1.44E-05	0.11185	vapor	185
5.1931	822.22	-0.11453	1.49E-05	0.11595	vapor	195
5.1931	843	-0.1147	1.54E-05	0.12	vapor	205
5.1931	863.29	-0.11477	1.59E-05	0.12398	vapor	215
5.1931	883.11	-0.11478	1.64E-05	0.12792	vapor	225
5.193	902.5	-0.11472	1.69E-05	0.1318	vapor	235
5.193	921.47	-0.11461	1.74E-05	0.13564	vapor	245
5.193	940.07	-0.11446	1.78E-05	0.13943	vapor	255
5.193	958.3	-0.11427	1.83E-05	0.14317	vapor	265
5.193	976.2	-0.11406	1.88E-05	0.14688	vapor	275
5.193	993.77	-0.11383	1.92E-05	0.15054	vapor	285
5.193	1011	-0.11358	1.97E-05	0.15417	vapor	295
5.193	1028	-0.11331	2.02E-05	0.15777	vapor	305

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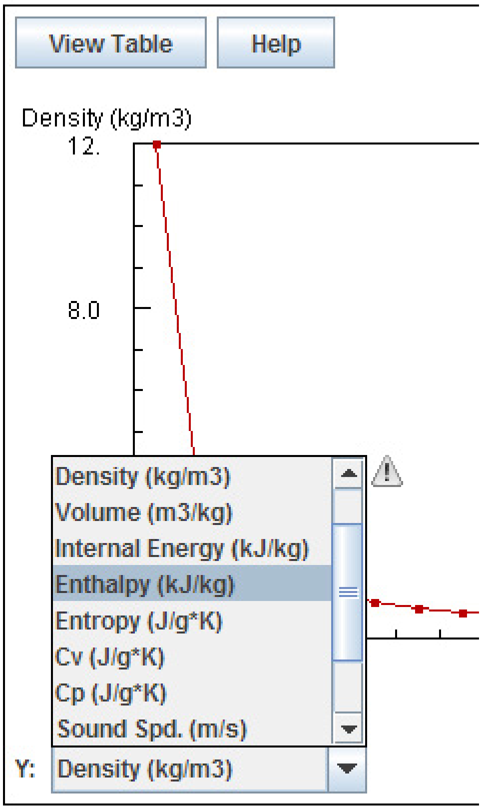
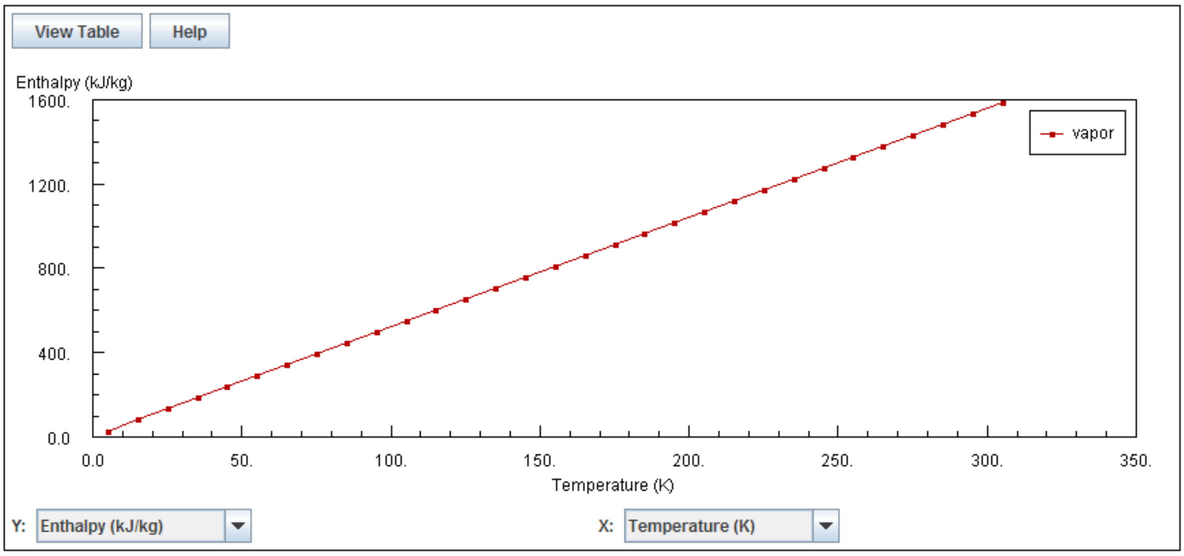
In addition to the plot shown above, many other plots are possible, by selecting different parameters for X-axis and Y-axis:



For example, if we select Temp for X-axis and **Enthalpy** s Y-axis, we get immediately:



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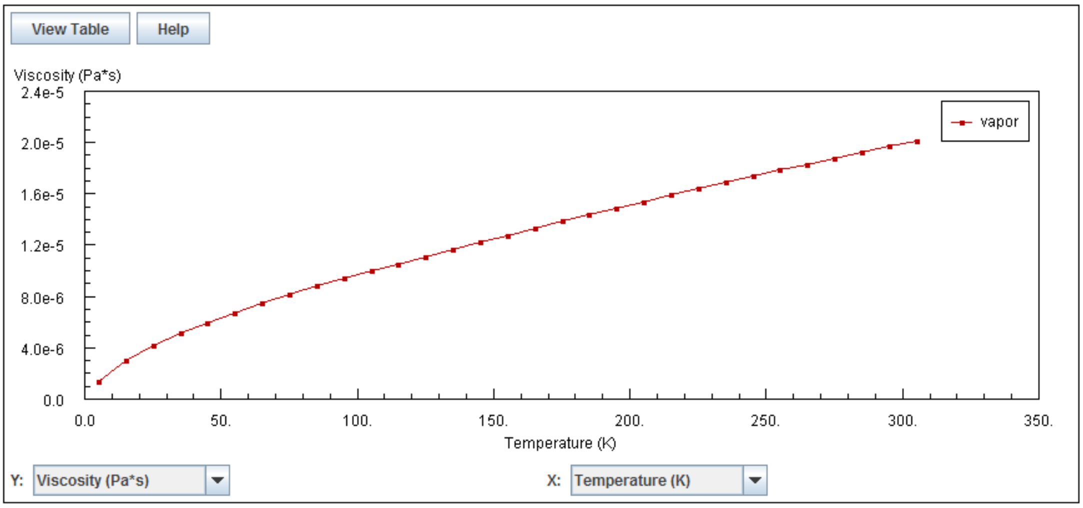
And, for viscosity of helium, we get:

Isobaric Data for P = 1.0000 atm



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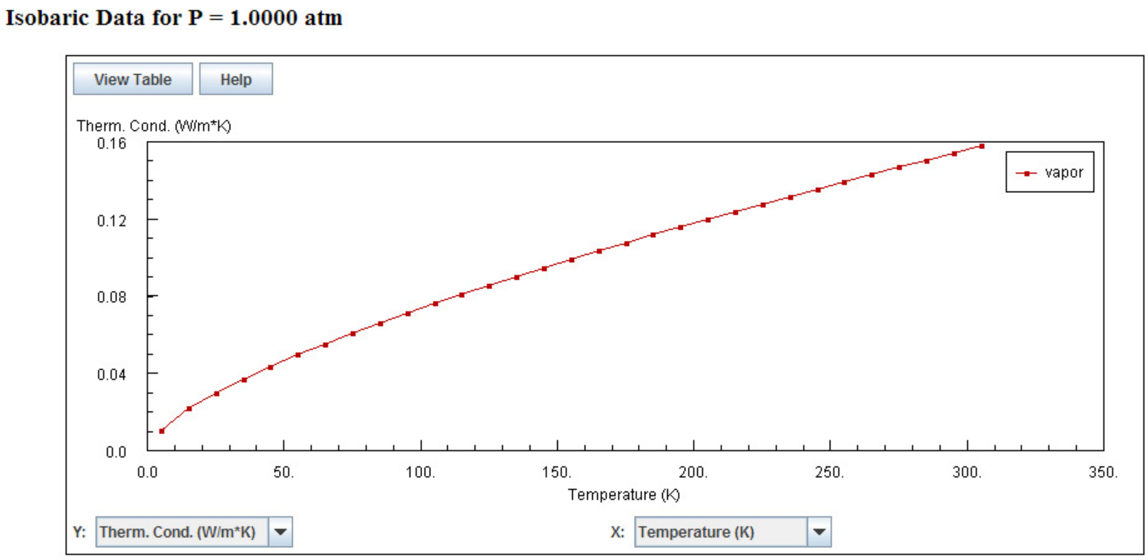
And, for thermal conductivity, we get:



Proceeding along similar lines, we get data for other cryogenic fluids:

1.4.2 For Hydrogen at 1 atm.:

Temperature (K)	Pressure (atm)	Density (kg/m3)	Volume (m3/kg)	Internal Energy (kJ/kg)	Enthalpy (kJ/kg)	Entropy (J/g*K)	Cv (J/g*K)
21	1	1.2813	0.78047	377.14	456.23	22.393	6.3952
31	1	0.81774	1.2229	443.61	567.51	26.739	6.2312
41	1	0.60795	1.6449	507.39	674.06	29.719	6.2162
51	1	0.48538	2.0602	570.42	779.17	32.014	6.2246
61	1	0.40444	2.4725	633.43	883.96	33.89	6.2798
71	1	0.34684	2.8832	697.14	989.28	35.488	6.4
81	1	0.30369	3.2928	762.29	1095.9	36.894	6.5868
91	1	0.27014	3.7018	829.53	1204.6	38.158	6.8279
101	1	0.24328	4.1104	899.32	1315.8	39.318	7.1042
111	1	0.2213	4.5187	971.95	1429.8	40.394	7.397
121	1	0.20297	4.9267	1047.5	1546.7	41.402	7.6912
131	1	0.18746	5.3346	1125.9	1666.5	42.352	7.9758
141	1	0.17414	5.7423	1207.1	1789	43.254	8.2443
151	1	0.1626	6.15	1290.9	1914	44.11	8.4928
161	1	0.1525	6.5575	1377	2041.5	44.927	8.7199
171	1	0.14357	6.965	1465.3	2171	45.708	8.9255
181	1	0.13564	7.3724	1555.5	2302.5	46.456	9.1101
191	1	0.12854	7.7798	1647.5	2435.8	47.172	9.2751
201	1	0.12214	8.1871	1741	2570.6	47.86	9.4219
221	1	0.11109	9.0017	1932.1	2844.2	49.157	9.6666
231	1	0.10628	9.409	2029.3	2982.6	49.77	9.7675
241	1	0.10187	9.8162	2127.4	3122	50.361	9.856
251	1	0.097815	10.223	2226.4	3262.3	50.931	9.9333
261	1	0.094068	10.631	2326.1	3403.2	51.482	10
271	1	0.090598	11.038	2426.4	3544.8	52.014	10.059
281	1	0.087375	11.445	2527.3	3686.9	52.529	10.109
291	1	0.084373	11.852	2628.6	3829.5	53.028	10.152
301	1	0.081571	12.259	2730.3	3972.5	53.511	10.19
311	1	0.078949	12.666	2832.4	4115.8	53.979	10.221
321	1	0.076491	13.074	2934.7	4259.4	54.434	10.248

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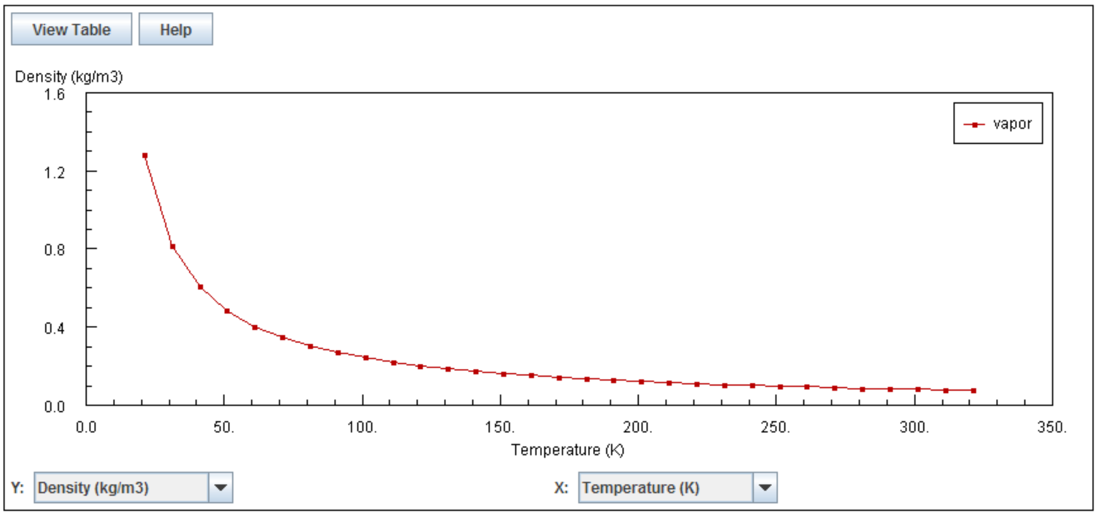
Cp (J/g*K)	Sound Spd. (m/s)	Joule-Thomson (F/atm)	Viscosity (Pa*s)	Therm. Cond. (W/m*K)	Phase	Temperature (K)
11.825	363.69	3.1599	1.11E-06	0.017584	vapor	21
10.786	455.75	1.7539	1.61E-06	0.02545	vapor	31
10.56	528.22	1.1723	2.08E-06	0.032568	vapor	41
10.48	590.61	0.84458	2.51E-06	0.039028	vapor	51
10.491	645.58	0.63452	2.90E-06	0.045223	vapor	61
10.586	694.31	0.48811	3.26E-06	0.051346	vapor	71
10.757	737.68	0.38044	3.60E-06	0.057074	vapor	81
10.987	776.68	0.29868	3.92E-06	0.062792	vapor	91
11.256	812.28	0.23536	4.22E-06	0.069001	vapor	101
11.544	845.35	0.1856	4.51E-06	0.075625	vapor	111
11.834	876.54	0.14601	4.79E-06	0.082141	vapor	121
12.116	906.34	0.11411	5.06E-06	0.088747	vapor	131
12.382	935.04	0.088081	5.33E-06	0.095257	vapor	141
12.628	962.87	0.066589	5.59E-06	0.10162	vapor	151
12.854	989.98	0.048627	5.84E-06	0.10816	vapor	161
13.058	1016.5	0.033446	6.09E-06	0.1146	vapor	171
13.242	1042.4	0.020478	6.33E-06	0.12087	vapor	181
13.406	1067.8	0.0092918	6.57E-06	0.12704	vapor	191
13.552	1092.7	-0.0004462	6.80E-06	0.13303	vapor	201
13.795	1141.3	-0.016555	7.26E-06	0.14463	vapor	221
13.896	1165	-0.023289	7.49E-06	0.15025	vapor	231
13.984	1188.3	-0.029326	7.71E-06	0.15577	vapor	241
14.061	1211.3	-0.03477	7.92E-06	0.16111	vapor	251
14.128	1234	-0.039704	8.14E-06	0.16636	vapor	261
14.186	1256.3	-0.044199	8.35E-06	0.17151	vapor	271
14.236	1278.3	-0.048311	8.56E-06	0.17649	vapor	281
14.279	1300	-0.052088	8.77E-06	0.18145	vapor	291
14.316	1321.4	-0.055571	8.97E-06	0.18624	vapor	301
14.347	1342.6	-0.058791	9.18E-06	0.19102	vapor	311
14.374	1363.5	-0.061779	9.38E-06	0.19568	vapor	321

Isobaric Data for P = 1.0000 atm



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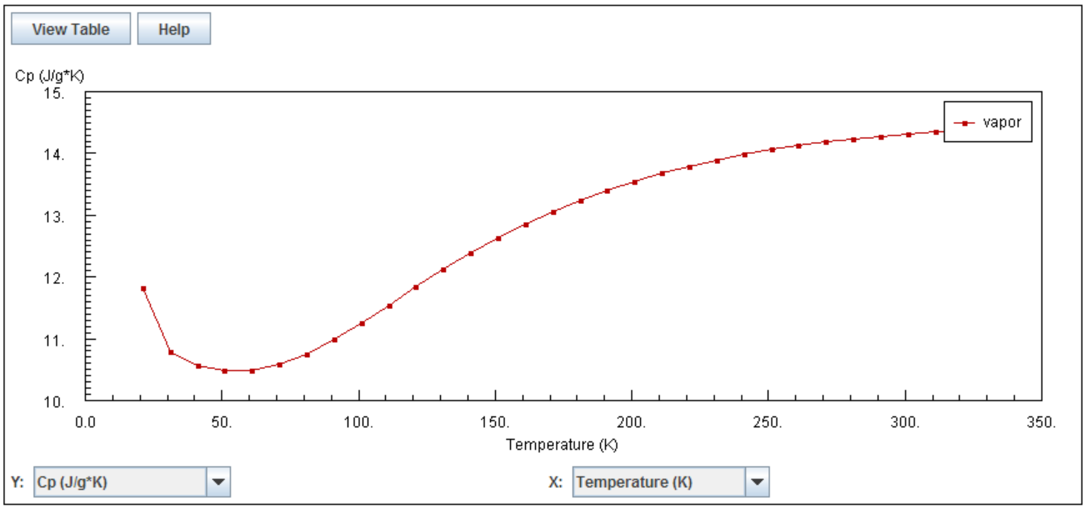

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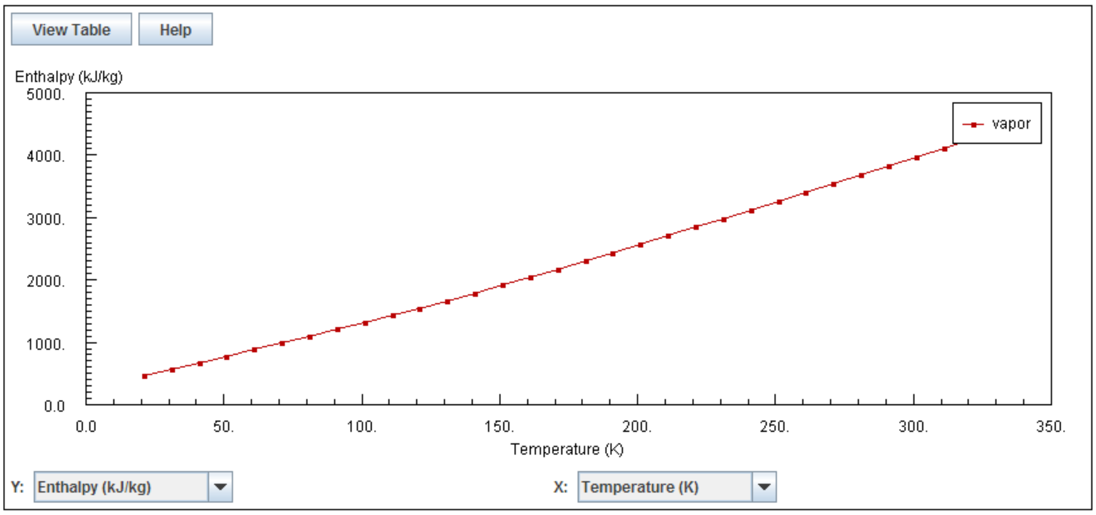

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1.4.3 For Neon at 1 atm.:

Temperature (K)	Pressure (atm)	Density (kg/m3)	Volume (m3/kg)	Internal Energy (kJ/kg)	Enthalpy (kJ/kg)	Entropy (J/g*K)	Cv (J/g*K)
27	1	1208.8	0.00082727	-0.27864	-0.19481	-0.0072013	0.89235
27.104	1	1207	0.00082853	-0.083951	2.99E-15	7.40E-17	0.89131
27.104	1	9.5773	0.10441	75.173	85.752	3.1638	0.87949
37	1	6.7898	0.14728	81.936	96.859	3.5147	0.62667
47	1	5.2891	0.18907	88.286	107.44	3.768	0.62128
57	1	4.3406	0.23038	94.556	117.9	3.9697	0.61965
67	1	3.6836	0.27148	100.79	128.3	4.1378	0.61901
77	1	3.2006	0.31244	107.01	138.67	4.2821	0.61871
87	1	2.8302	0.35333	113.22	149.02	4.4085	0.61855
97	1	2.537	0.39417	119.42	159.36	4.521	0.61845
107	1	2.299	0.43497	125.62	169.7	4.6224	0.61839
117	1	2.102	0.47575	131.82	180.02	4.7146	0.61835
127	1	1.9361	0.5165	138.01	190.34	4.7993	0.61831
137	1	1.7946	0.55724	144.2	200.66	4.8775	0.61829
147	1	1.6723	0.59797	150.39	210.98	4.9502	0.61827
157	1	1.5657	0.63869	156.58	221.29	5.0181	0.61825
167	1	1.4719	0.6794	162.76	231.6	5.0817	0.61824
177	1	1.3887	0.7201	168.95	241.92	5.1417	0.61822
187	1	1.3144	0.7608	175.14	252.23	5.1984	0.61821
197	1	1.2477	0.8015	181.32	262.53	5.2521	0.6182
207	1	1.1874	0.84219	187.51	272.84	5.3031	0.61819
217	1	1.1327	0.88288	193.69	283.15	5.3517	0.61819
227	1	1.0828	0.92356	199.88	293.45	5.3982	0.61818
237	1	1.0371	0.96424	206.06	303.76	5.4426	0.61817
247	1	0.9951	1.0049	212.24	314.07	5.4852	0.61817
257	1	0.95639	1.0456	218.43	324.37	5.5261	0.61816
267	1	0.92057	1.0863	224.61	334.68	5.5654	0.61816
277	1	0.88734	1.127	230.79	344.98	5.6033	0.61815
287	1	0.85643	1.1676	236.97	355.28	5.6399	0.61815
297	1	0.8276	1.2083	243.16	365.59	5.6751	0.61814
307	1	0.80065	1.249	249.34	375.89	5.7093	0.61814

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Cp (J/g*K)	Sound Spd. (m/s)	Joule-Thomson (F/atm)	Viscosity (Pa*s)	Therm. Cond. (W/m*K)	Phase	Temperature (K)
1.8603	596.02	-0.049344	0.00011734	0.15565	liquid	27
1.8621	594.15	-0.049126	0.0001161	0.155	liquid	27.104
1.4151	126.64	2.7826	4.53E-06	0.0066704	vapor	27.104
1.0704	157.92	1.5135	6.17E-06	0.0093328	vapor	37
1.0501	178.97	1.0289	7.75E-06	0.011928	vapor	47
1.0422	197.55	0.76098	9.23E-06	0.014254	vapor	57
1.0383	214.42	0.58899	1.06E-05	0.01639	vapor	67
1.036	229.99	0.46851	1.19E-05	0.018382	vapor	77
1.0346	244.55	0.37914	1.31E-05	0.020259	vapor	87
1.0336	258.27	0.31014	1.43E-05	0.022041	vapor	97
1.0329	271.28	0.25525	1.54E-05	0.023742	vapor	107
1.0324	283.69	0.21056	1.64E-05	0.025372	vapor	117
1.032	295.57	0.17351	1.74E-05	0.026938	vapor	127
1.0317	306.99	0.14232	1.84E-05	0.028448	vapor	137
1.0315	317.99	0.11574	1.93E-05	0.029905	vapor	147
1.0313	328.63	0.092849	2.03E-05	0.031317	vapor	157
1.0311	338.92	0.072951	2.11E-05	0.032686	vapor	167
1.031	348.92	0.055519	2.20E-05	0.034016	vapor	177
1.0309	358.63	0.040142	2.28E-05	0.035312	vapor	187
1.0308	368.08	0.026495	2.37E-05	0.036576	vapor	197
1.0307	377.3	0.014316	2.45E-05	0.037812	vapor	207
1.0307	386.3	0.0033956	2.52E-05	0.039021	vapor	217
1.0306	395.09	-0.0064405	2.60E-05	0.040206	vapor	227
1.0306	403.69	-0.015335	2.68E-05	0.041368	vapor	237
1.0305	412.11	-0.023407	2.75E-05	0.042511	vapor	247
1.0305	420.36	-0.030756	2.82E-05	0.043634	vapor	257
1.0304	428.45	-0.037469	2.90E-05	0.04474	vapor	267
1.0304	436.39	-0.043616	2.97E-05	0.04583	vapor	277
1.0304	444.19	-0.04926	3.04E-05	0.046904	vapor	287
1.0304	451.86	-0.054455	3.10E-05	0.047964	vapor	297
1.0303	459.39	-0.059246	3.17E-05	0.04901	vapor	307

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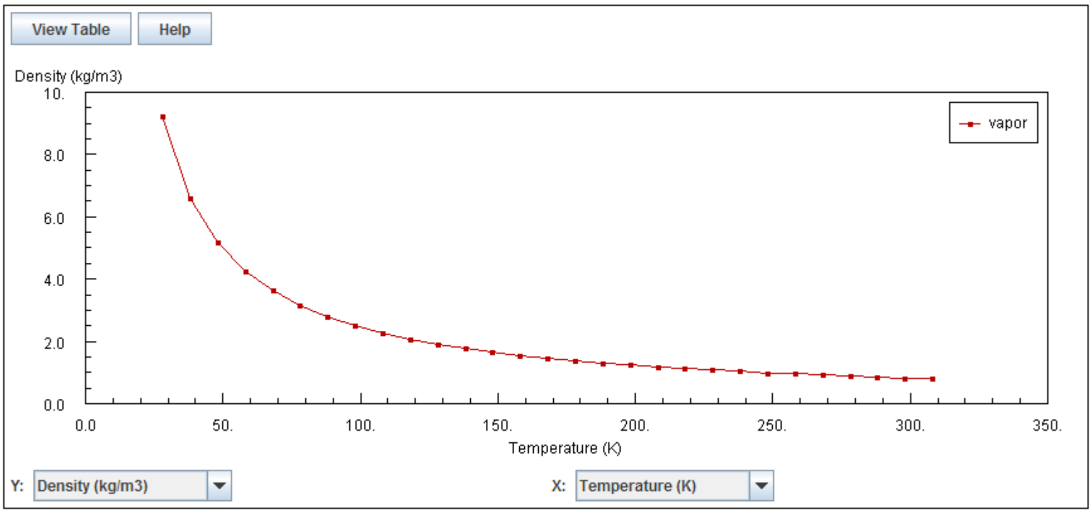

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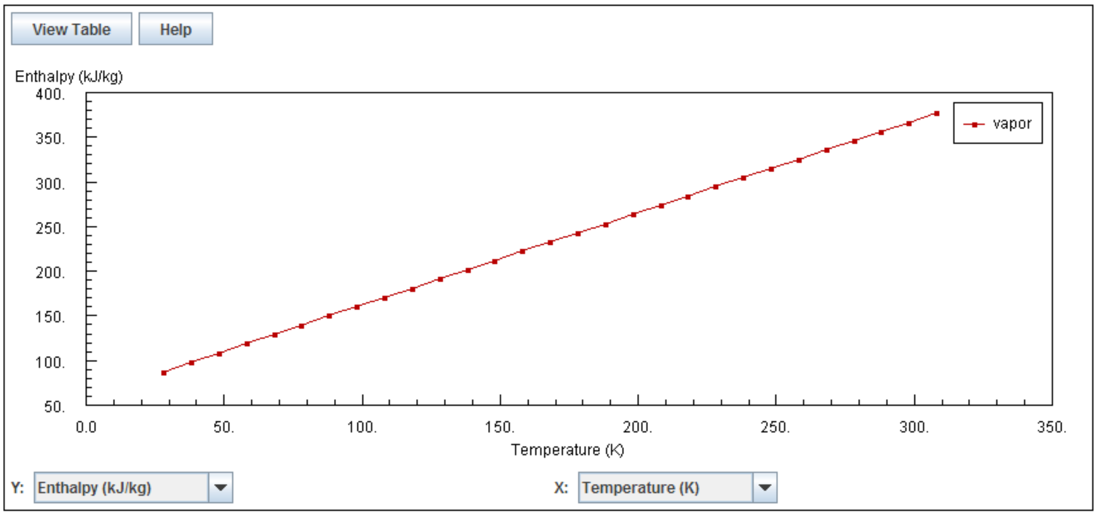

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1.4.4 For Nitrogen at 1 atm.:

Temperature (K)	Pressure (atm)	Density (kg/m3)	Volume (m3/kg)	Internal Energy (kJ/kg)	Enthalpy (kJ/kg)	Entropy (J/g*K)	Cv (J/g*K)
77	1	807.7	0.0012381	-122.87	-122.74	2.8248	1.0861
77.355	1	806.08	0.0012406	-122.14	-122.02	2.8342	1.0841
77.355	1	4.6121	0.21682	55.189	77.158	5.409	0.77128
87	1	4.0458	0.24717	62.786	87.83	5.5391	0.75916
97	1	3.5977	0.27795	70.499	98.662	5.6569	0.7528
107	1	3.2433	0.30833	78.12	109.36	5.7619	0.74927
117	1	2.9547	0.33844	85.686	119.98	5.8568	0.74716
127	1	2.7146	0.36838	93.217	130.54	5.9434	0.74582
137	1	2.5114	0.39819	100.72	141.07	6.0232	0.74494
147	1	2.3369	0.42791	108.21	151.57	6.0972	0.74433
157	1	2.1855	0.45756	115.69	162.06	6.1662	0.7439
167	1	2.0527	0.48716	123.16	172.52	6.2308	0.74359
177	1	1.9353	0.51672	130.62	182.98	6.2916	0.74336
187	1	1.8307	0.54624	138.08	193.43	6.3491	0.74319
197	1	1.7369	0.57573	145.53	203.87	6.4035	0.74306
207	1	1.6524	0.6052	152.98	214.3	6.4551	0.74297
217	1	1.5757	0.63465	160.42	224.73	6.5043	0.74289
227	1	1.5058	0.66408	167.87	235.15	6.5513	0.74285
237	1	1.442	0.6935	175.31	245.58	6.5962	0.74282
247	1	1.3833	0.7229	182.75	256	6.6393	0.74281
257	1	1.3293	0.7523	190.19	266.41	6.6806	0.74282
267	1	1.2793	0.78168	197.62	276.83	6.7204	0.74285
277	1	1.233	0.81106	205.06	287.24	6.7587	0.74291
287	1	1.1899	0.84043	212.5	297.66	6.7956	0.743
297	1	1.1497	0.8698	219.94	308.07	6.8313	0.74312
307	1	1.1122	0.89916	227.38	318.48	6.8658	0.74328

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Cp (J/g*K)	Sound Spd. (m/s)	Joule-Thomson (F/atm)	Viscosity (Pa*s)	Therm. Cond. (W/m*K)	Phase	Temperature (K)
2.0398	855.04	-0.062624	0.00016295	0.14657	liquid	77
2.0415	851.39	-0.062215	0.00016065	0.14581	liquid	77.355
1.1239	174.82	4.942	5.44E-06	0.0075047	vapor	77.355
1.0927	186.89	3.8561	6.10E-06	0.0085006	vapor	87
1.0754	198.34	3.1097	6.77E-06	0.0095597	vapor	97
1.0652	209	2.5838	7.42E-06	0.010577	vapor	107
1.0588	219.05	2.1945	8.07E-06	0.011552	vapor	117
1.0544	228.58	1.8951	8.70E-06	0.012492	vapor	127
1.0513	237.69	1.6581	9.31E-06	0.013403	vapor	137
1.0491	246.43	1.4659	9.92E-06	0.014288	vapor	147
1.0474	254.85	1.307	1.05E-05	0.015152	vapor	157
1.0461	262.98	1.1735	1.11E-05	0.015996	vapor	167
1.0451	270.85	1.0599	1.17E-05	0.016822	vapor	177
1.0443	278.49	0.96193	1.22E-05	0.017631	vapor	187
1.0437	285.91	0.87671	1.28E-05	0.018425	vapor	197
1.0431	293.14	0.80191	1.33E-05	0.019203	vapor	207
1.0427	300.19	0.73573	1.38E-05	0.019967	vapor	217
1.0423	307.08	0.67679	1.43E-05	0.020719	vapor	227
1.042	313.8	0.62397	1.49E-05	0.021457	vapor	237
1.0418	320.38	0.57637	1.54E-05	0.022184	vapor	247
1.0416	326.83	0.53326	1.59E-05	0.022899	vapor	257
1.0415	333.14	0.49405	1.63E-05	0.023603	vapor	267
1.0414	339.34	0.45823	1.68E-05	0.024297	vapor	277
1.0413	345.42	0.42539	1.73E-05	0.024982	vapor	287
1.0413	351.39	0.39518	1.78E-05	0.025658	vapor	297
1.0414	357.26	0.36729	1.82E-05	0.026324	vapor	307

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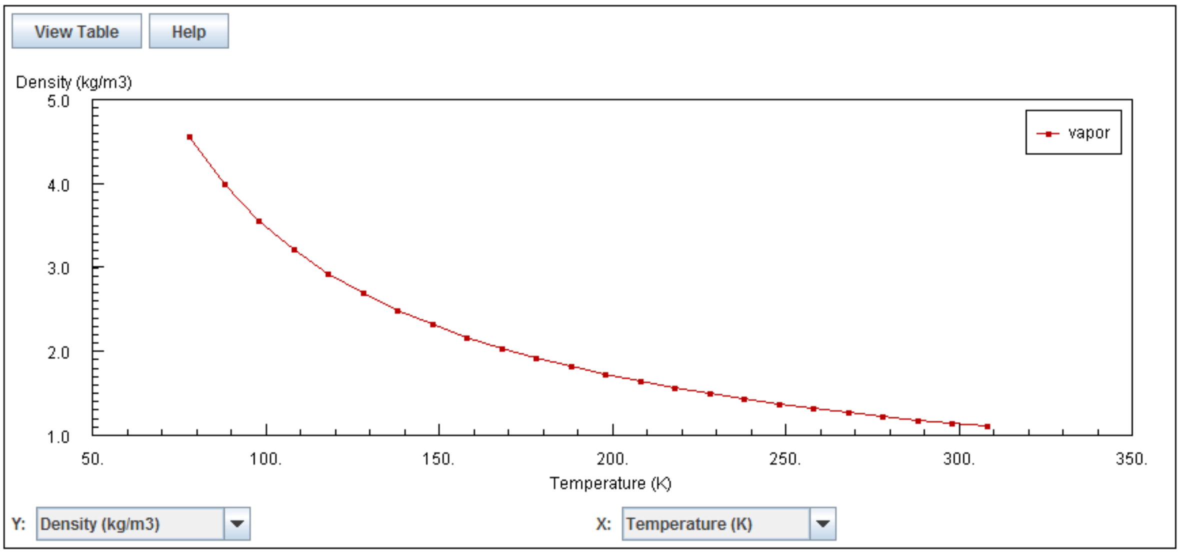

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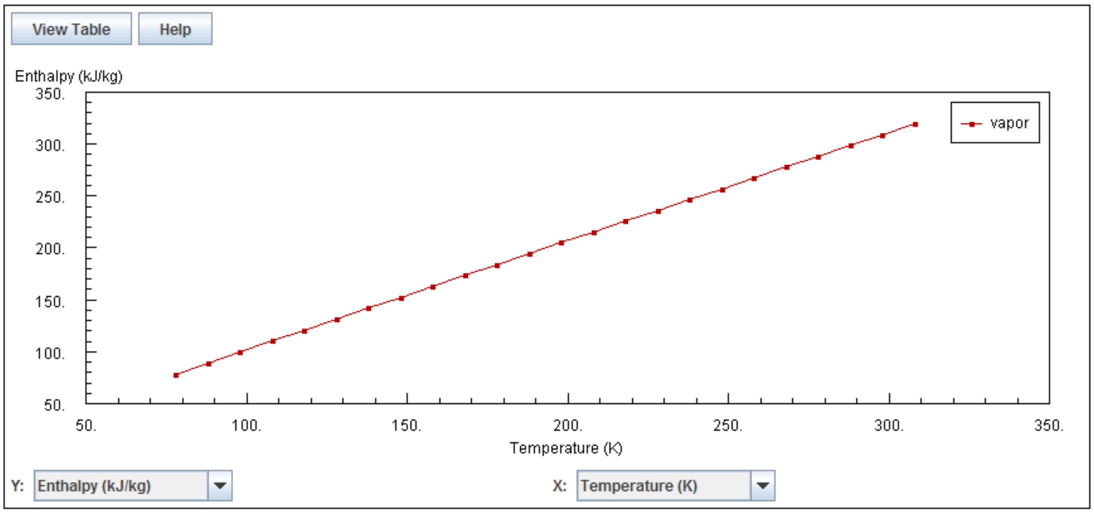

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1.4.5 For Oxygen at 1 atm.:

Temperature (K)	Pressure (atm)	Density (kg/m3)	Volume (m3/kg)	Internal Energy (kJ/kg)	Enthalpy (kJ/kg)	Entropy (J/g*K)	Cv (J/g*
90	1	1142.1	0.00087557	-133.78	-133.69	2.9383	0.9295
90.188	1	1141.2	0.00087629	-133.46	-133.37	2.9418	0.9288
90.188	1	4.4671	0.22386	57.006	79.688	5.3042	0.6755
100	1	3.9946	0.25034	63.598	88.963	5.4019	0.6527
110	1	3.6106	0.27697	70.235	98.299	5.4908	0.6541
120	1	3.2962	0.30338	76.859	107.6	5.5718	0.6543
130	1	3.0336	0.32964	83.463	116.86	5.6459	0.6537
140	1	2.8107	0.35578	90.048	126.1	5.7144	0.6530
150	1	2.619	0.38183	96.617	135.31	5.7779	0.6524
160	1	2.4521	0.40781	103.17	144.49	5.8372	0.6519
170	1	2.3055	0.43374	109.72	153.67	5.8928	0.6515
180	1	2.1757	0.45963	116.26	162.83	5.9452	0.6513
190	1	2.0598	0.48549	122.79	171.99	5.9947	0.6512
200	1	1.9557	0.51132	129.33	181.13	6.0416	0.6512
210	1	1.8618	0.53713	135.86	190.28	6.0862	0.6513
220	1	1.7765	0.56291	142.39	199.42	6.1288	0.6516
230	1	1.6987	0.58869	148.92	208.57	6.1694	0.6519
240	1	1.6275	0.61445	155.45	217.71	6.2083	0.6524
250	1	1.562	0.6402	161.99	226.86	6.2457	0.6531
260	1	1.5016	0.66594	168.53	236.01	6.2816	0.6539
270	1	1.4458	0.69167	175.09	245.17	6.3161	0.6548
280	1	1.3939	0.71739	181.65	254.34	6.3495	0.656
290	1	1.3457	0.74311	188.22	263.52	6.3817	0.6572
300	1	1.3007	0.76882	194.81	272.71	6.4128	0.6587
310	1	1.2586	0.79453	201.41	281.92	6.443	0.6603

Cp (J/g*K)	Sound Spd. (m/s)	Joule-Thomson (F/atm)	Viscosity (Pa*s)	Therm. Cond. (W/m*K)	Phase	Temperatu (K)
1.6988	905.91	-0.05709	0.00019685	0.15189	liquid	90
1.6994	904.35	-0.056969	0.00019582	0.15161	liquid	90.188
0.97068	177.45	4.2933	7.01E-06	0.0083691	vapor	90.188
0.9356	188.33	3.3717	7.75E-06	0.0093114	vapor	100
0.93186	198.09	2.8735	8.49E-06	0.010266	vapor	110
0.92824	207.32	2.4702	9.22E-06	0.011212	vapor	120
0.92481	216.14	2.142	9.94E-06	0.012148	vapor	130
0.92198	224.58	1.876	1.06E-05	0.013074	vapor	140
0.91978	232.68	1.6594	1.13E-05	0.013989	vapor	150
0.91808	240.5	1.481	1.20E-05	0.014892	vapor	160
0.9168	248.04	1.3322	1.27E-05	0.015785	vapor	170
0.91583	255.35	1.2064	1.34E-05	0.016668	vapor	180
0.91513	262.44	1.0987	1.40E-05	0.01754	vapor	190
0.91464	269.33	1.0056	1.47E-05	0.018403	vapor	200
0.91436	276.04	0.92429	1.53E-05	0.019256	vapor	210
0.91425	282.58	0.85254	1.59E-05	0.020102	vapor	220
0.91433	288.95	0.78875	1.65E-05	0.020939	vapor	230
0.91459	295.17	0.73164	1.71E-05	0.02177	vapor	240
0.91502	301.25	0.68019	1.77E-05	0.022595	vapor	250
0.91563	307.19	0.63358	1.83E-05	0.023415	vapor	260
0.91642	313.01	0.59114	1.89E-05	0.02423	vapor	270
0.9174	318.69	0.55232	1.94E-05	0.025042	vapor	280
0.91855	324.27	0.51669	2.00E-05	0.025851	vapor	290
0.91989	329.72	0.48386	2.06E-05	0.026657	vapor	300
0.9214	335.07	0.45352	2.11E-05	0.027462	vapor	310

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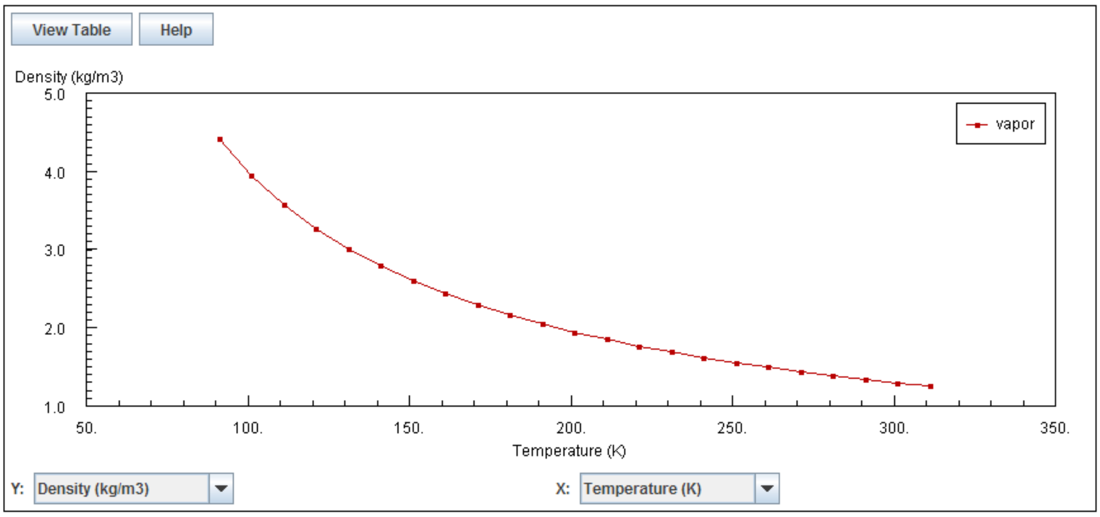

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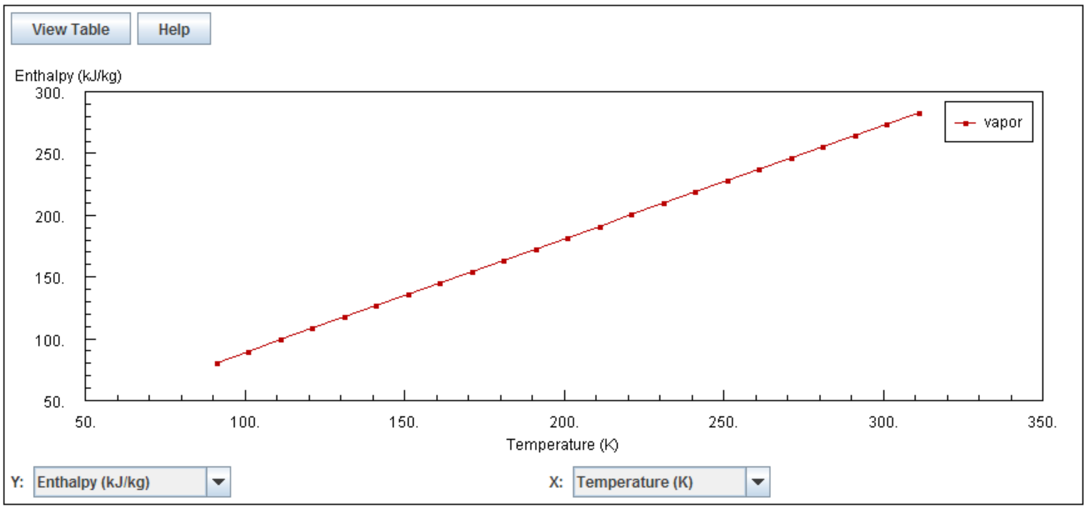

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1.4.6 For Fluorine at 1 atm.:

Temperature (K)	Pressure (atm)	Density (kg/m3)	Volume (m3/kg)	Internal Energy (kJ/kg)	Enthalpy (kJ/kg)	Entropy (J/g*K)	Cv (J/g*K)
80	1	1536.6	0.00065079	-7.6364	-7.5704	-0.091767	0.83532
85.037	1	1501.8	0.00066587	-0.067469	-1.21E-14	-1.91E-17	0.82091
85.037	1	5.6413	0.17726	156.41	174.37	2.0505	0.56993
90	1	5.2976	0.18876	159.31	178.43	2.097	0.56564
100	1	4.7271	0.21154	165.06	186.49	2.1819	0.55989
110	1	4.2739	0.23398	170.73	194.43	2.2576	0.55644
120	1	3.9032	0.2562	176.34	202.3	2.3261	0.55437
130	1	3.5937	0.27827	181.93	210.12	2.3887	0.55328
140	1	3.3308	0.30023	187.5	217.92	2.4464	0.55296
150	1	3.1044	0.32212	193.06	225.7	2.5001	0.5533
160	1	2.9073	0.34396	198.62	233.47	2.5503	0.55424
170	1	2.7341	0.36575	204.19	241.25	2.5974	0.55575
180	1	2.5806	0.38751	209.77	249.04	2.642	0.55778
190	1	2.4435	0.40925	215.38	256.85	2.6842	0.5603
200	1	2.3203	0.43097	221.01	264.68	2.7243	0.56324
210	1	2.2091	0.45267	226.67	272.54	2.7627	0.56658
220	1	2.1081	0.47436	232.36	280.43	2.7994	0.57024
230	1	2.016	0.49604	238.09	288.35	2.8346	0.57419
240	1	1.9316	0.51771	243.86	296.32	2.8685	0.57837
250	1	1.854	0.53938	249.67	304.33	2.9012	0.58273
260	1	1.7824	0.56104	255.53	312.38	2.9328	0.58723
270	1	1.7162	0.58269	261.43	320.47	2.9633	0.59182
280	1	1.6547	0.60434	267.38	328.61	2.9929	0.59648
290	1	1.5975	0.62598	273.37	336.8	3.0217	0.60117
300	1	1.5441	0.64762	279.41	345.03	3.0496	0.60586

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Cp (J/g*K)	Sound Spd. (m/s)	Joule-Thomson (F/atm)	Viscosity (Pa*s)	Therm. Cond. (W/m*K)	Phase	Temperature (K)
1.4963	871.37	-0.051309	undefined	undefined	liquid	80
1.5106	823.56	-0.048324	undefined	undefined	liquid	85.037
0.82522	158.37	4.6817	undefined	undefined	vapor	85.037
0.81405	163.45	4.1187	undefined	undefined	vapor	90
0.79907	173.08	3.2575	undefined	undefined	vapor	100
0.78995	182.06	2.6418	undefined	undefined	vapor	110
0.78419	190.52	2.1862	undefined	undefined	vapor	120
0.78057	198.55	1.8397	undefined	undefined	vapor	130
0.77846	206.22	1.5705	undefined	undefined	vapor	140
0.7775	213.56	1.3573	undefined	undefined	vapor	150
0.77748	220.6	1.1859	undefined	undefined	vapor	160
0.77826	227.38	1.0459	undefined	undefined	vapor	170
0.77973	233.92	0.93021	undefined	undefined	vapor	180
0.78179	240.23	0.83348	undefined	undefined	vapor	190
0.78439	246.33	0.75178	undefined	undefined	vapor	200
0.78743	252.25	0.68211	undefined	undefined	vapor	210
0.79086	257.98	0.6222	undefined	undefined	vapor	220
0.79462	263.56	0.57028	undefined	undefined	vapor	230
0.79863	268.99	0.52496	undefined	undefined	vapor	240
0.80286	274.27	0.48515	undefined	undefined	vapor	250
0.80724	279.43	0.44995	undefined	undefined	vapor	260
0.81174	284.47	0.41865	undefined	undefined	vapor	270
0.81632	289.4	0.39068	undefined	undefined	vapor	280
0.82093	294.23	0.36555	undefined	undefined	vapor	290
0.82556	298.96	0.34287	undefined	undefined	vapor	300

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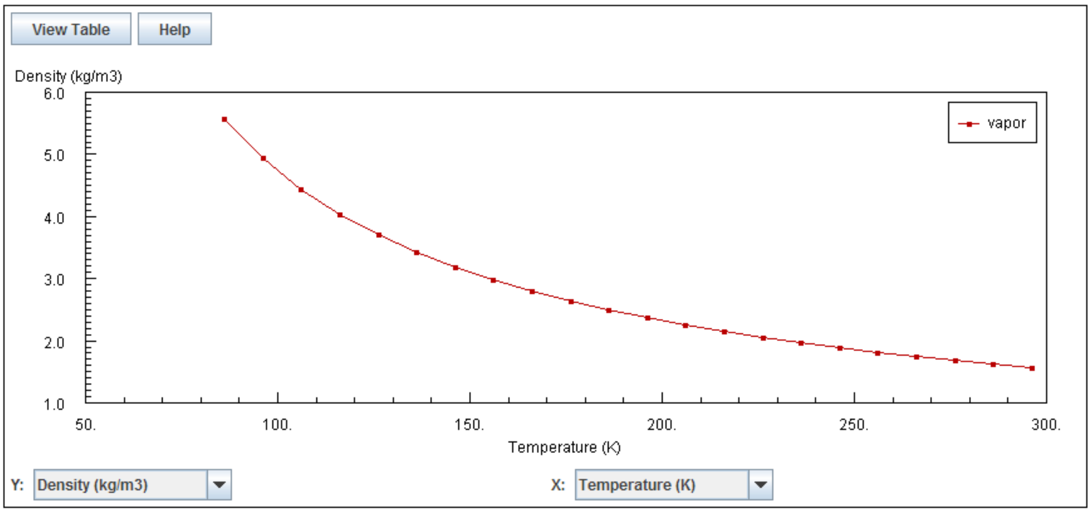

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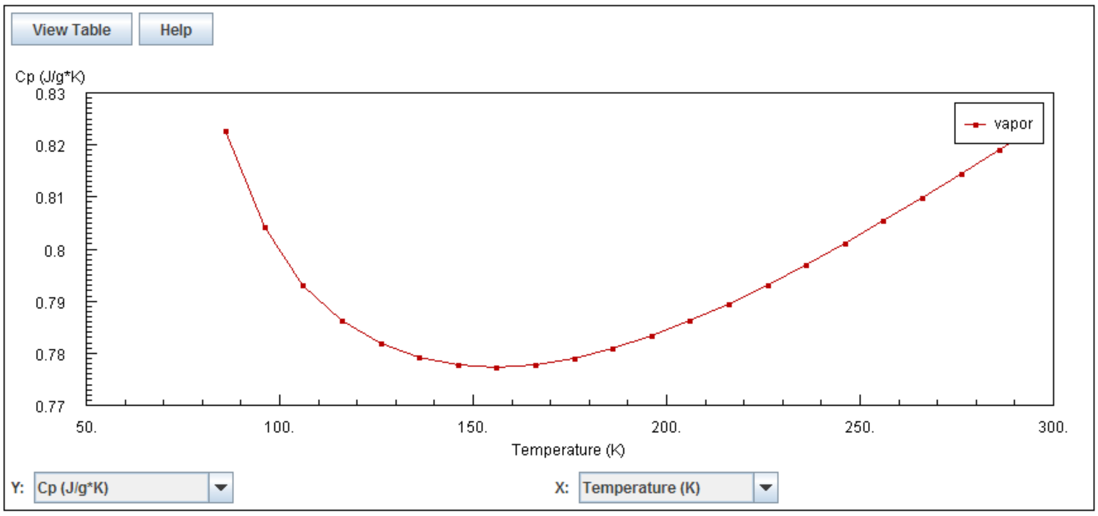

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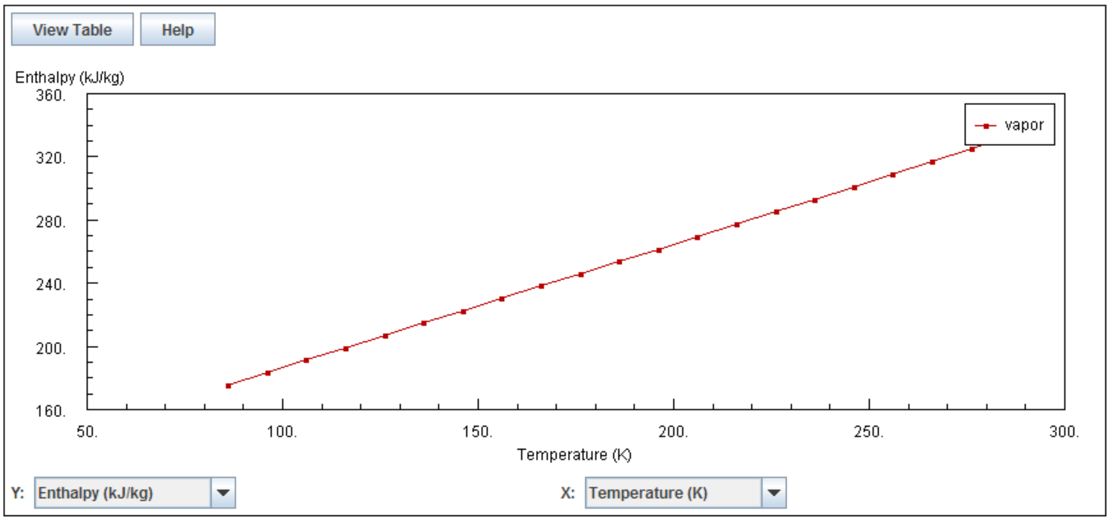

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1.4.7 For Argon at 1 atm.:

Temperature (K)	Pressure (atm)	Density (kg/m3)	Volume (m3/kg)	Internal Energy (kJ/kg)	Enthalpy (kJ/kg)	Entropy (J/g*K)	Cv (J/g*K)
87	1	1397.3	0.00071568	-117.93	-117.86	1.3711	0.53722
87.302	1	1395.4	0.00071664	-117.59	-117.52	1.375	0.53612
87.302	1	5.7736	0.1732	26.069	43.618	3.2208	0.32804
97	1	5.1472	0.19428	29.339	49.024	3.2795	0.32192
107	1	4.6366	0.21568	32.628	54.482	3.333	0.31855
117	1	4.222	0.23685	35.87	59.869	3.3812	0.3166
127	1	3.8776	0.25789	39.08	65.211	3.425	0.31538
137	1	3.5864	0.27883	42.271	70.523	3.4653	0.31458
147	1	3.3367	0.2997	45.447	75.814	3.5025	0.31403
157	1	3.12	0.32051	48.613	81.088	3.5372	0.31364
167	1	2.9301	0.34128	51.771	86.351	3.5697	0.31336
177	1	2.7623	0.36202	54.924	91.605	3.6003	0.31315
187	1	2.6128	0.38273	58.072	96.852	3.6291	0.31299
197	1	2.4788	0.40342	61.216	102.09	3.6564	0.31286
207	1	2.358	0.42409	64.357	107.33	3.6824	0.31276
217	1	2.2485	0.44475	67.496	112.56	3.707	0.31268
227	1	2.1487	0.46539	70.633	117.79	3.7306	0.31262
237	1	2.0575	0.48603	73.769	123.02	3.7531	0.31257
247	1	1.9737	0.50665	76.903	128.24	3.7747	0.31252
257	1	1.8966	0.52727	80.036	133.46	3.7954	0.31249
267	1	1.8252	0.54788	83.167	138.68	3.8154	0.31246
277	1	1.7591	0.56848	86.298	143.9	3.8346	0.31243
287	1	1.6976	0.58908	89.429	149.12	3.8531	0.31241
297	1	1.6402	0.60968	92.558	154.33	3.8709	0.31239
307	1	1.5866	0.63027	95.687	159.55	3.8882	0.31237

Cp (J/g*K)	Sound Spd. (m/s)	Joule-Thomson (F/atm)	Viscosity (Pa*s)	Therm. Cond. (W/m*K)	Phase	Temperature (K)
1.1169	840.45	-0.071837	0.00027352	0.12605	liquid	87
1.1172	838.33	-0.071613	0.00027071	0.12565	liquid	87.302
0.56583	170.86	6.0004	7.14E-06	0.0055249	vapor	87.302
0.55059	181.12	4.8479	7.95E-06	0.0061537	vapor	97
0.54167	190.92	4.0164	8.78E-06	0.00682	vapor	107
0.53616	200.12	3.4065	9.60E-06	0.0074756	vapor	117
0.53253	208.84	2.9412	1.04E-05	0.0081172	vapor	127
0.53001	217.17	2.5752	1.12E-05	0.0087458	vapor	137
0.52819	225.15	2.28	1.20E-05	0.0093626	vapor	147
0.52683	232.84	2.0373	1.28E-05	0.0099686	vapor	157
0.5258	240.26	1.8344	1.35E-05	0.010565	vapor	167
0.52499	247.45	1.6623	1.43E-05	0.011151	vapor	177
0.52434	254.42	1.5146	1.50E-05	0.011728	vapor	187
0.52382	261.21	1.3866	1.57E-05	0.012297	vapor	197
0.5234	267.81	1.2745	1.65E-05	0.012857	vapor	207
0.52304	274.25	1.1757	1.72E-05	0.01341	vapor	217
0.52275	280.54	1.0879	1.79E-05	0.013954	vapor	227
0.52249	286.68	1.0095	1.85E-05	0.014491	vapor	237
0.52228	292.7	0.93892	1.92E-05	0.015021	vapor	247
0.5221	298.59	0.87519	1.99E-05	0.015543	vapor	257
0.52194	304.36	0.81733	2.06E-05	0.016059	vapor	267
0.5218	310.03	0.76458	2.12E-05	0.016568	vapor	277
0.52168	315.59	0.7163	2.19E-05	0.01707	vapor	287
0.52157	321.05	0.67196	2.25E-05	0.017567	vapor	297
0.52147	326.42	0.6311	2.31E-05	0.018057	vapor	307

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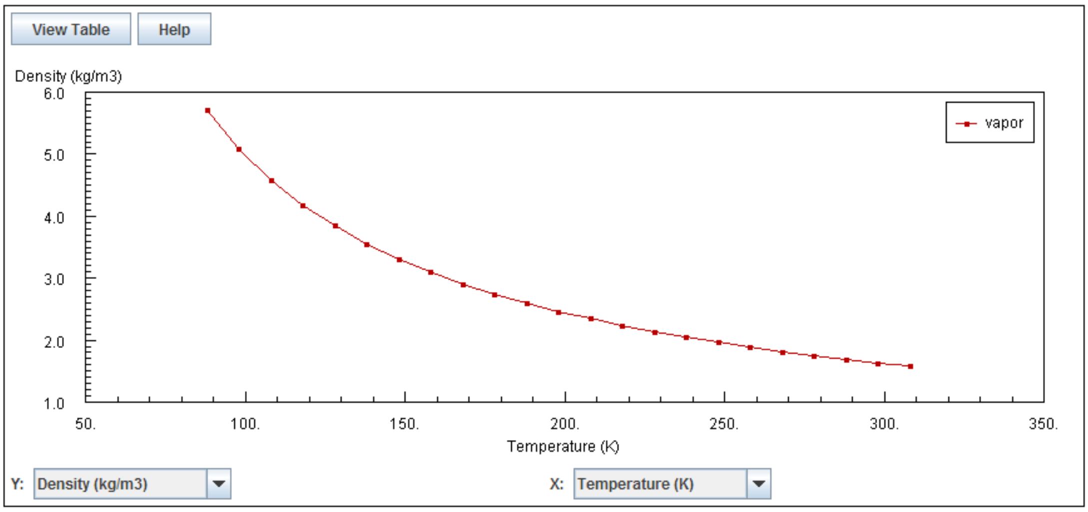

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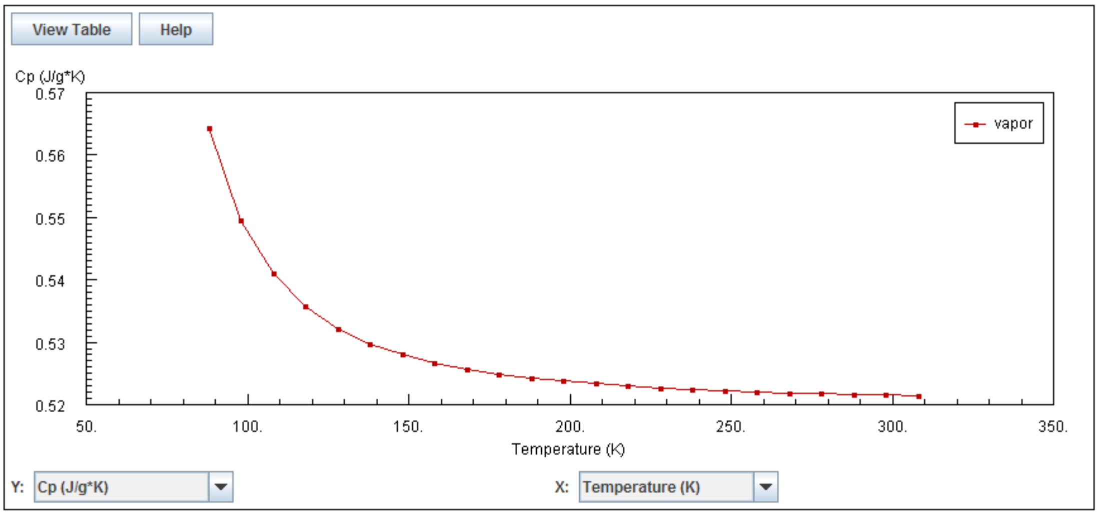

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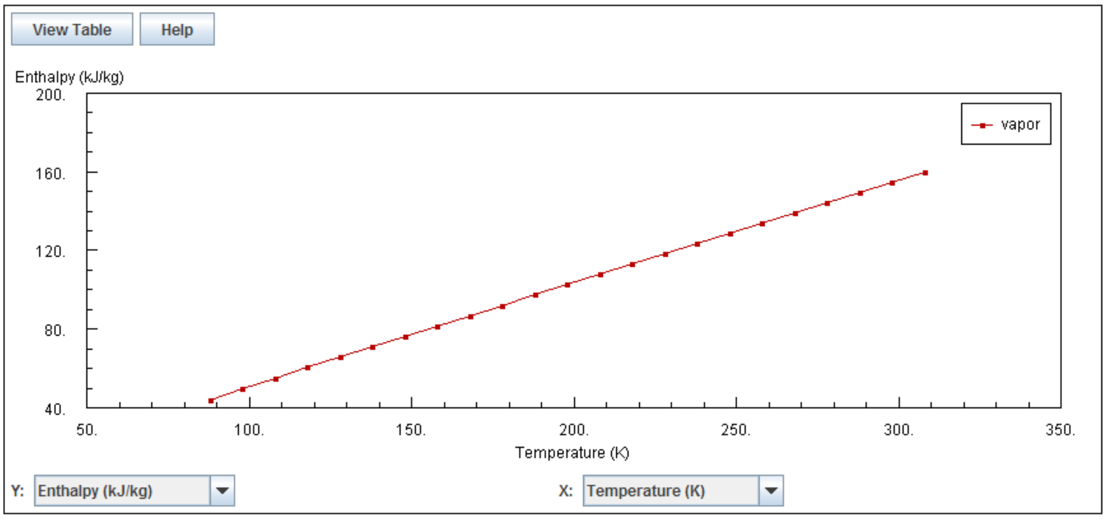

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2 Properties of materials at low temperatures

Learning objectives:

1. In this chapter, topics on 'Low temp properties of materials', such as mechanical properties, thermal properties, electrical properties and properties of some Type-I and Type-II and High temp. superconductors, are dealt with.
2. First, a very useful compilation of material properties from various sources is given.
3. Of particular interest are the polynomial curve fit equations for properties at low temperatures, and in some cases, graphs given by the NIST-Cryogenics website.
4. Several Functions are written in EES, EXCEL and Mathcad for thermal and mechanical properties of most of the materials of interest in cryogenics. This will make computer designs of cryogenic systems very easy. When no equations are available from the NIST- cryogenics site, graphs from standard text books are digitized and data is used either to get curve fit equations or to prepare look up tables for interpolation.
5. Many numerical problems are solved to illustrate the use of computer calculations.

==

2.1 Definitions, Statements and Formulas used [1-7]:

2.1.1 Properties at ambient temperatures:

Properties of materials undergo substantial changes – sometimes, dramatic – as temperature is lowered from ambient to cryogenic range (i.e. below 150 K).

Materials of interest are: Stainless steels (SS) of various grades, Aluminium and its alloys, copper and its alloys, plastics etc.

To start with, we show below the properties of Aluminium, copper and SS:

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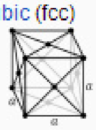
For Aluminium [6]:

Physical properties	
Phase	solid
Melting point	933.47 K (660.32 °C, 1220.58 °F)
Boiling point	2743 K (2470 °C, 4478 °F)
Density (near r.t.)	2.70 g·cm^{-3} (at 0 °C, 101.325 kPa)
Liquid density	at m.p.: 2.375 g·cm^{-3}
Heat of fusion	10.71 kJ·mol^{-1}
Heat of vaporization	284 kJ·mol^{-1}
Molar heat capacity	24.20 J·mol^{-1}·K^{-1}

Vapor pressure

P (Pa)	1	10	100	1 k	10 k	100 k
at T (K)	1482	1632	1817	2054	2364	2790

Miscellanea	
Crystal structure	face-centered cubic (fcc) 
Speed of sound	thin rod: (rolled) 5000 m·s^{-1} (at r.t.)
Thermal expansion	23.1 µm·m^{-1}·K^{-1} (at 25 °C)
Thermal conductivity	237 W·m^{-1}·K^{-1}
Electrical resistivity	at 20 °C: 28.2 nΩ·m
Magnetic ordering	paramagnetic[3]
Young's modulus	70 GPa
Shear modulus	26 GPa
Bulk modulus	76 GPa
Poisson ratio	0.35
Mohs hardness	2.75
Vickers hardness	167 MPa
Brinell hardness	245 MPa
CAS number	7429-90-5

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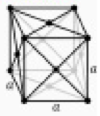
For Copper [7]:

Physical properties	
hase	solid
lelting point	1357.77 K (1084.62 °C, 1984.32 °F)
oiling point	2835 K (2562 °C, 4643 °F)
ensity (near r.t.)	8.96 g·cm^{-3} (at 0 °C, 101.325 kPa)
iquid density	at m.p.: 8.02 g·cm^{-3}
eat of fusion	13.26 kJ·mol^{-1}
eat of aporization	300.4 kJ·mol^{-1}
lolar heat apacity	24.440 J·mol^{-1}·K^{-1}

Vapor pressure

P (Pa)	1	10	100	1 k	10 k	100 k
at T (K)	1509	1661	1850	2089	2404	2834

Miscellanea	
Crystal structure	face-centered cubic (fcc) 
Speed of sound	thin rod: (annealed) 3810 m·s^{-1} (at r.t.)
Thermal expansion	16.5 µm·m^{-1}·K^{-1} (at 25 °C)
Thermal conductivity	401 W·m^{-1}·K^{-1}
Electrical resistivity	at 20 °C: 16.78 nΩ·m
Magnetic ordering	diamagnetic[1]
Young's modulus	110–128 GPa
Shear modulus	48 GPa
Bulk modulus	140 GPa
Poisson ratio	0.34
Mohs hardness	3.0
Vickers hardness	369 MPa
Brinell hardness	874 MPa (HB=35)

For Stainless Steel [8]:

Ambient Temperature Physical Properties of Common Stainless Steels

Carbon Steel									
Common Name	UNS No.	Density		Specific Heat		Electrical Resistivity		Young's Modulus	
		g/cm3	lb./in3	J/kg° K	Btu/lb./°F	micro ohm-m	micro ohm-in.	GPa	x106 psi
Carbon Steel	G10200	7.64	0.278	447	0.107	0.10	3.9	207	30.0
Austenitic Stainless Steels									
Common Name	UNS No.	Density		Specific Heat		Electrical Resistivity		Young's Modulus	
		g/cm3	lb./in3	J/kg° K	Btu/lb./°F	micro ohm-m	micro ohm-in.	GPa	x106 psi
201	S20100	7.86	0.284	502	0.12	0.67	-	207	30
301	S30100	8.03	0.29	-	-	0.72	28.3	193	28
304L	S30403	7.90	0.285	500	0.12	0.72	28.3	200	29
305	S30500	7.90	0.285	500	0.12	0.72	28.3	200	29
321	S32100	7.92	0.286	500	0.12	0.72	28.3	193	28
347	S34700	7.96	0.288	500	0.12	0.72	28.3	193	28
309	S30900	8.03	0.29	502	0.12	0.78	30.7	200	29
310	S31000	8.03	0.29	502	0.12	0.94	37.0	200	29
316L	S31603	7.95	0.287	469	0.112	0.74	29.1	200	29.0
317L	S31703	7.95	0.287	-	-	0.79	31.1	-	-
317LMN	S31726	8.02	0.290	502	0.112	0.85	33.5	200	29.0
904L	N08904	7.95	0.287	461	0.110	0.95	37.4	190	28.0
	S31254	7.95	0.287	498	0.119	0.85	33.5	200	29.0
	N08367	8.06	0.291	461	0.110	0.89	35.0	195	28.2

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Typical mechanical properties for architectural metals

Building Material	Tensile Strength to weight ratio	Tensile Strength ksi (MPa)	Yield Strength, ksi (MPa)	Elongation in 2in. (50mm), min. %
Stainless Steels				
316 Annealed	257	75 (515)	30 (205)	35
304 Annealed	257	75 (515)	30 (205)	35
2205	324	105 (723)	74 (510)	30
HSLA Steel, 3/4 - 1.5 in. (20-40 mm)	239	67 (460)	46 (315)	21
Structural Steel (plate and bar)	261	58/80 (400/550)	36 (250)	23
Carbon steel sheet, cold rolled	164	46 (317)	34 (234)	35
Aluminum Alloys				
3003-H14	222	22 (150)	21 (145)	40
3105-H14	255	25 (170)	22 (150)	5
5005-H16	265	26 (180)	25 (170)	5
6061-T6	459	45 (310)	40 (275)	12
6063-T5	276	27 (185)	21 (145)	12
Copper	112	36 (250)	28 (195)	30

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Physical constants and thermal properties

Building Material	Density Lbs/in³ (g/cm³)	Coef. Thermal Expansion 68-212°F (20-100°C) µin/in °F (µm/m·°K)	Thermal Conductivity 212°F (100°C) Btu·in/ft²·hr·F (W/m·°K)
Stainless Steels			
316	0.29 (8.0)	8.8 (15.9)	113 (16.3)
304	0.29 (8.0)	9.6 (17.2)	113 (16.3)
2205	0.285 (7.85)	7.22 (13.0)	110 (16.0)
Gray Iron	0.27 (7.5)	6.6 (11.9)	348 (50)
Carbon Steel	0.28 (7.8)	6.7 (12.1)	324 (47)
HSLA Weathering Steel	0.28 (7.8)	6.7 (12.1)	324 (47)
Copper C11000	0.321 (8.89)	9.6 (17.2)	2688 (387)
Alluminum Alloys			
3003 H14	0.099 (2.73)	12.9 (23.2)	1100 (159)
3105	0.098 (2.72)	13.1 (23.6)	1190 (172)
5005	0.098 (2.70)	13.2 (23.75)	1390 (200)
6061 T6	0.098 (2.70)	13.1 (23.6)	1160 (167)
6063 T5	0.097 (2.70)	13.0 (23.4)	1450 (209)

(i) Metals Handbook Vol. 2, 10th Edition, Properties and Selection: Nonferrous Alloys and Special-Purpose Materials, ASM International, 1990
(ii) Harold E. McGannon, The Making, Shaping & Treating of Steel, 9th Edition, 1971, United States Steel

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Representative design values for longitudinal and transverse compression and tension:

Grade	Direction and type of stress	0.2% Yield Strength ksi (MPa)	Young's modulus, E x 10^6 psi (GPa)	Shear modulus, G 10^6 psi (GPa)
304L	LT	38 (262)	28 (193)	11 (77)
	LC	36 (250)		
	TT	38 (259)	29 (198)	
	TC	37 (255)		
316L	LT	40 (277)	28 (193)	10.7 (74)
	LC	41 (285)		
	TT	41 (286)	29 (198)	
	TC	43 (297)		
2205	LT	75 (518)	29 (200)	11.3 (78)
	LC	76 (525)		
	TT	79 (544)	30 (207)	
	TC	78 (540)		

From NiDI *Design Manual for Structural Stainless Steel*
LT - Longitudinal tension LC - Longitudinal compression
TT - Transverse tension TC - Transverse compression

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2.1.2 Variation of properties with temperature:

As temperature falls down to cryogenic range, yield stress and ultimate stress increase, generally. This is shown in Tables below [9]:

Yield stress and ultimate stress:

Yield stress σ_y of several materials (units are MPa)

Material	σ_y (0 K)	σ_y (80 K)	σ_y (300 K)
304L-SS	1,350	1,300	1,150
6061-T6 Al	345	332	282
OFHC-Cu (Annealed)	90	88	75
Cu + 2 Be	752	690	552
Brass (70% Cu, 30% Zn)	506	473	420
Inconel X-750	940	905	815
G 10 – CR	758	703	414
Teflon	130	65	20

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Ultimate stress of several materials (units are MPa)

Material	σ_u (0 K)	σ_u (80 K)	σ_u (300 K)
304 L-SS	1,600	1,410	1,200
6061-T6 Al	580	422	312
OFHC Cu (annealed)	418	360	222
Cu + 2 Be	945	807	620
Brass (70% Cu, 30% Zn)	914	804	656
Inconel X-750	1,620	1,496	1,222
G-10 – CR	758	703	414
Teflon	194	86	21

Barron [1] gives graphical presentation of variation of different properties of materials with temp:

a) **Ultimate strength:**

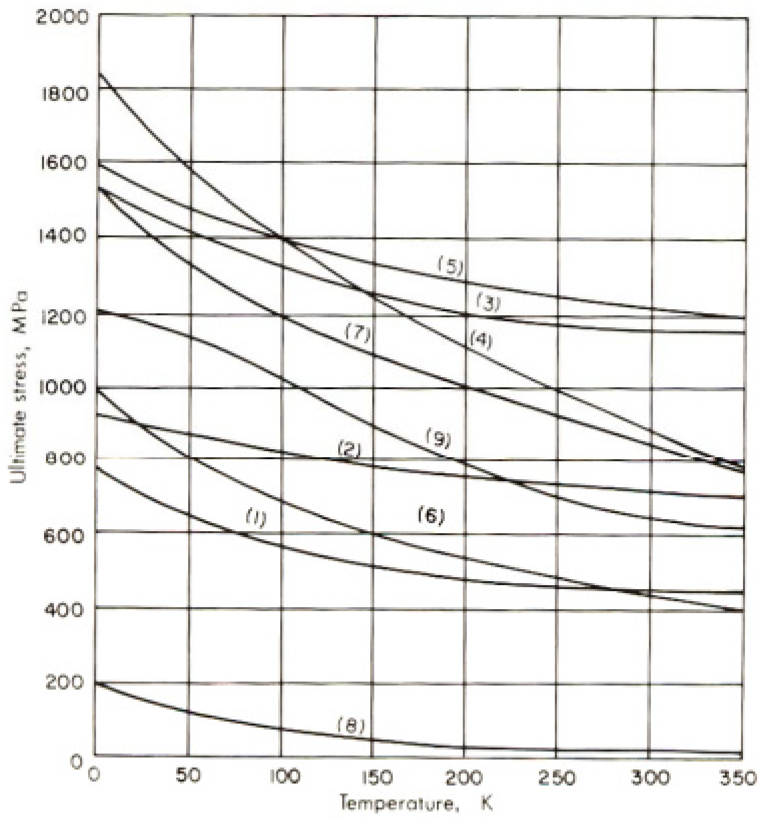

Fig.2.1.2.a Ultimate strength for several engineering materials: (l) 2024-T4 aluminum; (2) beryllium copper; (3) K Monel; (4) titanium; (5) 304 stainless steel; (6) Cl020 carbon steel; (7) 9 percent Ni steel; (8) Teflon; (9) Invar-36 (Durham et al. 1962).

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b) **Yield strength:**

Variation with temp:

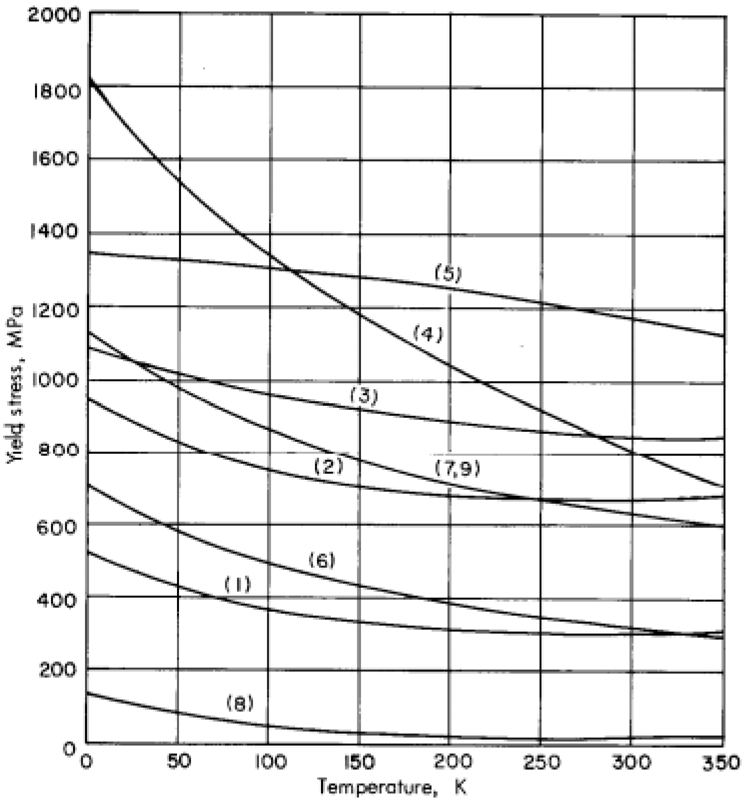

Fig. 2.1.2.b Yield strength for several engineering materials: (1) 2024- T4 aluminum: (2) beryllium copper; (3) K Monel; (4) titanium; (5) 304 stainless steel; (6) CI020 carbon steel; (7) 9 percent Ni steel; (8) Teflon; (9) Invar-36 (Durham et al. 1962).

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c) **Fatigue strength:**

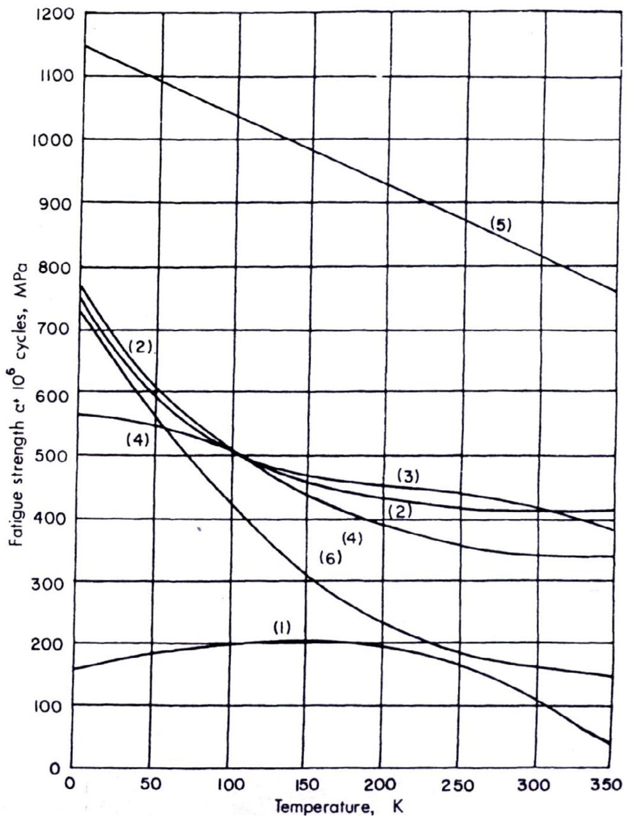

Fig. 2.1.2.c Fatigue strength at 10^6 cycles: (I) 2024- T4 aluminum; (2) beryllium copper; (3) K Monel; (4) titanium; (5) 304 stainless steel; (6) CI020 carbon steel (Durham et al. 1962).

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d) **Impact strength:**

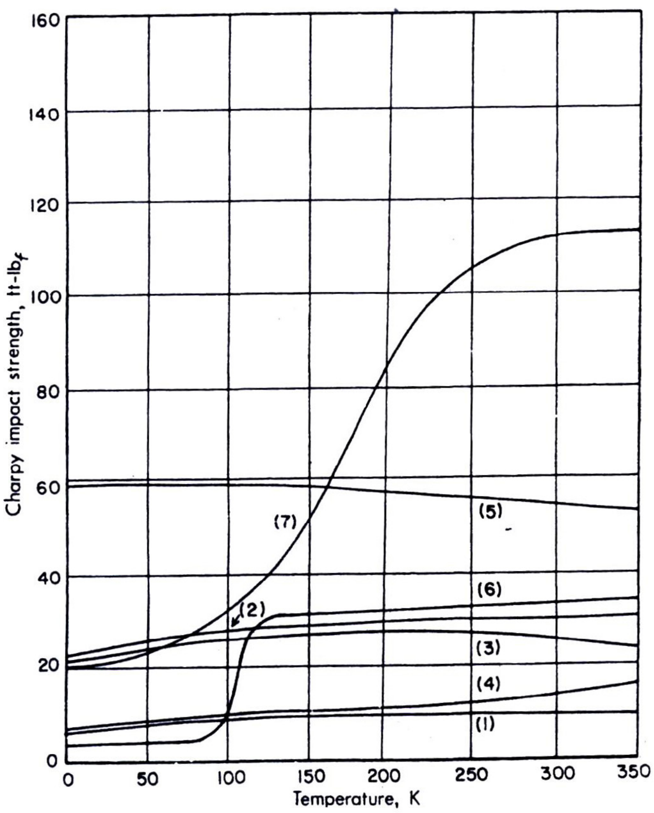

Fig. 2.1.2.d Charpy impact strength at low temperatures: (l) 2024·T4 aluminum; (2) beryl· lium copper; (3) K Monel; (4) titanium; (5) 304 stainless steel; (6) Cl020 carbon steel; (7) 9 percent Ni steel (Durham et al. 1962).

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e) **Ductility (% elongation):**

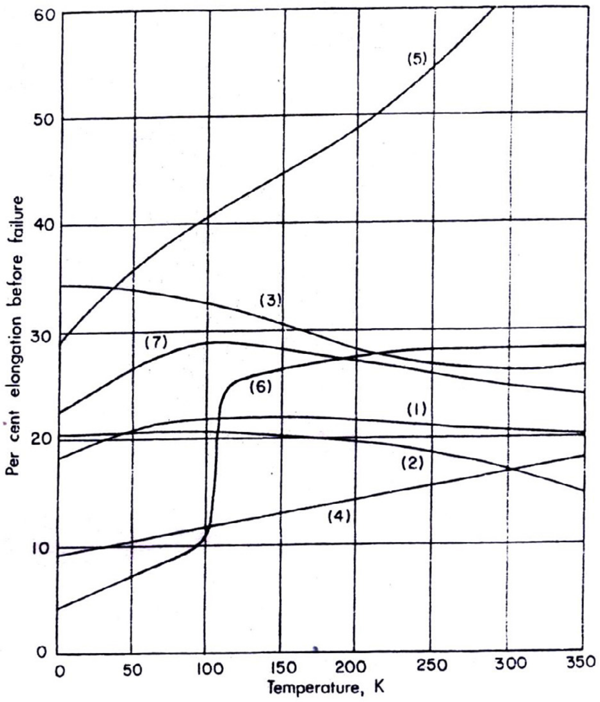
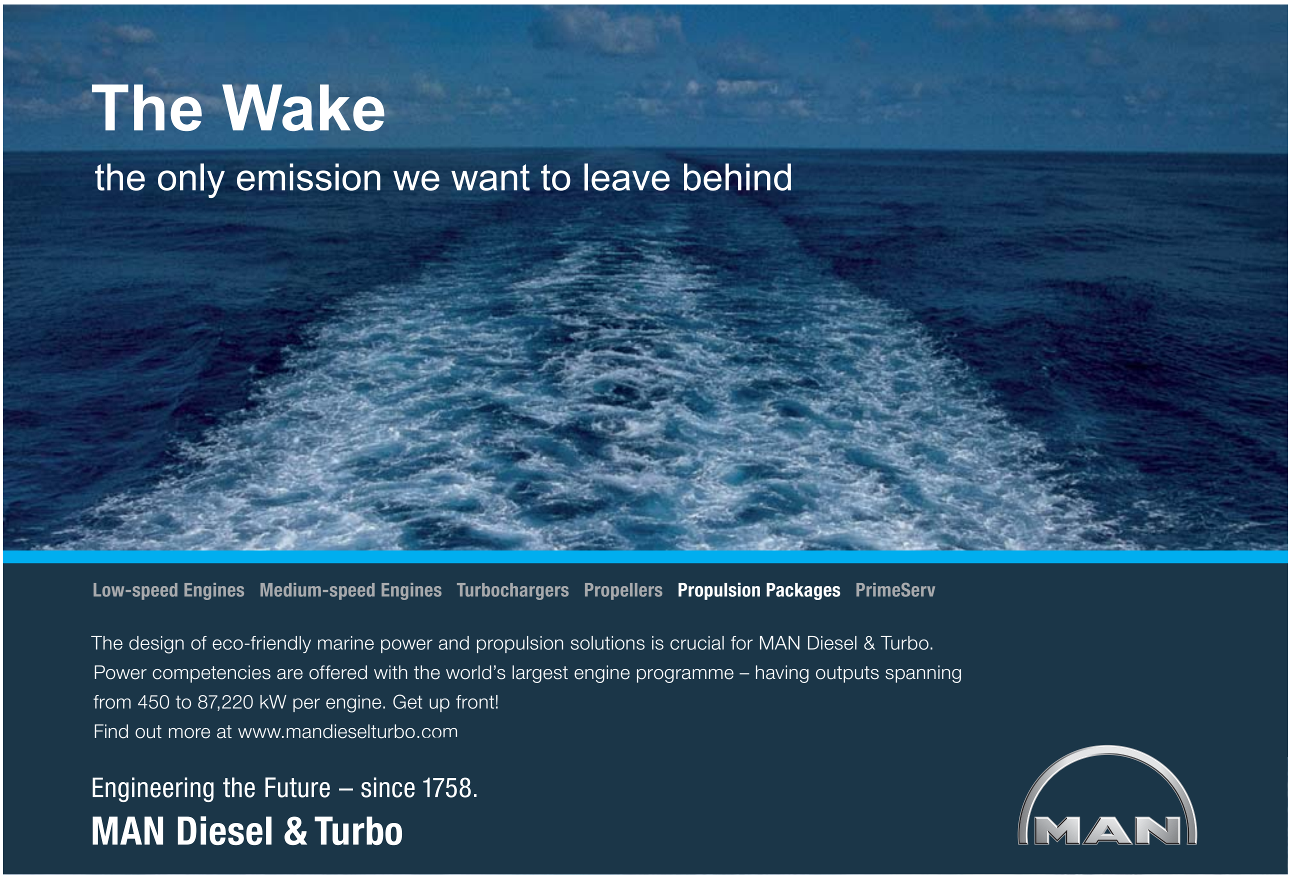


Fig. 2.1.2.e Percent elongation for various materials: (I) 2024-T4 aluminum; (2) beryllium copper; (3) K Monel; (4) titanium; (5) 304 stainless steel; (6) C1020 carbon steel; (7) 9 percent Ni steel (Durham et al. 1962).



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f) **Young's Modulus E** (i.e. the rate of change of tensile stress with respect to strain at constant temperature in the elastic region):

Variation of E with temp [9, 1]:

Young's modulus E_y of several materials (units are GPa)

Material	E_y (0 K)	E_y (80 K)	E_y (300 K)
304 -SS	210	214	199
6061-T6 Al	78	77	70
OFHC-Cu (annealed)	139	139	128
Cu + 2 Be	134	130	118
Brass (70% Cu, 30% Zn)	110	110	103
Inconel(X-750)	252	223	210
G-10-CR	36	34	28
Teflon	0.7	2.8	4

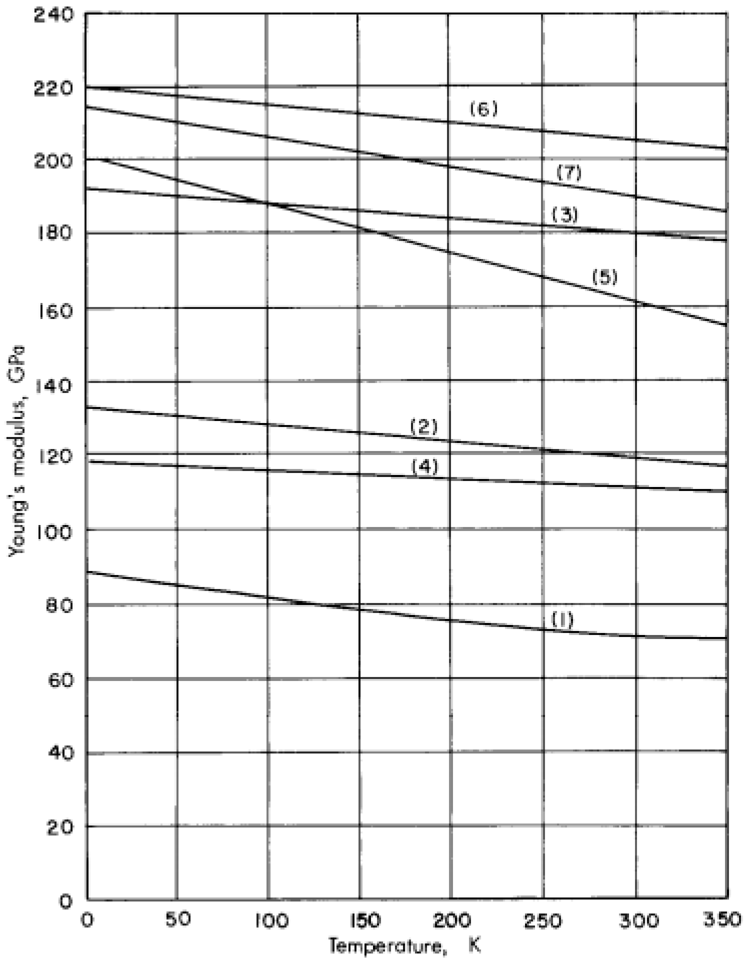

Fig. 2.1.2.f Young's modulus at low temperatures: (l) 2024- T 4 aluminum; (2) beryllium copper; (3) K Monel; (4) titanium; (5) 304 stainless steel; (6) ClO20 carbon steel; (7) 9 percent Ni steel (Durham et al. 1962).

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In addition to **Young's Modulus, E**, there are two other moduli defined:

a) **Shear modulus, G:** defined as the rate of change of shear stress with respect to shear strain at constant temperature in the elastic region; and
b) **Bulk modulus, B:** defined as the rate of change of pressure (corresponding to a uniform three-dimensional stress) with respect to volumetric strain (change in volume per unit volume) at constant temperature.

These three moduli are related through Poisson's ratio ν, (i.e. the ratio of strain in one direction due to a stress applied perpendicular to that direction to the strain parallel to the applied stress) as follows:

$$B = \frac{E}{3(1-2\nu)}$$

$$G = \frac{E}{2(1+\nu)}$$

Typical values of Poisson's ratio for a few materials:

(Ref: http://www.engineeringtoolbox.com/poissons-ratio-d_1224.html)

Material	Poisson's Ratio - ν -
Upper limit	0.5
Aluminum	0.334
Aluminum, 6061-T6	0.35
Aluminum, 2024-T4	0.32
Beryllium Copper	0.285
Brass, 70-30	0.331
Brass, cast	0.357
Bronze	0.34
Concrete	0.1 - 0.2
Copper	0.355
Cork	0
Glass, Soda	0.22
Glass, Float	0.2 - 0.27
Granite	0.2 - 0.3
Ice	0.33
Inconel	0.27 - 0.38
Iron, Cast - gray	0.211
Iron, Cast	0.22 - 0.30
Iron, Ductile	0.26 - 0.31
Iron, Malleable	0.271

Material	Poisson's Ratio - ν -
Lead	0.431
Limestone	0.2 - 0.3
Magnesium	0.35
Magnesium Alloy	0.281
Marble	0.2 - 0.3
Molybdenum	0.307
Monel metal	0.315
Nickel Silver	0.322
Nickel Steel	0.291
Polystyrene	0.34
Phosphor Bronze	0.359
Rubber	0.48 - ~0.5
Stainless Steel 18-8	0.305
Steel, cast	0.265
Steel, Cold-rolled	0.287
Steel, high carbon	0.295
Steel, mild	0.303
Titanium (99.0 Ti)	0.32
Wrought iron	0.278
Z-nickel	0.36
Zinc	0.331

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Elastic Modulii for some common materials:

(Ref: http://www.engineeringtoolbox.com/stress-strain-d_950.html)

Material	Young's Modulus		Shear Modulus		Bulk Modulus	
	10^{10} N/m^2	10^6 lb/in^2	10^{10} N/m^2	10^6 lb/in^2	10^{10} N/m^2	10^6 lb/in^2
Aluminum	7.0	10	2.4	3.4	7.0	10
Brass	9.1	13	3.6	5.1	6.1	8.5
Copper	11	16	4.2	6.0	14	20
Glass	5.5	7.8	2.3	3.3	3.7	5.2
Iron	9.1	13	7.0	10	10	14
Lead	1.6	2.3	0.56	0.8	0.77	1.1
Steel	20	29	8.4	12	16	23

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MODULI OF ELASTICITY AND POISSON'S RATIO

Material	Modulus of elasticity E		Shear modulus of elasticity G		Poisson's ratio ν
	ksi	GPa	ksi	GPa	
Aluminum alloys	10,000- 11,400	70-79	3,800-4,300	26-30	0.33
2014- T6	10,600	73	4,000	28	0.33
6061- T6	10,000	70	3,800	26	0.33
7075- T6	10,400	72	3,900	27	0.33
Brass	14,000-16,000	96-110	5,200-6,000	36-41	0.34
Bronze	14,000-17,000	96-120	5,200-6,300	36-44	0.34
Cast iron	12,000-25,000	83-170	4,600-10,000	32-69	0.2-0.3
Concrete (compression)	2,500-4,500	17-31			0.1-0.2
Copper and Copper alloys	16,000-18,000	110-120	5,800-6,800	40-47	0.33-0.36
Glass	7,000-12,000	48-83	2,700-5,100	19-35	0.17-0.27
Magnesium alloys	6,000-6,500	41-45	2,200-2,400	15-17	0.35
Nickel	30,000	210	11,400	80	0.31
Plastics					
Nylon	300-500	2.1-3.4			0.4
Polyethylene	100-200	0.7-1.4			0.4
Rock (Compression)					
Granite, marble, quartz	6,000-14,000	40-100			0.2-0.3
Limestone, sandstone	3,000-10,000	20-70			0.2-0.3
Rubber	0.1-0.6	0.0007-0.004	0.03-0.20	0.0002-0.001	0.45-0.50
Steel	28,000-30,000	190-210	10,800-11,800	75-80	0.27-0.30
Titanium alloys	15,000-17,000	100-120	5,600-6,400	39-44	0.33
Tungsten	50,000-55,000	340-380	21,000-23,000	140-160	0.2
Wood (bending)					
Douglas fir	1,600-1,900	11-13			
Oak	1,600-1,800	11-12			
Southern pine	1,600-2,000	11-14			

Reference : "Mechanics of Material" by James M. Gere, Stephen P. Timoshenko, 1997

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Note:

There is a web calculator to calculate the various Elastic constants when *any two* are given:

Ref: (http://www.efunda.com/formulae/solid_mechanics/mat_mechanics/calc_elastic_constants.cfm#calc)

For isotropic materials, only two independent elastic constants are needed for describing the stress-strain relationship, i.e., Hooke's Law.

This calculator computes the inter-relations among the 5 commonly used elastic constants:

Symbol	Name	Other Names
E	Youngs modulus	Elastic modulus, tension modulus
n	Poisson ratio	
G or m	Shear modulus	Rigidity modulus, 2nd Lamé constant
K	Bulk modulus	Compression modulus
l	1st Lamé constant	

Input

E: Young's Modulus	70
nu: Poisson's Ratio	0.3
Units for modulii (*E*, *G*, *K*, l)	GPa

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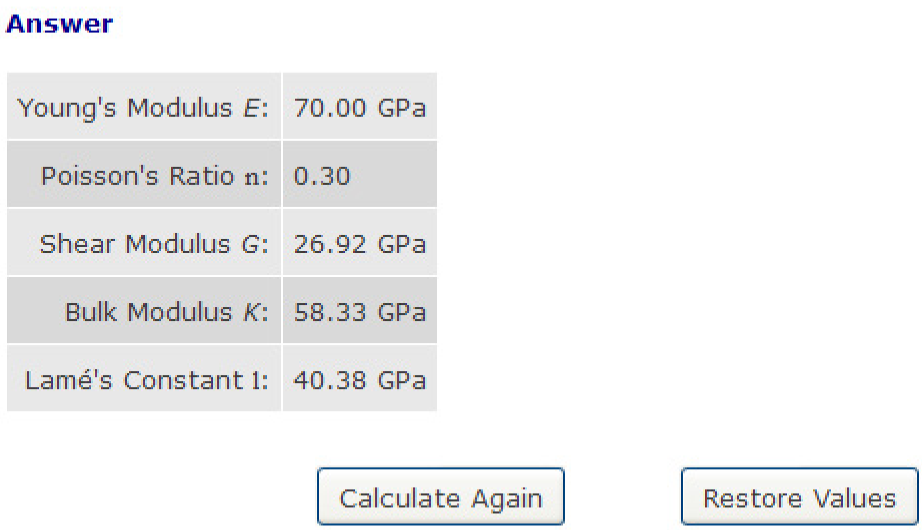
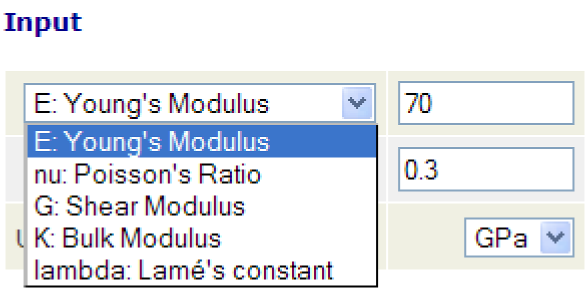


Possible Inputs are:



And the possible Units are:

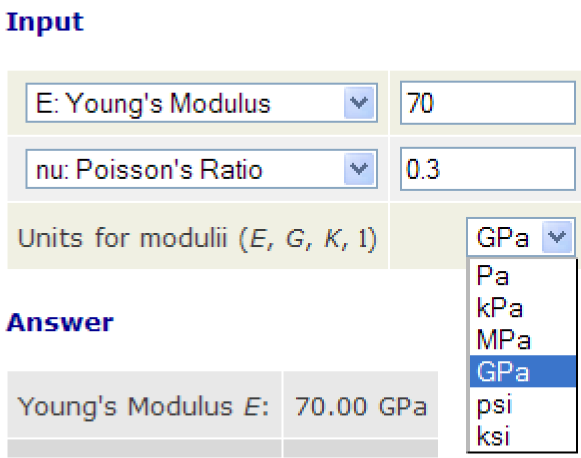


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Table of Relations among Elastic Constants

The relationships amongst the 5 elastic constants are shown in the table below.

In the following, K is the Bulk Modulus:

Input Constants	Output Relations				
	E =	n =	G =	K =	l =
E, n	-	-	$\frac{E}{2(1+\nu)}$	$\frac{E}{3(1-2\nu)}$	$\frac{E\nu}{(1+\nu)(1-2\nu)}$
E, G	-	$\frac{E-2G}{2G}$	-	$\frac{EG}{3(3G-E)}$	$\frac{G(E-2G)}{3G-E}$
E, K	-	$\frac{3K-E}{6K}$	$\frac{3KE}{9K-E}$	-	$\frac{3K(3K-E)}{9K-E}$
E, l	-	$\frac{2\lambda}{E+\lambda+R}$	$\frac{E-3\lambda+R}{4}$	$\frac{E+3\lambda+R}{6}$	-
n, G	$2G(1+\nu)$	-	-	$\frac{2G(1+\nu)}{3(1-2\nu)}$	$\frac{2G\nu}{1-2\nu}$
n, K	$3K(1-2\nu)$	-	$\frac{3K(1-2\nu)}{2(1+\nu)}$	-	$\frac{3K\nu}{1+\nu}$
n, l	$\frac{\lambda(1+\nu)(1-2\nu)}{\nu}$	-	$\frac{\lambda(1-2\nu)}{2\nu}$	$\frac{\lambda(1+\nu)}{3\nu}$	-
G, K	$\frac{9KG}{3K+G}$	$\frac{3K-2G}{6K+2G}$	-	-	$\frac{3K-2G}{3}$
G, l	$\frac{G(3\lambda+2G)}{\lambda+G}$	$\frac{\lambda}{2(\lambda+G)}$	-	$\frac{3\lambda+2G}{3}$	-
K, l	$\frac{9K(K-\lambda)}{3K-\lambda}$	$\frac{\lambda}{3K-\lambda}$	$\frac{3}{2}(K-\lambda)$	-	-

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For the case of {*E*, l} input, the factor *R* is defined as,

$$R = \sqrt{E^2 + 9\lambda^2 + 2E\lambda}$$

The 2nd Law of Thermodynamics requires that the following limits hold on the elastic constants,

$$E,\ G,\ \text{and}\ K > 0$$

$$-1 < \nu \le \frac{1}{2}$$

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Example:

For 304SS at 80 K: Young's Modulus, Ey = 214 GPa, ν = 0.305. Then, we have:

Input

E: Young's Modulus	214
nu: Poisson's Ratio	0.305
Units for modulii (*E*, *G*, *K*, l)	GPa

Answer

Young's Modulus *E*:	214.0 GPa
Poisson's Ratio n:	0.31
Shear Modulus *G*:	81.99 GPa
Bulk Modulus *K*:	182.9 GPa
Lamé's Constant l:	128.2 GPa

---

g) **Thermal conductivity** [9]:

Conductivity of various technical alloys (units are W/m K)

Alloy	10 K	20 K	50 K	100 K	200 K	300 K
AL 5083	30.3	30.3	31.3	35.5	47.9	59.2
AL 6061-T6	23.8	50.1	100	120	135	160
304 SUS	0.77	1.95	5.8	9.4	13	14.9
BeCu	5.1	10.3	24	44.5	79.5	112
Manganin	1.7	4.1	10.1	14	17.2	22
Constantan	3.5	8.7	18.1	20	22.8	24.9
Ti-6%Al-4%V	0.87	1.5	2.6	4	5.9	7.7
PbSn (56-44)	20	28.5	40.7	45	48	51

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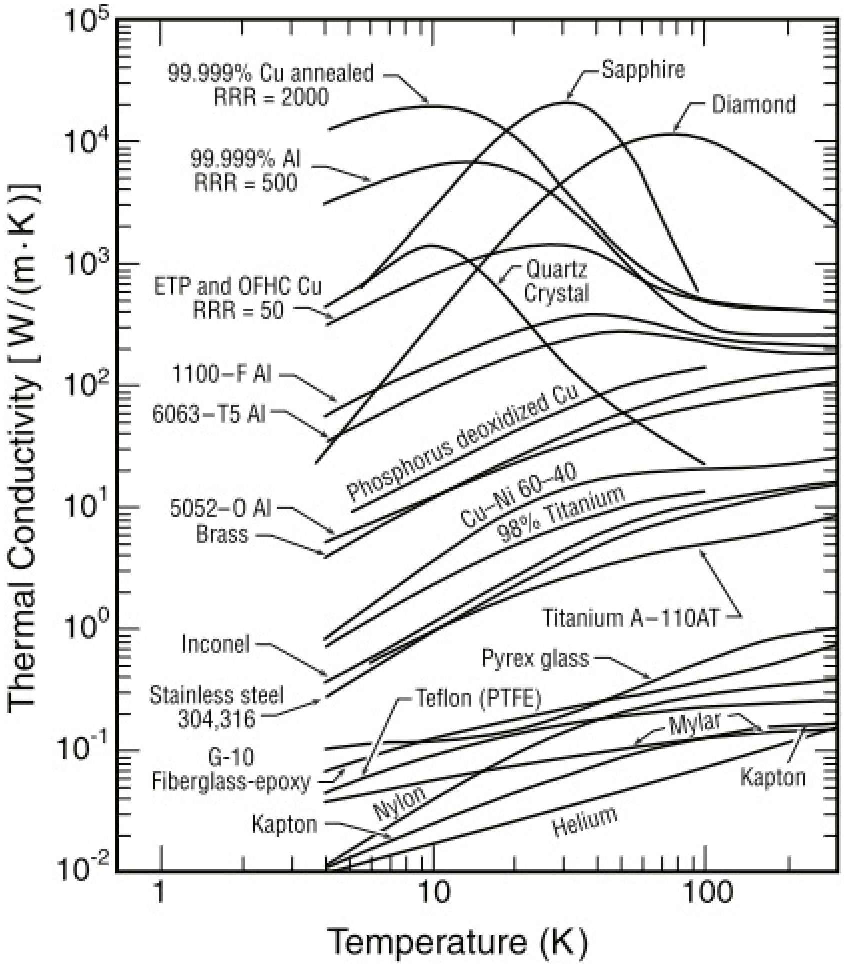

Fig. 2.1.2.g1 Thermal conductivity of materials at low temperatures

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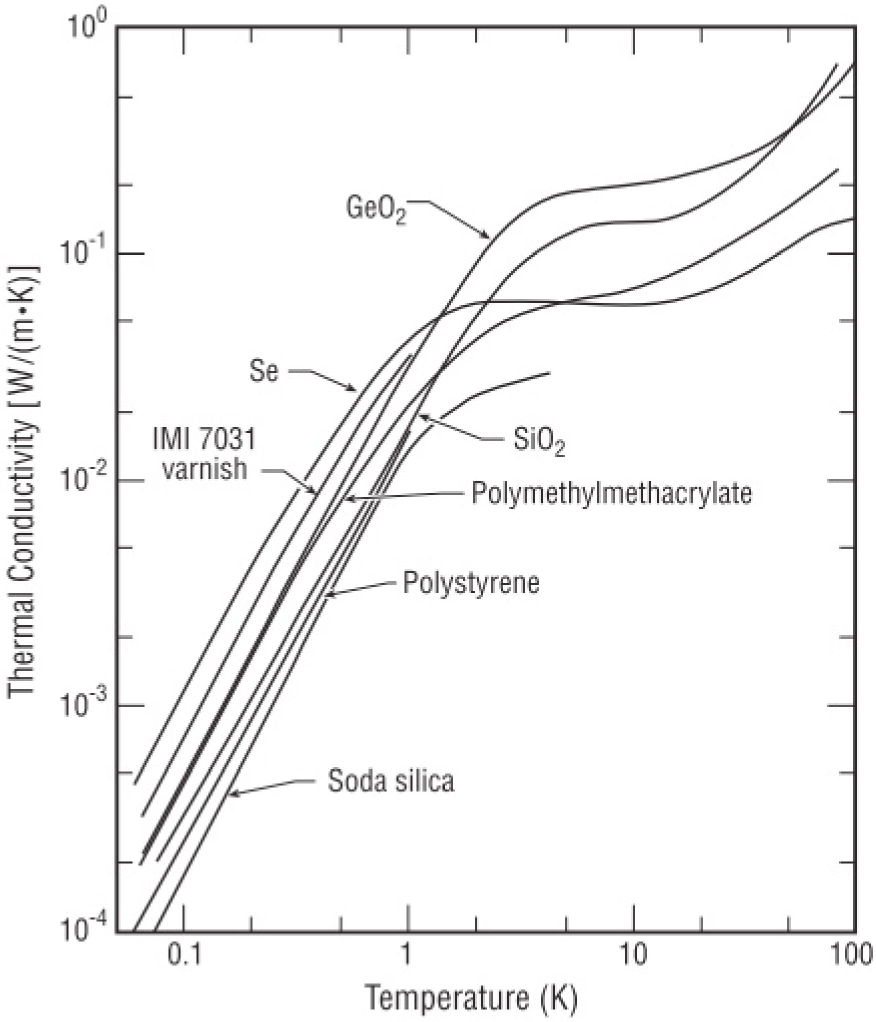

Fig. 2.1.2.g2 Thermal conductivity of amorphous solids

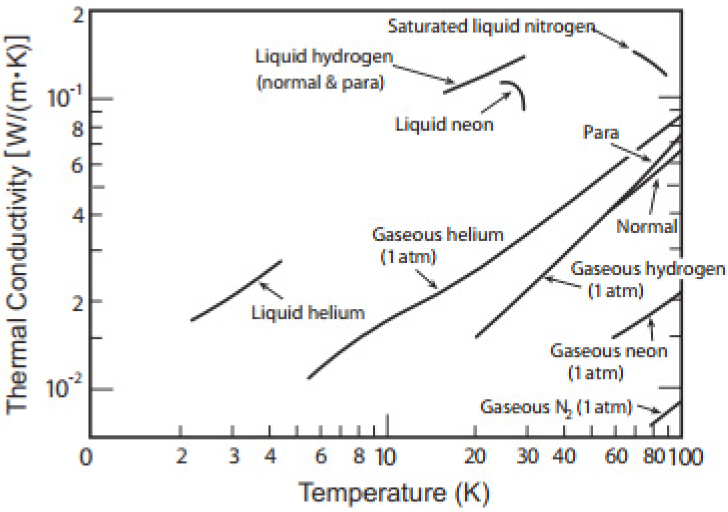

Fig. 2.1.2.g3 Thermal conductivity of cryogenic gases and liquids

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Thermal conductivity of a pure metal is affected by Residual Resistivity Ratio (RRR) [9]:

Ordinary copper:	5<RRR<150
OFHC copper:	100<RRR<200
Very pure copper	200<RRR<5000

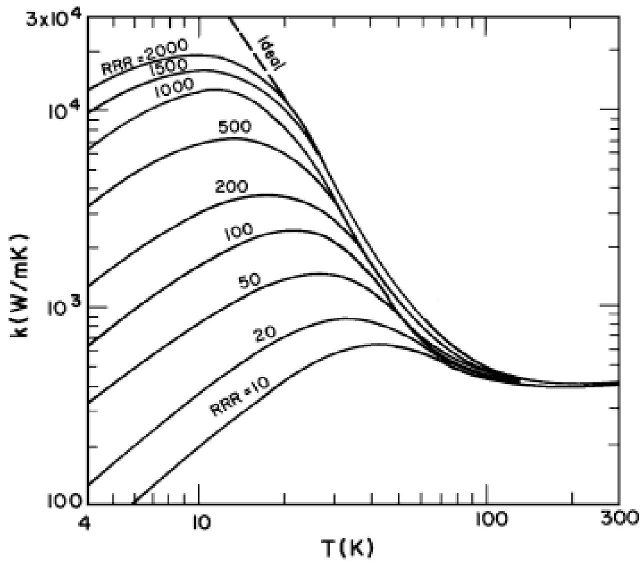
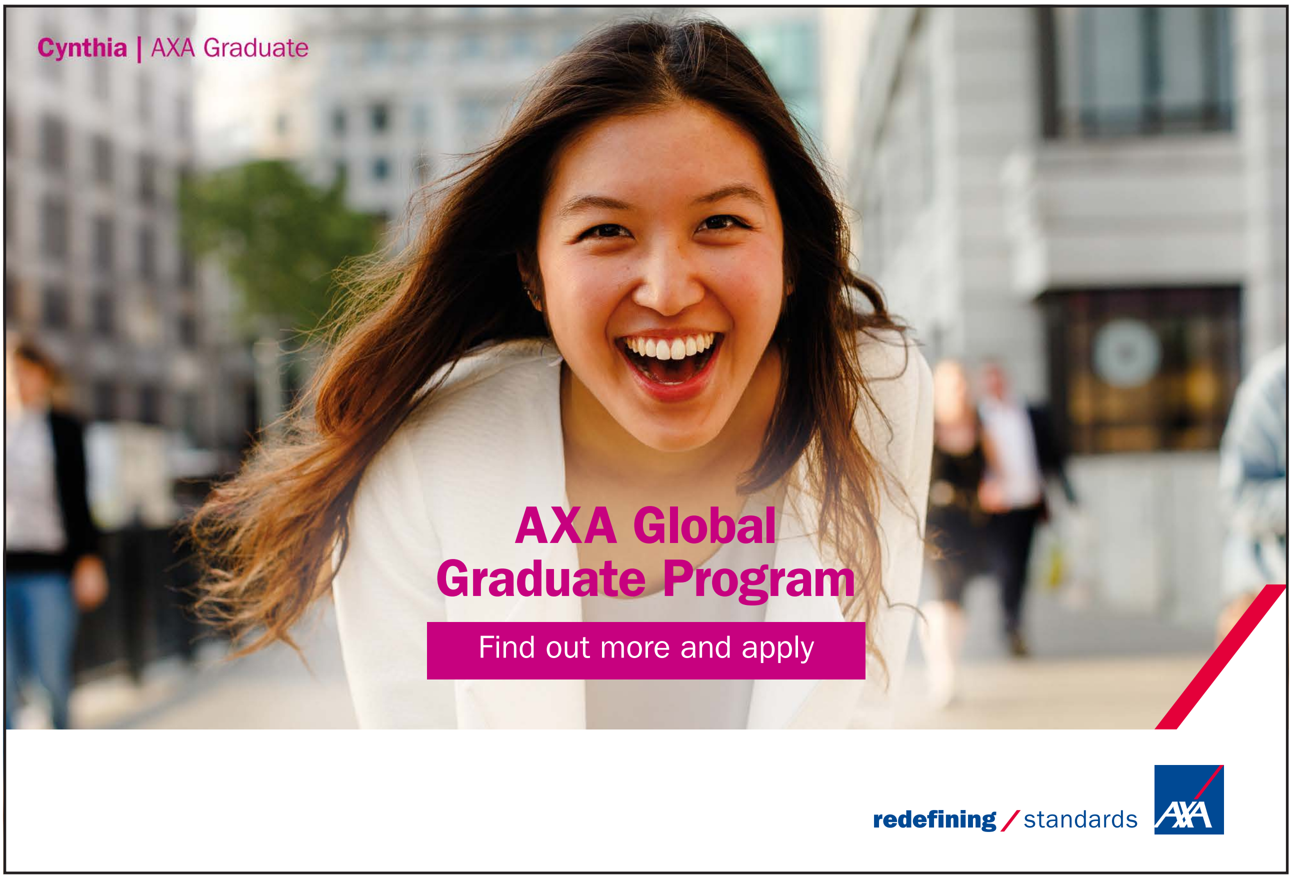


Fig.2.1.2.g4 Thermal conductivity versus temperature of differing purities of copper



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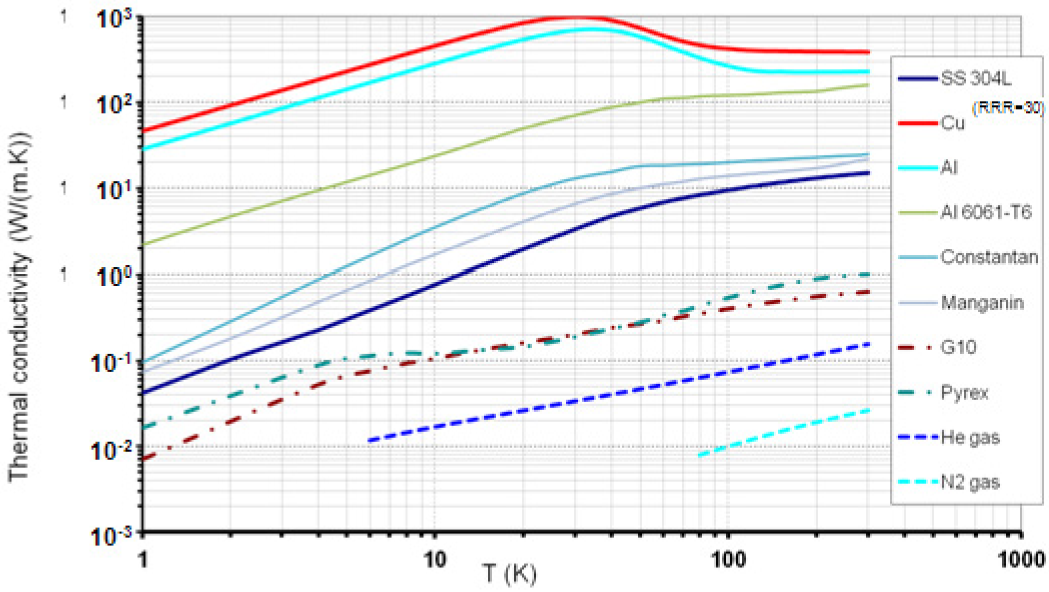
Ref.[14] gives *very useful* Tables of thermal conductivities of materials:

➢ Thermal conductivity

k (W·m^{-1}·K^{-1}) — Metals and alloys

Temp. (K)	SS 304	Cu-RRR=30	Brass	Constantan	Manganin	Inconel 718	K Monel	Invar-36	Ti-6Al-4V	Al-RRR=30	6061-T6	5083-T0	Niobium	NbTi
1	0.042	46	0.626	9.50E-02	7.30E-02	0.107	0.138	1.98E-02	0.124	28.6	22	0677	0.4	2.60E-02
2	0.103	92	1.5	0.285	0.18	0.233	0.35	6.05E-02	0.223	57.1	4.7	1.45	1.8	6.00E-02
4	0.227	184	3.59	0.878	0.484	0.504	0.889	0.185	0.403	114	9.53	3.12	899	0.176
6	0.381	276	6.08	1.64	0.848	0.809	1.53	0.345	0.569	171	14.3	4.89	21.6	0.304
8	0.565	367	8.86	2.52	1.26	1.14	2.26	0.533	0.725	228	19	6.73	37.7	0.436
10	0.77	457	11.8	3.5	17	1.48	3.05	0.74	0.87	284	23.8	8.6	55	057
15	1.33	670	18.5	6.07	2.86	2.25	5.09	1.26	1.21	420	37	13.2	75.9	0.858
20	1.95	848	24.6	8.7	4.1	2.95	7.1	1.8	1.5	541	50.1	17.8	85	1.13
25	2.61	957	29.2	11	5.38	3.53	8.68	2.36	1.71	636	61.1	22.3	87.9	142
30	3.3	1000	32.8	13	66	4	10	2.9	1.9	698	71	26.6	86	1.7
35	4.02	974	35.8	14.4	7.66	4.35	11.2	3.38	2.11	711	80.3	30.6	82.3	198
40	4.7	903	38.3	15.5	86	4.65	12.2	3.85	2.3	690	88.5	34.5	77	226
50	5.8	732	42	18.1	10.1	5.3	13.5	4.9	2.6	579	100	42	66	281
60	6.8	598	46.3	18.3	11.2	5.7	14.2	5.8	2.9	467	111	48.2	61	337
70	7.6	514	51	18.8	12	6.1	14.9	6.6	3.2	386	113	54	58	393
77	8.07	477	53.7	19	12.6	6.35	15.3	7.17	3.39	344	117	57.6	56.5	432
80	8.26	465	55	19.1	12.9	6.45	15.5	7.4	3.46	329	118	59	56	449
90	8.86	438	60.6	19.5	13.5	6.8	16	8	3.7	291	120	63	55	504
100	9.4	422	65	20	14	7.1	16.5	8.5	3.98	265	121	67	54.5	5.5
120	10.4	403	72.9	20.8	14.8	7.63	17.4	9.33	4.45	235	124	74	54.5	628
140	11.2	396	79.7	21.4	15.4	8.09	18.2	10	4.83	227	128	80.1	54.5	689
160	11.9	394	85	21.9	16	8.5	18.8	10.6	5.19	226	131	86	54.5	738
180	12.5	392	89.3	22.4	16.6	8.86	19.5	11.2	5.55	225	133	92.1	54.5	776
200	13	391	93.3	22.8	17.2	9.2	20	11.7	5.9	226	135	98	54.5	8.1
220	13.5	390	98.2	23.2	18	9.52	20.4	12.3	6.22	226	141	104	54.5	8.5
240	13.9	389	103	23.6	19	9.84	20.8	12.8	6.54	226	147	110	54.5	885
260	14.3	388	108	23.9	20.1	10.2	21.3	13.1	6.87	227	152	116	54.5	9.12
280	14.6	387	113	24.2	21.1	10.5	21.8	13.4	7.24	228	156	122	54.5	932
300	14.9	386	116	24.9	22	11	22.2	13.7	7.7	229	160	128	54.5	9.5

Thermal conductivities



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h) **Strength to conductivity ratio (Figure of Merit):**

Figure of merit (σ/k) for several different structural materials (units are MPa-m-K/W)

Material	σ/k (4 K)	σ/k (80 K)	σ/k (300 K)
304 ss	6,000	160	80
6061 T6 AL	36	3	2
G-10	12,000	1,600	500
Brass	150	9	3
Copper	2	2.5	3

Note: High FOM materials have high strength and low thermal conductivity, such as stainless steel or certain fiberglass composites (G-10). And, a low FOM material has a high thermal conductivity and low strength, e.g. pure metals like aluminum and copper.

i) **Thermal conductivity integrals [1, 10]:**

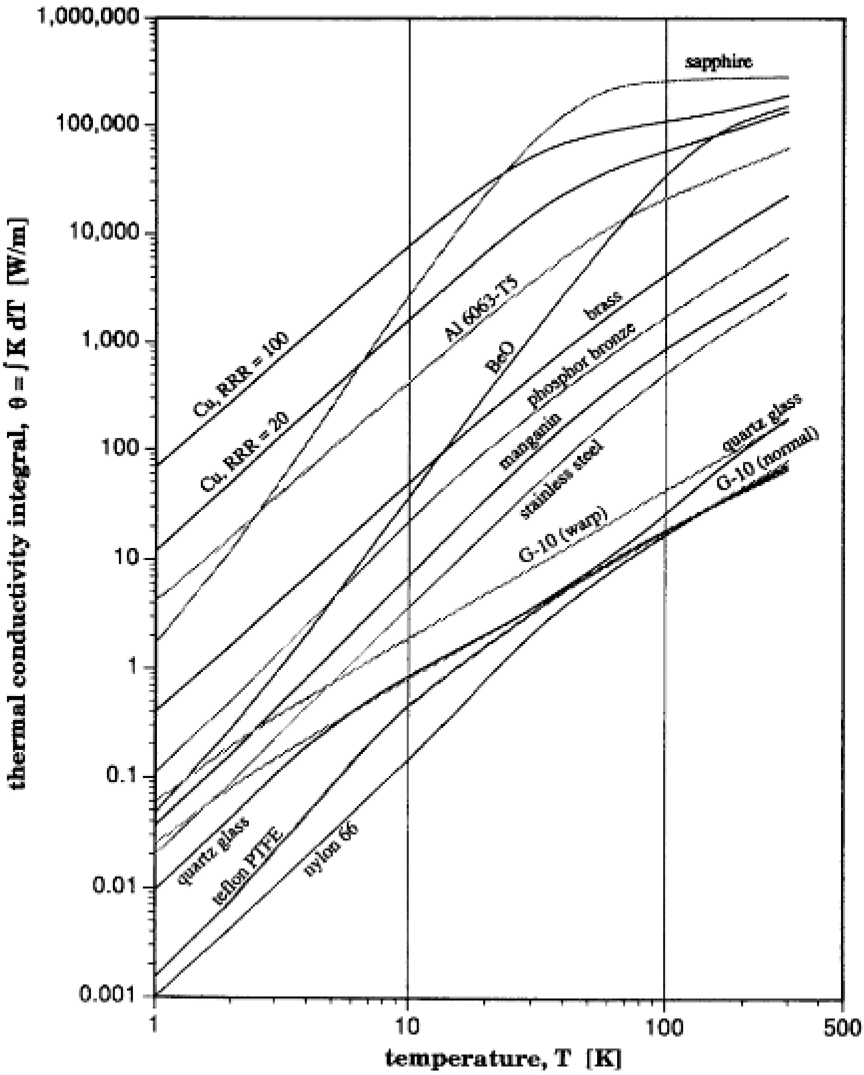

Fig.2.1.2.i Thermal conductivity integrals

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Using the Thermal conductivity integrals:

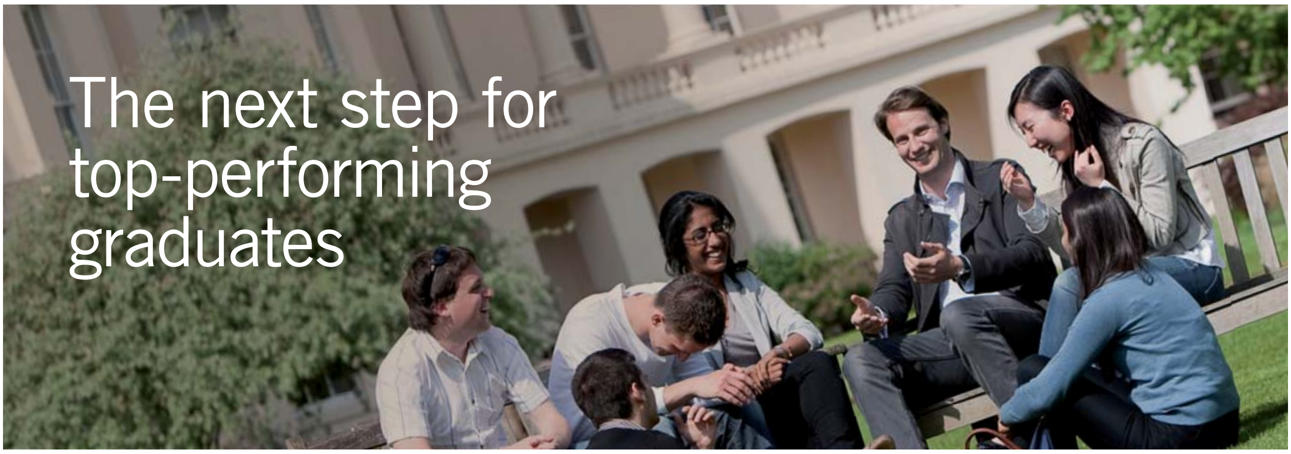
Heat transfer rate, Q:

$$Q = K \cdot \frac{A}{L}$$ W...where A = area of cross-section (m^2), and

L = Length of section (m)

$$K = \int_{4K}^{T} k_t \, dT$$ W/m .... thermal cond. integral

k_t .... thermal cond, W/m.K



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* Figures taken from London Business School's Masters in Management 2010 employment report

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Following Table gives Thermal conductivity integrals (W/m) for a few materials [1]:

Temperature (K)	Aluminum (6063-T5)		Beryllium copper		Steel (C1020)		Stainless steel (304)	
	k_t	K	k_t	K	k_t	K	k_t	K
4	34	0	1.9	0	3.0	0	0.24	0
10	86	360	4.8	19	11.5	43	0.77	2.9
20	170	1,650	10.6	95	24.0	222	1.95	16.3
30	230	3,650	16.2	229	32.0	502	3.30	42.4
40	270	6,200	21.0	415	38.6	867	4.70	82.4
50	280	8,950	26.1	650	47.6	1,310	5.80	135
60	270	11,700	30.0	930	53.6	1,810	6.80	198
70	248	14,300	33.7	1,250	57.5	2,360	7.60	270
80	230	16,700	37.0	1,600	60.0	2,950	8.26	349
90	222	19,000	40.1	1,990	61.8	3,550	8.86	436
100	216	21,100	43.0	2,400	62.9	4,170	9.40	528
120	207	25,300	48.4	3,300	64.1	5,450	10.36	726
140	201	29,300	53.3	4,320	64.6	6,750	11.17	939
160	200	33,300	57.6	5,440	64.8	8,050	11.86	1,170
180	200	37,300	61.5	6,640	64.9	9,350	12.47	1,410
200	200	41,300	65.0	7,910	65.0	10,700	13.00	1,660
250	200	51,300	72.4	11,300	65.0	13,900	14.07	2,340
300	200	61,300	78.5	15,000	65.0	17,200	14.90	3,060

Temperature (K)	Monel (drawn)		Teflon		Glass	
	k_t	K	k_t	K	k_t	K
4	0.43	0	0.046	0.0	0.097	0.00
10	1.74	6	0.096	0.44	0.120	0.68
20	4.30	36	0.141	1.64	0.146	2.00
30	6.90	93	0.174	3.23	0.190	3.68
40	9.00	173	0.193	5.08	0.24	5.86
50	10.95	273	0.208	7.16	0.29	8.46
60	12.09	368	0.219	9.36	0.34	11.5
70	13.06	513	0.228	11.6	0.39	15.1
80	13.90	647	0.235	13.9	0.44	19.4
90	14.63	791	0.241	16.3	0.50	24.0
100	15.27	940	0.245	18.7	0.55	29.2
120	16.26	1,260	0.251	23.7	0.64	40.8
140	17.34	1,590	0.255	28.7	0.73	54.2
160	18.25	1,950	0.257	33.8	0.79	64.4
180	19.02	2,320	0.258	39.0	0.85	85.8
200	19.69	2,710	0.259	44.2	0.90	103.0
250	21.02	3,730	0.260	57.2	0.98	150.0
300	22.0	4,800	0.260	70.2	1.02	199.0

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Ref.[14] gives *very useful* Tables for thermal cond. integrals of materials:

➢ Thermal conductivity integrals

$\int_{T_{LR}}^{T} k(T)dT$ (W/m) — Metals and alloys

Temp. (K)	SS304	Cu-RRR=300	Cu-RRR=30	Brass	Constantan	Manganin	Inconel 718	K Monel	Invar-36	Ti-6Al-4V	Al-RRR=30	6061-T6	5083-T0	Niobium	NbTi
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	0.0726		69	1.05	0.183	0.124	0.169	0.241	0.0388	0.174	42.8	3.46	1.06	0.968	0.04
4	0.4	3560	345	6.07	1.31	0.773	0.901	1.46	0.276	0.804	214	17.7	5.61	10.9	0.27
6	1.02	8360	807	16	3.87	2.12	2.24	3.91	0.819	1.78	501	41.4	13.7	46.2	0.756
8	1.96	14900	1450	31	8.03	4.22	4.19	7.72	1.7	3.07	900	74.6	25.3	107	1.5
10	3.28	22800	2270	51.2	13.9	7.15	6.77	13	2.95	4.67	1410	118	40.5	192	2.5
15	8.51	46600	5130	128	38.2	18.6	16.2	33.6	7.93	9.91	3190	272	95.2	515	6.04
20	16.7	72900	8910	235	74.8	35.9	29.2	63.8	15.6	16.7	5590	487	173	932	11.1
25	28.1	95800	13500	370	124	59.7	45.4	103	26	24.7	8560	765	273	1360	17.4
30	42.8	115000	18400	525	184	89.6	64.3	150	39.1	33.8	11900	1100	395	1800	25.2
35	61.2	130000	23300	697	252	125	85	204	54.7	43.8	15400	1480	538	2220	34.4
40	82.9	140000	28000	883	328	166	108	262	72.9	54.8	18900	1900	701	2620	45
50	136	155000	36200	1280	497	260	158	391	117	79.4	25300	2840	1080	3340	70.4
60	199	164000	42900	1730	679	367	213	530	170	107	30500	3900	1540	3970	101
70	271	171000	48400	2210	865	483	272	675	232	137	34800	5020	2050	4560	138
77	326	176000	51800	2580	997	569	315	781	281	160	37300	5830	2440	4960	167
80	350	177000	53300	2740	1050	607	334	828	302	171	38300	6180	2610	5130	180
90	436	182000	57800	3320	1250	739	401	985	379	207	41400	7370	3220	5690	228
100	527	187000	62000	3950	1440	877	470	1150	462	245	44200	8580	3870	6230	280.49
120	725	196200	70270	5330	1847	1165	617	1489	640	329	49240	11040	5280	7320	398
140	940	204900	78200	6860	2269	1467	775	1845	834	422	53830	13560	6820	8400	530
160	1170	213300	86100	8500	2700	1781	941	2210	1040	522	58300	16130	8490	9490	673
180	1414	221700	94000	10240	3140	2107	1114	2600	1258	630	62800	18780	10270	10580	824
200	1667	229900	101800	12080	3600	2447	1295	2990	1482	744	67300	21480	12170	11665	983.3
220	1937	238200	109600	13950	4060	2797	1480	3400	1732	865	71800	24180	14170	12750	1150
240	2207	246300	117400	16050	4530	3167	1680	3810	1982	993	76400	27080	16370	13840	1323
260	2487	254400	125100	18150	5000	3557	1880	4230	2242	1127	80900	30080	18570	14930	1503
280	2777	262500	132900	20350	5480	3967	2080	4660	2502	1265	85400	33180	20970	16020	1687
300	3077	270500	140600	22650	5970	4397	2300	5100	2772	1415	90000	36380	23470	17119	1875.4

$\int_{T_{LR}}^{T} k(T)dT$ (W/m) — Thermal Insulators

Temp. (K)	Pyrex Glass	Teflon (PTFE)	Polycarbonate Amorphous	Nylon	G-10 (normal to cloth lay)	Epoxy	Carbon Reinforced Plastic, CRFP normal	Mylar, PET
1	0	0	0	0	0	0	0	0
2	0.0302	0.00831	0.0226	0.00271	0.0148	0.0262	0.00709	0.00174
4	0.165	0.0646	0.079	0.0154	0.0901	0.112	0.031	0.0115
6	0.358	0.171	0.143	0.041	0.214	0.212	0.065	0.0342
8	0.592	0.32	0.214	0.0803	0.381	0.322	0.109	0.0704
10	0.857	0.504	0.294	0.134	0.584	0.438	0.165	0.12
15	1.49	1.05	0.54	0.337	1.19	0.74	0.356	0.309
20	2.2	1.72	0.849	0.637	1.93	1.07	0.622	0.57
25	2.99	2.47	1.23	1.04	2.78	1.43	0.968	0.885
30	3.87	3.3	1.66	1.54	3.74	1.82	1.39	1.24
35	4.88	4.2	2.11	2.14	4.8	2.24	1.87	1.63
40	6.01	5.15	2.6	2.84	5.95	2.67	2.41	2.04
50	8.59	7.16	3.66	4.47	8.48	3.62	3.68	2.89
60	11.7	9.29	4.84	6.29	11.2	4.67	5.26	3.8
70	15.3	11.5	6.1	8.3	14.3	5.79	7.13	4.74
77	18.1	13.1	7.03	9.79	16.7	6.63	8.62	5.42
80	19.4	13.8	7.43	10.4	17.7	7	9.32	5.72
90	24.1	16.2	8.84	12.7	21.3	8.3	12	6.74
100	29.3	18.7	10.3	15.1	25.2	9.71	15.1	7.79
120	41.1	23.66	13.41	20.04	33.61	12.86	22.2	9.96
140	54.7	28.7	16.75	25.2	42.8	16.37	30.6	12.22
160	69.8	33.8	20.29	30.6	52.6	20.11	40.3	14.54
180	86.2	39	24	36.1	63	23.91	51.2	16.91
200	103.8	44.2	27.9	41.8	73.9	27.91	62.8	19.29
220	122.2	49.4	32	47.5	85.1	32.01	74.5	21.69
240	141.3	54.6	36.3	53.4	96.8	36.11	86.4	24.19
260	161.3	59.8	40.7	59.4	108.7	40.31	98.6	26.59
280	181.3	65	45.3	65.5	120.9	44.61	111.1	28.99
300	201.3	70.2	50	71.7	133.2	48.91	124.1	31.49

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j) **Specific heats of solids:**

For solids, the Debye model gives a satisfactory representation of the variation of the specific heat with temperature. From Debye theory:

$$C_\upsilon = \frac{9RT^3}{\theta^3_D}\int_0^{\theta_{D/T}} \frac{x^4 e^x dx}{(e^x - 1)^2} = 3R\left(\frac{T}{\theta_D}\right)D\left(\frac{T}{\theta_D}\right)$$ where θ_D is called the *Debye characteristic temperature* and is a property of the material, and $D(T/\theta_D)$ is called the *Debye function*.

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A plot of the specific heat as given by above eqn. is shown below:

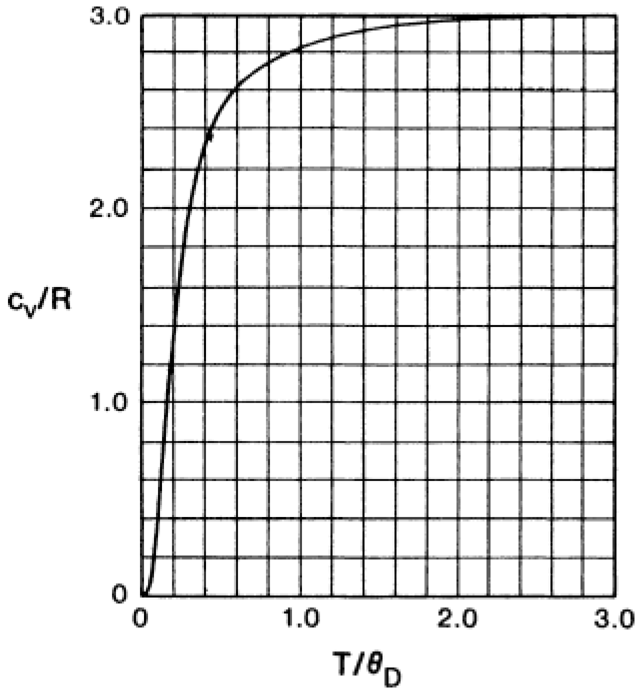

Fig.2.1.2.j1 Specific heat of a few materials (as per Debye Theory)

At high temperatures ($T > 2\ \theta_D$), sp. heat approaches a constant value of 3R, the Dulong Petit value.

At low temperatures ($T < \theta_D/12$), sp. heat cv is expressed as: $cv = 233.78 * R * (T/\theta_D)^3$

Table of Cv/R against T/θ_D [1]:

T/θ_D	c_v/R	T/θ_D	c_v/R	T/θ_D	c_v/R
0,05	0,1191	0,45	2,3725	1,60	2,9422
0,09	0,1682	0,50	2,4762	1,70	2,9487
0,10	0,2275	0,60	2,6214	1,80	2,9542
0,12	0,3733	0,70	2,7149	1,90	2,9589
0,14	0,5464	0,80	2,7481	2,00	2,9628
0,16	0,7334	0,90	2,8227	2,20	2,9692
0,18	0,9228	1,00	2,8552	2,40	2,9741
0,20	1,1059	1,10	2,8796	2,60	2,9779
0,25	1,5092	1,20	2,8984	2,80	2,9810
0,30	1,8231	1,30	2,9131	3,00	2,9834
0,35	2,0597	1,40	2,9248	4,00	2,9844
0,40	2,2376	1,50	2,9344	5,00	2,9900

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Debye Characteristic Temperatures (θ_D) of Some Representative Elements and Compounds [2]:

Element	θ_D °R	θ_D K	Element	θ_D °R	θ_D K	Element	θ_D °R	θ_D K	Compound	θ_D °R	θ_D K
Ac	180	100	Ge	666	370	Pb	153	85	AgCl	324	180
Ag	396	220	H (para)	207	115	Pd	495	275	Alums	144	80
Al	693	385	H (ortho)	189	105	Pr	216	120	As_2O_3	252	140
Ar	162	90	H (*n*-D_2)	189	105	Pt	405	225	As_2O_5	432	240
As	495	275	He	54	30	Rb	108	60	$AuCu_3$ (ord.)	360	200
Au	324	180	Hf	351	195	Re	540	300	$AuCu_3$ (disord.)	324	180
B	2196	1220	Hg	180	100	Rh	630	350	BN	1080	600
Be	1692	940	I	189	105	Rn	720	400	CaF_2	846	470
Bi	216	120	In	252	140	Sb	252	140	Cr_2O_3	648	360
C (diamond)	3650	2028	Ir	522	290	Se	270	150	FeS	1134	630
C (graphite)	1500	2700	K	180	100	Si	1134	630	KBr	324	180
Ca	414	230	Kr	108	60	Sn (fcc)	432	240	KCl	414	230
Cd (hcp)	504	280	La	234	130	Sn (tetra)	252	140	KI	351	195
Cd (bcc)	306	170	Li	756	420	Sr	306	170	LiF	1224	680
Ce	198	110	Mg	594	330	Ta	414	230	MgO	1440	800
Cl	297	165	Mn	756	420	Tb	315	175	MoS_2	522	290
Co	792	440	Mo	675	375	Te	234	130	NaCT	504	280
Cr	774	430	N	126	70	Th	252	140	RbBr	234	130
Cs	81	45	Na	270	150	Ti	639	355	RbI	207	115
Cu	558	310	Nb	477	265	Tl	162	90	SiO_2 (quartz)	459	255
Dy	279	155	Nd	270	150	V	504	280	TiO_2 (rutile)	810	450
Er	297	165	Ne	108	60	W	567	315	ZnS	468	260
Fe	828	460	Ni	792	440	Y	414	230			
Ga (rhomb)	432	240	O	162	90	Zn	450	250			
Ga (tetra)	225	125	Os	450	250	Zr	432	240			
Gd	288	160	Pa	270	150	AgBr	252	140			

Sp. heats of some materials of construction used in cryogenics [2]:

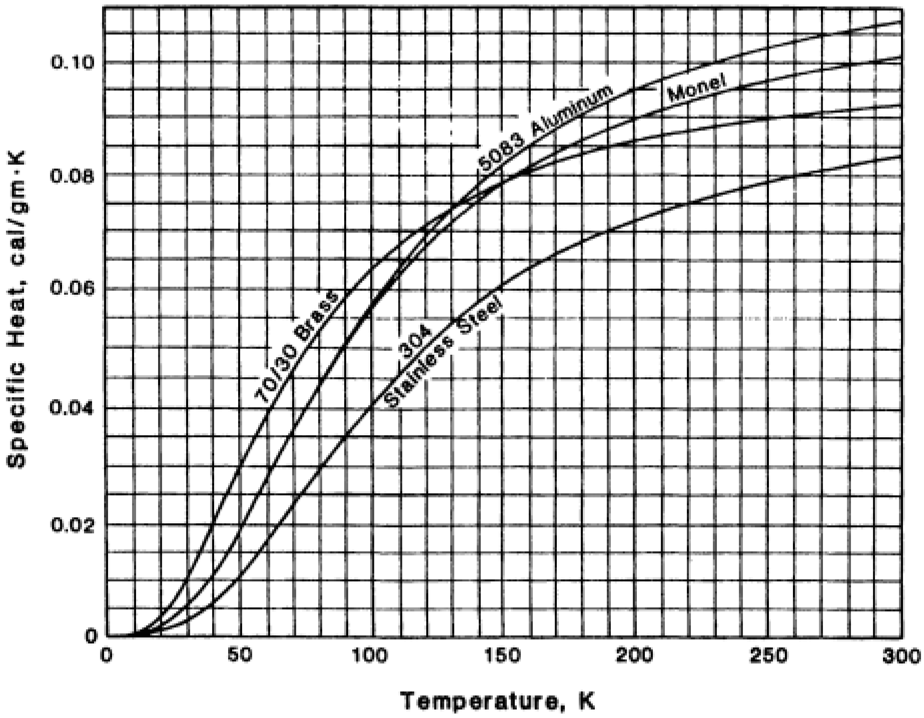

Fig.2.1.2.j2 Specific heat of a few materials of construction

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Sp. heats of some selected substances [2]:

Table 5.2 Specific Heats (C_P) of Some Selected Substances [cal/(g K)]

Temperature (K)	Al	Mg	Cu	Ni	α-Mn	α-Fe	γ-Fe	Cr	18–18 SS[a]	Monel	Fused silica	Pyrex	Teflon
20	0.0024	0.0040	0.0019	0.0012	0.0025	0.0011	0.0014	0.0006	0.0011	0.0014	0.006	0.0055	0.0183
50	0.0337	0.0580	0.0236	0.0164	0.0211	0.0129	0.0218	0.0090	0.016	0.0186	0.0272	0.0264	0.0491
77	0.0815	0.119	0.0471	0.0392	0.0473	0.0343	0.0487	0.0277	0.038	0.0417	0.0470	0.047	0.0739
90	0.102	0.141	0.0554	0.0488	0.0574	0.0441	0.0604	0.0381	0.050	0.0509	0.0570	0.0575	0.0851
100	0.116	0.155	0.0607	0.0555	0.0641	0.0516	0.0684	0.0459	0.057	0.0571	0.0643	0.065	0.0931
150	0.164	0.202	0.0774	0.0785	0.0872	0.0775	0.0975	0.0757	0.085	0.0782	0.0982	0.101	0.132
200	0.191	0.221	0.0854	0.0915	0.1003	0.0918	0.118	0.0925	0.099	0.0897	0.129	0.132	0.166
298	0.215	0.235	0.0924	0.1060	0.1146	0.1070	0.1251	0.1073	0.114	0.1019	0.177	0.182	0.248[b]

[a] SS = stainless steel.
[b] At 280 K.

Note: 1 cal/g.K = 4.1868 kJ/kg.K

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Sp. heats of some substances used in Cryogenics [9]:

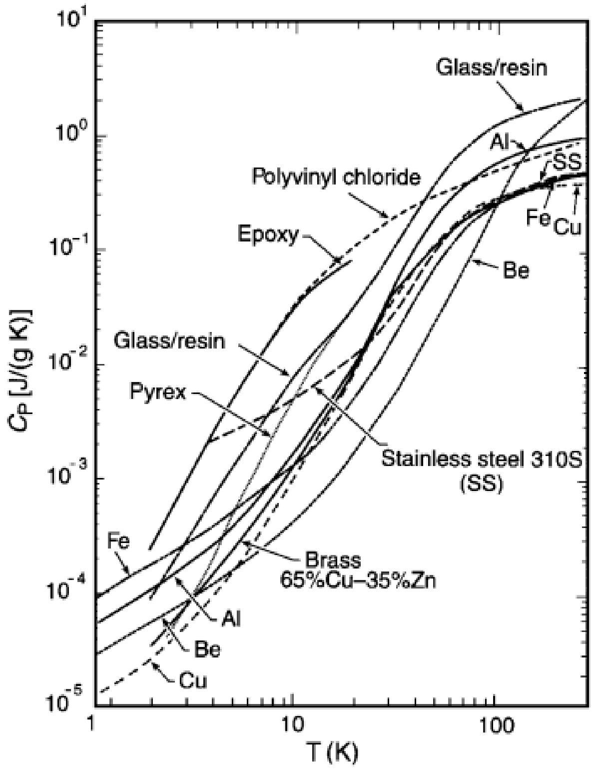

Fig.2.1.2.j3 Specific heat of a few materials

Sp.heats of some technical solids is given below (in J/g.K) [4]:

Material	25 K	50 K	75 K	100 K	150 K	200 K	293 K
Metals							
Al	0.0175	0.142	0.322	0.481	0.683	0.797	0.897
Cu	0.015	0.097	0.187	0.252	0.322	0.355	0.383
Fe	0.0080	0.051	0.136	0.216	0.324	0.384	0.444
Nb	0.020	0.085	0.147	0.188	0.230	0.248	0.262
Ni	0.0098	0.069	0.156	0.232	0.329	0.383	0.435
Si	0.0085	0.078	0.170	0.260	0.425	0.557	0.694
Ti	0.0137	0.098	0.210	0.300	0.408	0.466	0.518
W	0.0041	0.032	0.064	0.087	0.112	0.123	0.133
Alloys							
Al2024	—	—	—	0.46	0.65	0.73	0.84
CuZn (65/35)	0.022	0.118	0.21	0.27	0.33	0.36	0.377
Constantan	0.013	0.08	0.17	0.24	0.32	0.36	0.41
Inconel 718	—	0.07	0.16	0.27	0.36	0.40	0.43
Nb-38Ti	0.03	0.11	0.24	—	—	—	—
SnPb (50/50)	0.062	0.116	0.140	0.152	0.163	0.170	0.178
S.S. 304/316	0.019	0.092	0.19	0.28	0.35	0.42	0.47
Ti-6Al-4V	—	—	0.21	—	0.40	0.49	0.55
Non-metals							
Sapphire	0.0014	0.0148	0.0558	0.126	0.313	0.501	0.763
MgO	0.0019	0.0207	0.085	0.195	0.0449	0.661	0.916
Pyrex	0.043	—	—	0.28	0.406	0.533	0.72
Silica	0.038	0.111	0.188	0.268	0.420	0.546	0.728
ZrO_2	0.009	0.041	0.095	0.15	0.26	0.35	0.45
Polymers							
Epoxy	0.13	0.27	0.39	0.48	—	1.0	1.3
G10 (GFRP)	—	0.3	0.4	0.5	—	1.0	1.5
Nylon 6	—	—	0.47	—	0.81	1.01	1.5
Stycast	0.032	0.088	0.15	0.22	—	—	—
Teflon	0.10	0.21	0.29	0.39	0.56	0.72	1.0

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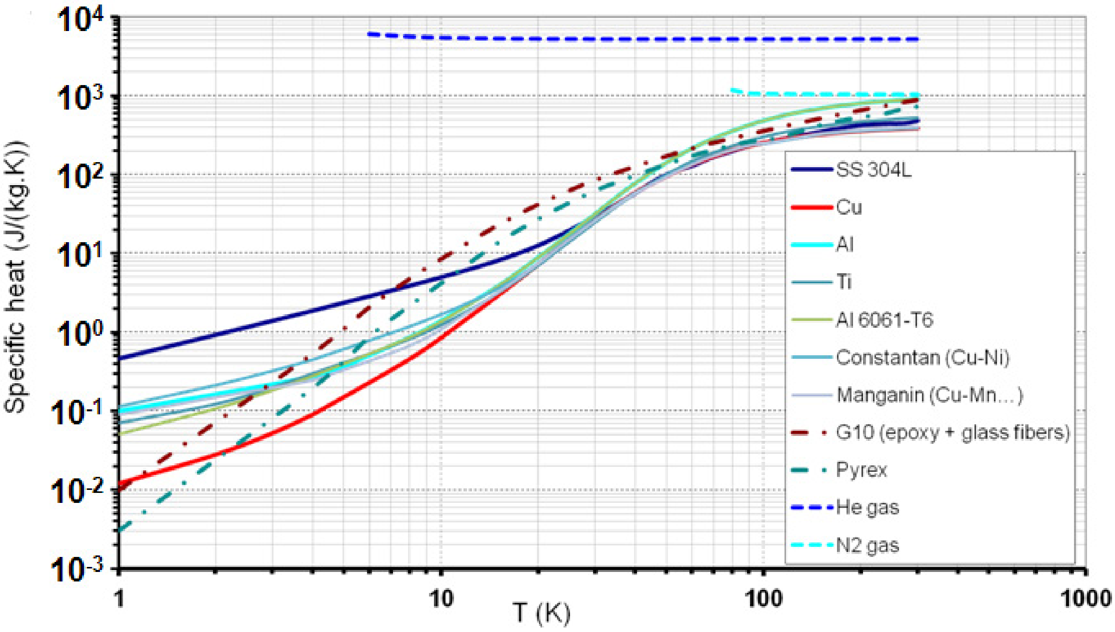
Ref.[14] gives graphs and *very useful* tables for sp. heats and Δh of a large number of materials:

➢ Specific heat capacity curves for some materials



➢ Specific heat capacities of some materials

Temp. (K)	*Cp* (J/kg-K)													Metals and alloys
▼	SS 304	Cu	Brass	Constantan	Manganin	Inconel 718	K Monel	Invar-36	Ti-6Al-4V	Al	6061-T6	5083-T0	Niobium	NbTi
1	0.464	0.012	0.012	0.113	0.090	0.399	0.110	0.251	0.001	0.100	0.051	0.051	0.060	0.002
2	0.931	0.028	0.035	0.211	0.150	0.781	0.220	0.481	0.008	0.108	0.108	0.108	0.175	0.027
4	1.880	0.090	0.142	0.446	0.246	1.530	0.473	0.932	0.066	0.276	0.280	0.280	0.422	0.523
6	2.860	0.218	0.364	0.761	0.404	2.230	0.784	1.510	0.221	0.515	0.515	0.515	0.768	1.270
8	3.900	0.460	0.780	1.180	0.679	2.940	1.180	2.270	0.525	0.867	0.867	0.867	1.290	2.320
10	5.020	0.870	1.470	1.740	1.120	3.700	1.700	3.220	1.030	1.400	1.400	1.400	2.050	3.800
15	8.120	2.930	4.970	3.550	3.190	5.890	3.650	6.480	3.490	3.840	3.840	3.840	5.840	10.30
20	12.60	7.270	11.900	7.440	7.420	10.00	7.100	12.10	8.20	8.90	8.90	8.90	12.00	21.00
25	19.60	15.30	24.40	15.40	15.00	18.30	12.90	21.30	16.10	17.80	17.80	17.80	20.40	37.30
30	29.30	26.60	40.70	26.70	25.80	30.00	21.00	35.00	27.00	31.50	31.50	31.50	32.00	58.00
35	42.00	41.80	60.40	41.80	40.30	45.40	31.80	55.80	41.30	51.90	51.90	51.90	49.30	83.80
40	57.80	59.00	81.40	59.00	57.10	63.00	45.00	80.00	58.30	77.50	77.50	77.50	68.00	110.0
50	100.0	95.0	121.0	95.0	93.0	100.0	78.0	130.0	99.5	142.0	142.0	142.0	99.0	150.0
60	128.0	135.0	160.0	135.0	133.0	130.0	110.0	176.0	144.0	214.0	214.0	214.0	127.0	200.0
70	167.0	170.0	191.0	173.0	171.0	165.0	150.0	211.0	188.0	287.0	287.0	287.0	152.0	240.0
77	188.0	195.0	212.0	196.0	195.0	183.0	171.0	239.0	217.0	336.0	336.0	336.0	167.0	261.0
80	197.0	205.0	221.0	205.0	205.0	190.0	180.0	250.0	229.0	357.0	357.0	357.0	173.0	270.0
90	230.0	230.0	247.0	232.0	234.0	215.0	210.0	272.0	267.0	422.0	422.0	422.0	189.0	300.0
100	250.0	251.0	267.0	245.0	247.0	240.0	240.0	297.0	301.0	481.0	481.0	481.0	202.0	307.0
120	290.0	286.0	298.0	276.0	279.0	282.0	285.0	337.0	356.0	579.0	579.0	579.0	222.0	329.0
140	329.0	312.0	321.0	308.0	312.0	315.0	314.0	366.0	398.0	653.0	653.0	653.0	234.0	357.0
160	364.0	332.0	337.0	332.0	338.0	347.0	336.0	388.0	430.0	713.0	713.0	713.0	243.0	378.0
180	395.0	346.0	349.0	346.0	354.0	379.0	355.0	405.0	457.0	760.0	760.0	760.0	250.0	390.0
200	419.0	356.0	357.0	356.0	365.0	405.0	370.0	419.0	478.0	797.0	797.0	797.0	254.0	400.0
220	431.0	364.0	365.0	364.0	374.0	416.0	385.0	431.0	494.0	826.0	826.0	826.0	258.0	410.0
240	439.0	371.0	370.0	371.0	382.0	422.0	399.0	441.0	508.0	849.0	849.0	849.0	261.0	417.0
260	447.0	377.0	373.0	377.0	389.0	429.0	410.0	448.0	519.0	869.0	869.0	869.0	264.0	422.0
280	459.0	382.0	376.0	382.0	394.0	438.0	420.0	454.0	530.0	886.0	886.0	886.0	266.0	425.0
300	470.0	386.0	380.0	386.0	400.0	444.0	430.0	463.0	539.0	902.0	902.0	902.0	268.0	426.0

Constantan: Cu-Ni
Manganin: Cu-Mn-Ni
Monel: Ni-Cu-Fe

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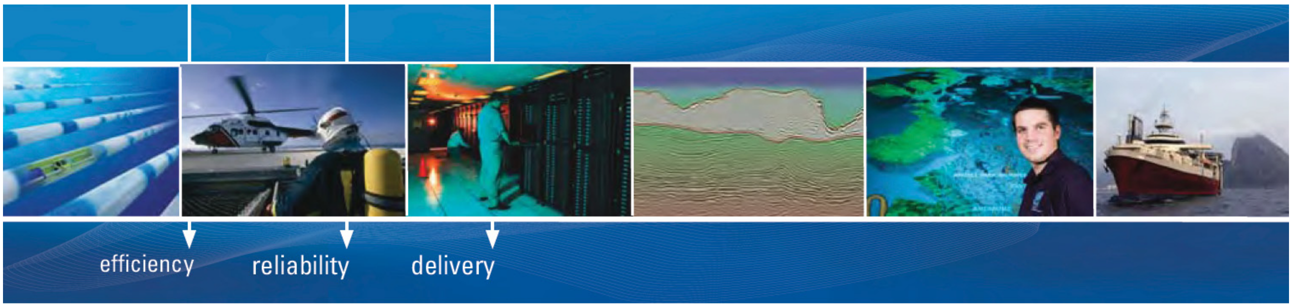
➢ Specific heat capacities of some materials

Temp. (K)	*Cp* (J/kg-K)							Thermal Insulators
	Pyrex Glass	Teflon (PTFE)	Polycarbonate Amorphous	Nylon	G-10 (normal to cloth lay)	Epoxy	Carbon Reinforced Plastic, CRFP normal	Mylar, PET
1	0.003	0.04	0.024	0.018	0.00986	0.03	0.0184	0.013
2	0.025	0.32	0.192	0.144	0.0613	0.17	0.24	0.104
4	0.197	2.62	1.54	1.15	0.538	1.56	1.61	0.829
6	0.883	6.33	6.1	3.97	2.09	5.72	3.79	3.37
8	2.19	11.4	13.7	8.85	4.76	12.4	6.63	7.55
10	4.19	18	24	16	8.47	21.3	10	13
15	13.7	44.5	60.4	48.3	22.7	49.8	19.4	27
20	27.4	76	102	93	41.5	84	30	48
25	44.3	102	132	143	62.5	117	40.1	84.3
30	62.8	125	159	197	84.6	150	50.6	125
35	80.5	146	185	248	105	180	61.4	162
40	98.4	165	210	300	126	210	73.5	195
50	136	202	255	410	170	270	105	240
60	174	238	286	500	213	328	140	282
70	209	274	325	587	252	380	173	323
77	229	301	352	653	277	422	200	349
80	237	312	364	680	288	440	211	360
90	264	350	403	750	321	490	239	400
100	272	386	439	820	355	540	274	442
120	321	453	515	953	420	638	341	531
140	396	517	595	1080	481	733	405	621
160	459	589	675	1200	539	826	467	704
180	502	668	754	1330	595	915	528	777
200	539	741	832	1450	648	1000	592	845
220	570	785	910	1570	698	1080	666	906
240	606	832	989	1690	745	1150	741	967
260	659	901	1070	1800	791	1230	808	1040
280	714	973	1150	1900	836	1290	881	1110
300	737	1010	1230	2000	880	1360	980	1160



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$$\Delta h = \int_{1K}^{T} c_p \, dT \quad \text{(J/kg)}$$

Metals and alloys

Temp. (K)	SS 304	Cu	Brass	Constantan	Manganin	Inconel 718	K Monel	Invar-36	Ti-6Al-4V	Al	6061-T6	5083-T0	Niobium	NbTi
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	0.697	0.0195	0.0219	0.161	0.121	0.591	0.164	0.367	0.00384	0.0992	0.078	0.078	0.118	0.0002
4	3.5	0.128	0.18	0.807	0.514	2.9	0.848	1.77	0.0635	0.457	0.452	0.452	0.703	0.473
6	8.2	0.315	0.488	1.97	1.06	6.58	2.03	4.15	0.226	1.1	1.11	1.11	1.7	1.97
8	14.9	0.931	1.53	3.88	2.08	11.7	3.96	7.88	0.905	2.42	2.42	2.42	3.65	5.42
10	23.9	2.37	3.97	6.82	3.98	18.5	6.9	13.4	2.56	4.83	4.82	4.82	7.18	11.8
15	55	9.66	17	17.3	12.7	39.6	18.9	35.3	12.1	15.5	15.5	15.5	25.9	44.3
20	107	35.5	59.4	45.8	39.5	80.5	45.9	82.2	41.2	47.6	47.6	47.6	69.5	122
25	186	90.5	150	102	94	150	94.6	162	101	110	110	110	147	266
30	308	194	310	205	195	269	179	303	207	234	234	234	279	502
35	484	366	565	378	362	459	310	533	378	441	441	441	487	864
40	733	615	916	627	602	727	501	866	625	761	761	761	774	1340
50	1520	1380	1930	1390	1350	1540	1110	1920	1410	1850	1850	1850	1610	2640
60	2660	2530	3330	2540	2480	2690	2050	3450	2630	3620	3620	3620	2740	4390
70	4140	4060	5090	4090	4000	4170	3350	5390	4280	6130	6130	6130	4140	6600
77	5380	5340	6500	5380	5290	5390	4470	6970	5700	8310	8310	8310	5260	8350
80	5960	5940	7150	5980	5890	5950	5000	7700	6370	9350	9350	9350	5770	9150
90	8100	8120	9490	8170	8090	7980	6950	10300	8850	13300	13300	13300	7580	12000
100	10500	10500	12100	10600	10500	10300	9210	13200	11700	17800	17800	17800	9540	15112
120	15920	15870	17750	15860	15810	15500	14440	19530	18260	28400	28400	28400	13770	21530
140	22100	21900	24000	21700	21700	21500	20410	26600	25800	40800	40800	40800	18340	28400
160	29100	28300	30500	28000	28200	28200	27010	34100	34100	54400	54400	54400	23140	35700
180	36700	35100	37400	34800	35100	35500	33910	42000	43000	69200	69200	69200	28040	43300
200	44800	42100	44500	41900	42300	43300	41210	50300	52400	84800	84800	84800	33095	51306
220	53200	49300	51700	49100	49700	51400	48710	58800	62100	101000	101000	101000	38220	59410
240	62000	56700	59100	56500	57300	59800	56610	67500	72100	117800	117800	117800	43440	67700
260	70700	64200	66500	63900	65000	68400	64710	76400	82400	134800	134800	134800	48640	76100
280	79600	71800	74000	71500	72800	77000	73010	85500	92900	152800	152800	152800	53940	84500
300	88800	79500	81600	79200	80800	85900	81510	94600	103600	170800	170800	170800	59275	93080

$$\Delta h = \int_{1K}^{T} c_p \, dT \quad \text{(J/kg)}$$

Thermal Insulators

Temp. (K)	Pyrex Glass	Teflon (PTFE)	Polycarbonate Amorphous	Nylon	G-10 (normal to cloth lay)	Epoxy	Carbon Reinforced Plastic, CRFP normal	Mylar, PET
1	0	0	0	0	0	0	0	0
2	0.0128	0.126	0.0899	0.0655	2.86E-02	0.0757	0.101	0.0489
4	0.179	2.75	1.47	1.13	0.504	1.48	1.78	0.794
6	0.953	11	9.35	5.32	3.02	9.22	7.34	5.65
8	3.82	28.4	28.9	17.5	9.69	27.3	17.8	16.7
10	10.4	58.1	65.3	42.9	22.7	59.5	33.9	35.7
15	54.8	223	289	206	101	241	108	126
20	154	512	678	547	257	567	230	317
25	336	955	1260	1140	520	1070	405	659
30	600	1520	1990	1990	884	1740	632	1170
35	957	2200	2860	3090	1360	2560	910	1890
40	1400	2980	3840	4470	1940	3540	1250	2780
50	2580	4820	6180	8020	3420	5940	2140	4970
60	4130	7020	8890	12600	5330	8930	3360	7580
70	6050	9580	11900	18000	7650	12500	4920	10600
77	7580	11600	14300	22400	9510	15300	6230	13000
80	8280	12500	15400	24400	10400	16600	6850	14000
90	10800	15800	19200	31500	13400	21200	9100	17800
100	13500	19500	23400	39400	16800	26400	11700	22000
120	19590	12360	32960	57100	7740	38200	17840	31770
140	26700	31100	44100	77400	16800	51900	25300	43300
160	35100	52600	56700	100300	27000	67500	34000	56500
180	44700	77300	71000	125600	38300	84900	43900	71300
200	55200	104500	86900	153400	50700	104100	55200	87600
220	66100	134100	104300	183400	64200	124900	67800	105000
240	77900	165900	123300	216400	78600	147400	81900	124000
260	90600	200700	143400	251400	94000	171400	97300	144000
280	104300	237000	166400	288400	110000	196400	114700	165000
300	118500	276000	189400	327400	127000	222400	132700	188000

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Note: Above two tables for Δh will be very helpful to calculate the amount of heat to be removed while cooling from a given temp T1 to a lower temp T2.

k) **Coeff. of thermal expansion [1,4,9,14]:**

Linear thermal contraction $\Delta L/L$ (%) from 293 K, and a at 293 K (10^{-6} K^{-1}) [79,81–85]

	$\Delta L/L$ (%)						$a(10^{-6}\,K^{-1})$
Material	4 K	40 K	80 K	100 K	150 K	200 K	293 K
Metals							
Al	0.414	0.412	0.390	0.369	0.294	0.201	22.9
Cu	0.326	0.323	0.302	0.283	0.221	0.149	16.65
Fe	0.204	0.202	0.195	0.185	0.149	0.102	11.8
Ni	0.229	0.227	0.217	0.206	0.165	0.112	12.8
Si	0.022	0.022	0.023	0.024	0.024	0.019	2.56
Ti (pc)	0.151	0.150	0.142	0.134	0.107	0.073	8.6
W	0.088	0.087	0.081	0.076	0.059	0.040	4.42
Alloys							
Al2024	0.396	0.394	0.372	0.351	0.278	0.190	21.2
Al5083	0.415	0.413	0.390	0.368	0.294	0.201	22.8
Berylco 25	0.316	0.315	0.296	0.277	0.218	0.151	17.9
Brass (65/35)	0.384	0.380	0.350	0.326	0.253	0.169	19.6
$Fe_{64}Ni_{36}$	0.045	0.048	0.048	0.045	0.030	0.020	~1
Hastelloy C	0.218	0.216	0.204	0.193	0.154	0.105	12.8
Inconel X	0.229	0.228	0.217	0.205	0.164	0.112	13.0
Nb-45Ti	0.188	0.184	0.167	0.156	0.117	0.078	≈10
Cu/NbTi	0.265	0.262	0.245	0.231	0.178	0.117	≈12
S.S. 304/316	0.296	0.296	0.278	0.260	0.203	0.138	15.8
S.S. 310	0.273	0.270	0.252	0.237	0.187	0.127	14.5
Ti-6Al-4V	0.173	0.171	0.162	0.154	0.118	0.078	8
Non-metals							
Sapphire (‖)	0.0715	0.0715	0.0705	0.069	0.061	0.045	5.80
Sapphire (⊥)	0.0605	0.0605	0.0595	0.0585	0.052	0.039	5.06
MgO	0.139	0.0139	0.137	0.133	0.114	0.083	10.3
Pyrex	0.056	0.057	0.054	0.050	0.0395	0.027	3.0
Silica	−0.0005	−0.0003	0.0001	0.0013	0.0030	0.0031	0.45
ZrO_2 (stab)	0.131	0.130	0.124	0.118	0.098	0.068	8.0
YBCO-123(ab)	0.15	0.15	—	0.14	0.115	0.08	10
YBCO-123(c)	0.36	0.35	0.33	0.31	0.25	0.17	17
Polymers							
Torlon	0.448	0.434	0.387	0.358	0.279	0.191	~24
Araldite	1.06	1.02	0.935	0.88	0.71	0.505	~60
Nylon	1.39	1.35	1.25	1.17	0.95	0.67	~80
Stycast	0.44	0.43	0.40	0.38	0.32	0.225	30
Teflon	2.14	2.06	1.93	1.85	1.60	1.25	~200
G10 (‖)	0.705	0.69	0.64	0.60	0.49	0.35	~40
G10 (⊥)	0.24	0.235	0.21	0.20	0.155	0.11	~12

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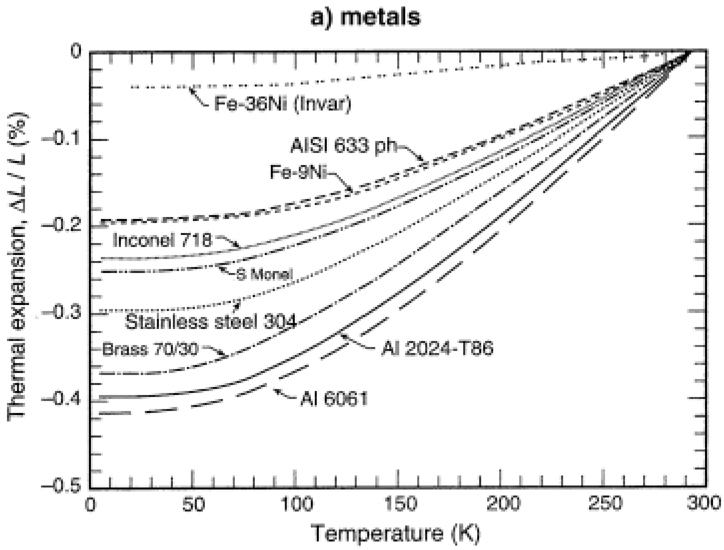
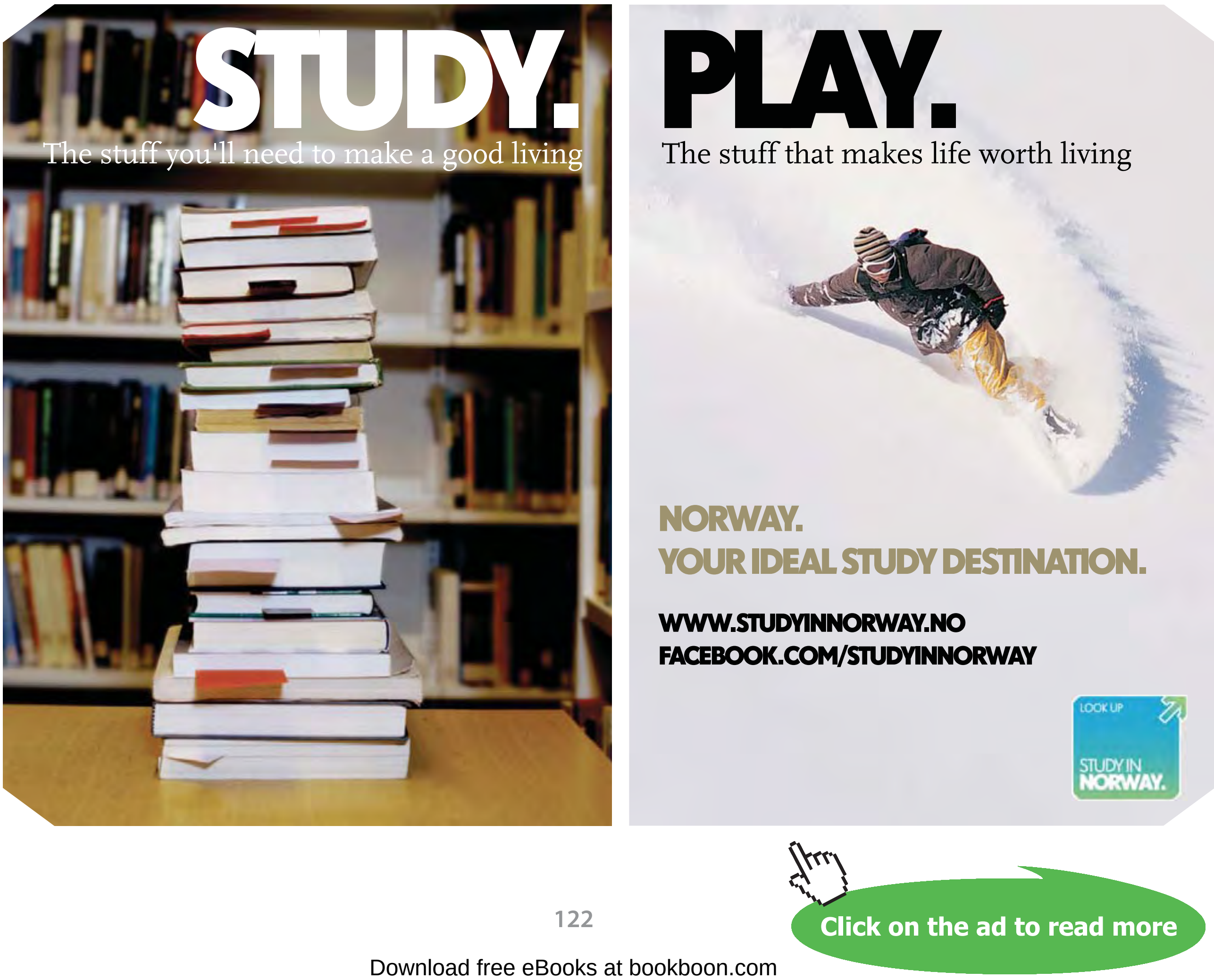


Fig.2.1.2.k1 Thermal expansion of a few metals



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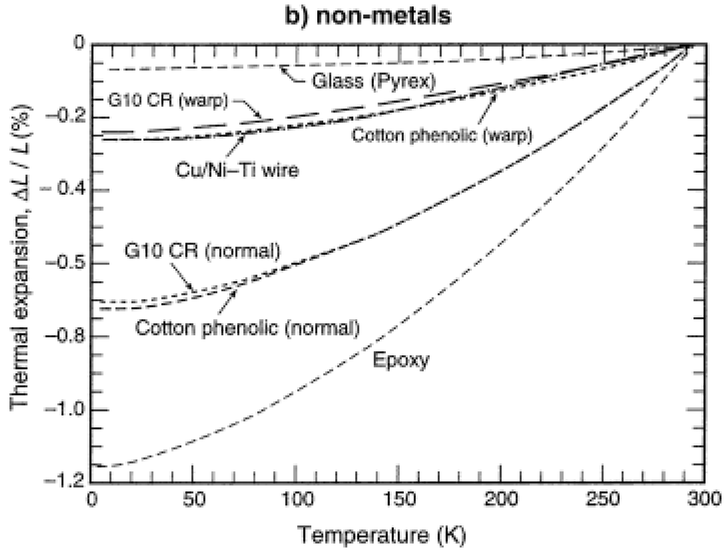

Fig.2.1.2.k2 Thermal expansion of a few non-metals

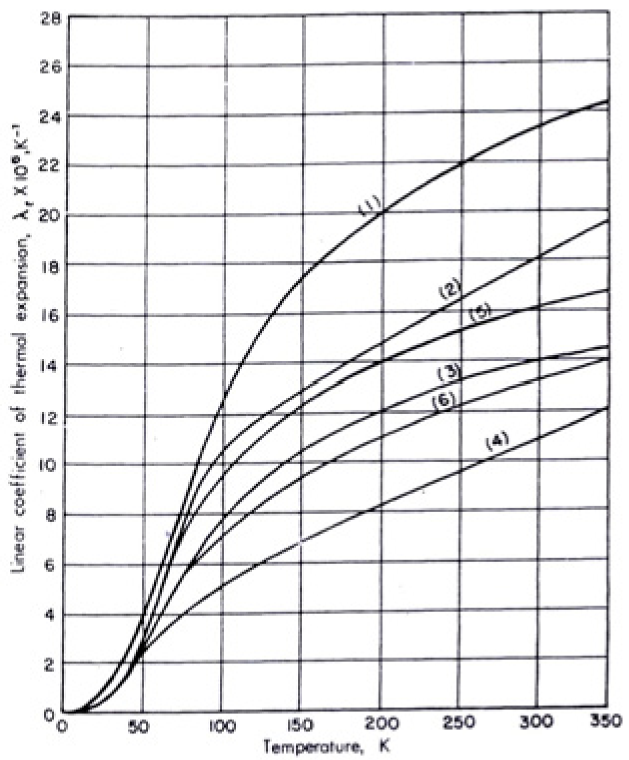

Fig. 2.1.2k3 Linear coefficient of thermal expansion for several materials at low temperature: (l) 2024-T4 aluminum; (2) beryllium copper; (3) K Monel; (4) titanium; (5) 304 stainless steel; (6) C1020 carbon steel (NBS Monograph 29, Thermal Expansion of Solids at Low Temperatures).

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Relationship between sp. heat and coeff. of thermal expansion [1]:

For crystalline solids, the Gruneisen relation is:

$$\beta = \frac{G \cdot c_V \cdot \rho}{B}$$

where β = vol. coeff. of thermal expansion, defined as the fractional change in volume per unit change in temp while the pressure on the material remains constant,

ρ = density of the material,
B = Bulk modulus, and
G is the Gruneisen constant given by:

$$G = \frac{V}{\theta_D} \cdot \frac{d}{dV} \theta_D$$ ... where V is the volume of material

G has values between 1 and 3 for solids.

Also, we have:

$$\frac{\beta_T}{\beta_{300K}} = \frac{cv_T}{cv_{300K}}$$

Values of Gruneisen constants, computed from room temp properties, for a few materials are given below [2]:

Material	G	Material	G
Li	1.17	Mo	1.57
Na	1.25	W	1.62
K	1.34	Fe	1.60
Mg	1.51	Ni	1.88
Al	2.17	Co	1.87
Sn	2.14	Pd	2.23
Pb	2.73	Pt	2.54
Sb	0.92	NaCl	1.63
Bi	1.14	KCl	1.60
Cu	1.96	KBr	1.68
Au	3.03	FeS_2	1.47
Zn	2.01	PbS	1.94
Cd	2.19	Ta	1.75

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l) **Electrical conductivity [1,2,9]:**

Resistivity of pure metals (e.g. Copper):

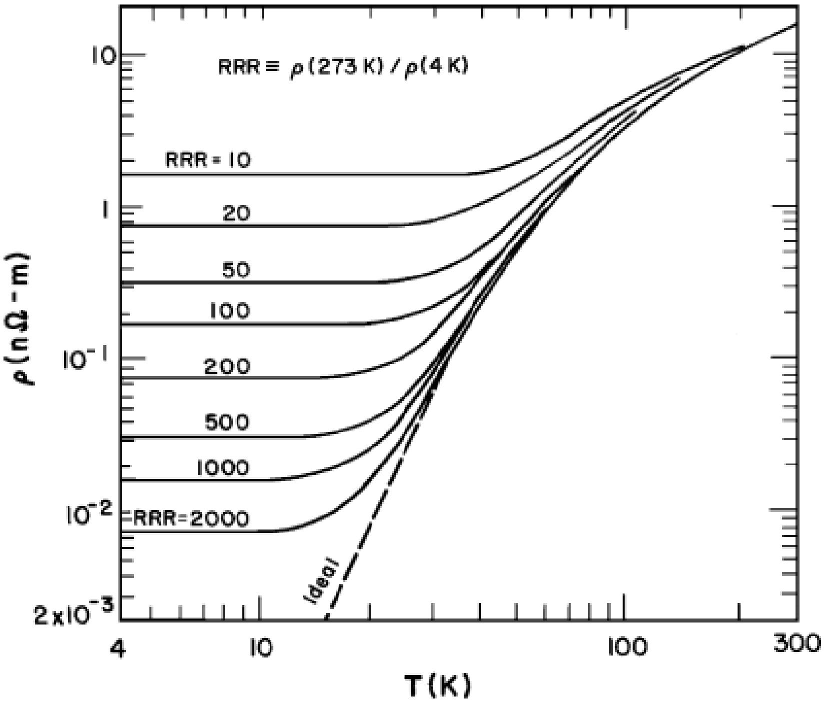

Fig.2.1.2.l1 ρ-vs-T for differing purities of copper, ρ(273K) = 15.45 nΩ (Powell & Fickett)

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Resistivity of various alloys:

Table 2.4 Electrical resistivity of various technical alloys (units of nΩ-m) [3, 14]

Alloy	10 K	20 K	50 K	100 K	200 K	300 K	RRR
AL 5083	30.3	30.3	31.3	35.5	47.9	59.2	1.95
AL 6061-T6	13.8	13.9	14.8	18.8	30.9	41.9	3
304 SUS	490	491	505	545	640	720	1.46
BeCu	56.2	57	58.9	63	72	83	1.48
Manganin	419	425	437	451	469	476	1.13
Constantan	461	461	461	467	480	491	1.07
Ti-6%Al-4%V	1,470	1,470	1,480	1,520	1,620	1,690	1.15
PbSn (56-44)	4.0	5.2	16.8	43.1	95.5	148	37
Pt	–	0.367	7.35	28	69.2	107	290

Ref.[1] gives following graph for variation of resistivity ratio with temp for a few materials:

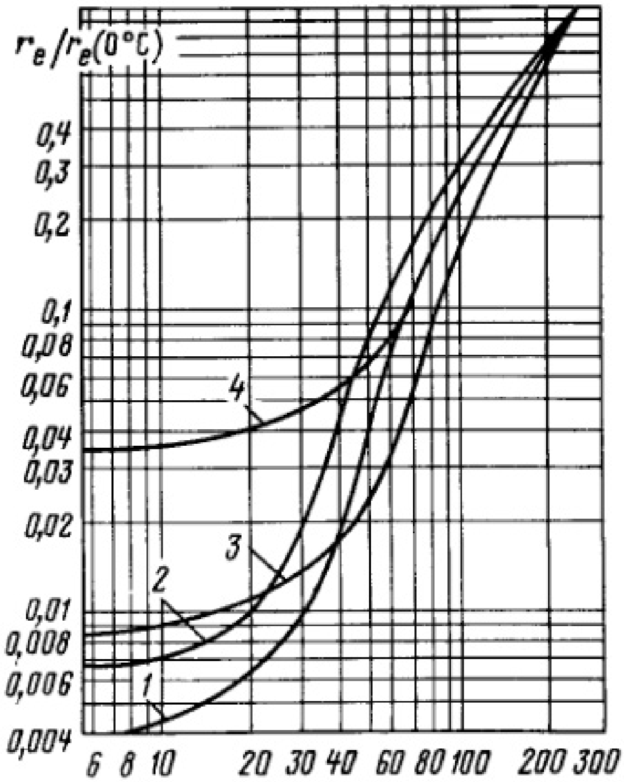

Fig. 2.1.2.I2. Electrical resistivity ratio for several materials at low temperatures: (1) copper; (2) silver; (3) iron; (4) aluminum (Stewart and Johnson 1961).

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m) **Emissivity (ε) [1]:**

Emissivity is the ratio of the energy emitted by the material to the energy that would be emitted by a 'perfect black body', at the same absolute temperature. *'Monochromatic emissivity'* refers to a particular wavelength whereas *'total emissivity'* considers the total energy emitted by a black body, integrated over all the wave lengths. In engineering calculations 'total emissivity' is used.

Emissivity depends on the surface, its surface treatment, the temp and of course, the wavelength of radiation.

Values of emissivity for a few materials are given below:

Emissivity ε for some materials at three temperatures

Material	T [K]	ε_n
Stainless steel	300	0.20
	80	0.12
	4	0.10
Aluminium (unpolished)	300	0.25
	80	0.12
	4	0.07
Aluminium (polished mechanically)	300	0.20
	80	0.10
	4	0.06
Aluminium (polished electronically)	300	0.15
	80	0.08
	4	0.04
Chromium	300	0.08
Copper (polished mechanically)	300	0.03
	80	0.019
	4	0.015
Tin	300	0.05
	80	0.013
	4	0.012
Brass (polished)	300	0.03
	80	0.029
	4	0.018
Nickel	300	0.045
	80	0.022
Gold	300	0.20
	80	0.10
Silver	300	0.022
	80	0.008
	4	0.005

Radiation from a 'gray' surface of emissivity (ε) at a temp of T (K) is = Q (W), given by:

$$Q = \varepsilon \sigma A T^4$$

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where Q is in W, and σ is the Stefan_Boltzmann constant = 5.67E-04 W/m^2.K^4.

Net radiation between two gray surfaces temperatures T1, T2 (in K) is:

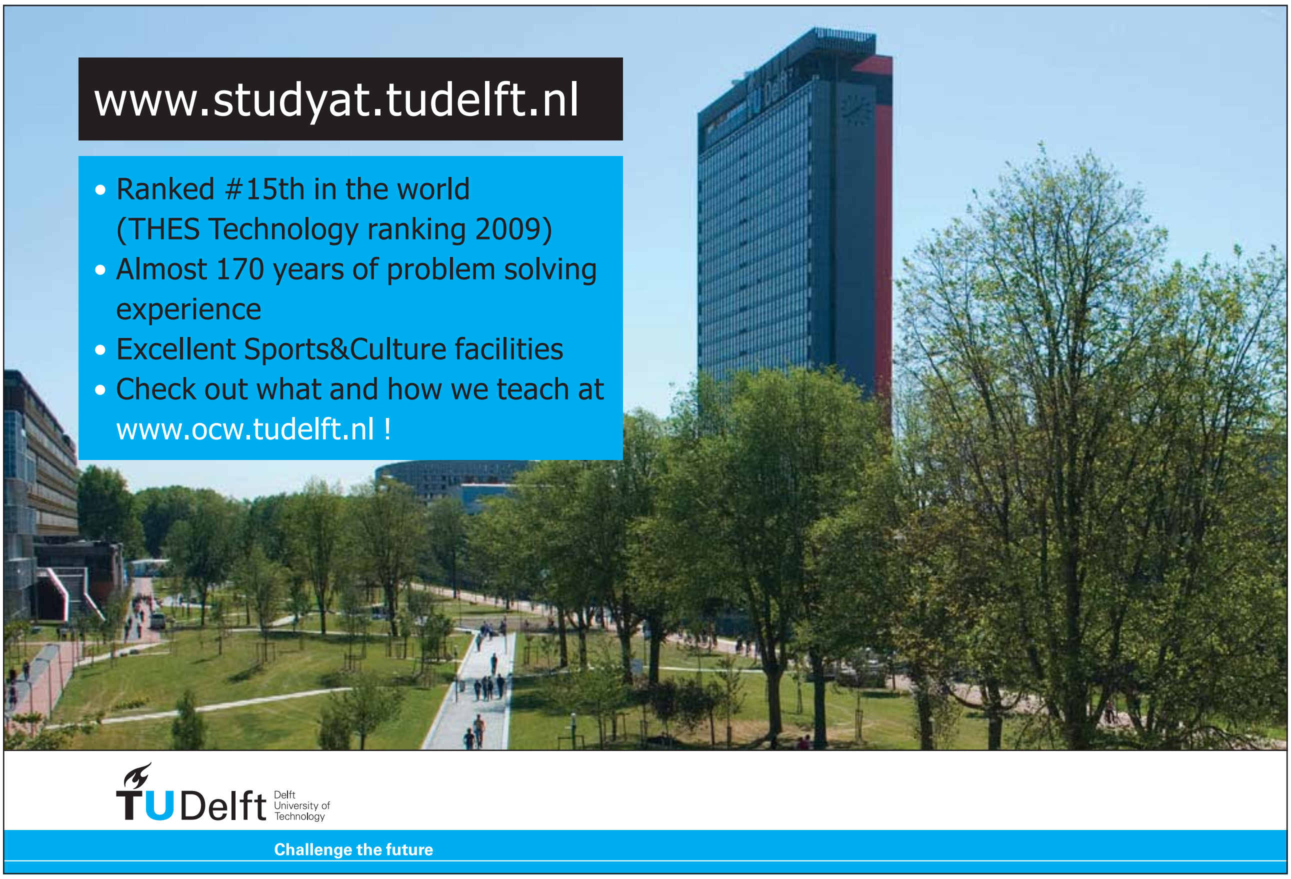
$$Q = E\,\sigma A\,(T_1^4 - T_2^4)$$

where E is the Emissivity factor which depends on the emissivities of two surfaces, their geometric configuration and orientation and the type of reflection (i.e. specular or diffuse).

For the *three important cases* of a small object in a large surrounding, two infinitely long parallel plates, two infinitely long concentric cylinders and concentric spheres, we have the net radiation heat transfer between the surfaces, given by the following [15]:

1. **Small object 1, in a large surrounding 2:**

$$Q_{12} = A_1 \cdot \sigma \cdot \varepsilon_1 \cdot \left(T_1^4 - T_2^4\right)$$



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2. **Parallel plates:**

$$Q_{12} = \frac{A \cdot \sigma \cdot \left(T_1^{\,4} - T_2^{\,4}\right)}{\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1}$$

3. **Concentric cylinders (inner cylinder is represented as 1):**

$$Q_{12} = \frac{A_1 \cdot \sigma \cdot \left(T_1^{\,4} - T_2^{\,4}\right)}{\frac{1}{\varepsilon_1} + \left(\frac{A_1}{A_2}\right) \cdot \left(\frac{1}{\varepsilon_2} - 1\right)}$$

where

$$\frac{A_1}{A_2} = \frac{r_1}{r_2}$$

4. **Concentric spheres (inner sphere is 1):**

$$Q_{12} = \frac{A_1 \cdot \sigma \cdot \left(T_1^{\,4} - T_2^{\,4}\right)}{\frac{1}{\varepsilon_1} + \left(\frac{A_1}{A_2}\right) \cdot \left(\frac{1}{\varepsilon_2} - 1\right)}$$

where

$$\frac{A_1}{A_2} = \left(\frac{r_1}{r_2}\right)^2$$

(n) Superconductivity [1,2,9]:

Certain elements, alloys and compounds, when cooled below a certain temp (called transition or critical temp. T_c), lose their electrical resistance, and the material is said to be '*superconducting*'. The phenomenon of superconductivity was discovered by Kamerlingh Onnes in 1911.

It is observed that if an external magnetic field is applied, when a 'critical field, H_c' is reached, superconductivity is destroyed and the material becomes 'normal'.

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Depending upon the magnetization characteristics, superconductors are classified as of Type-I or Type-II:

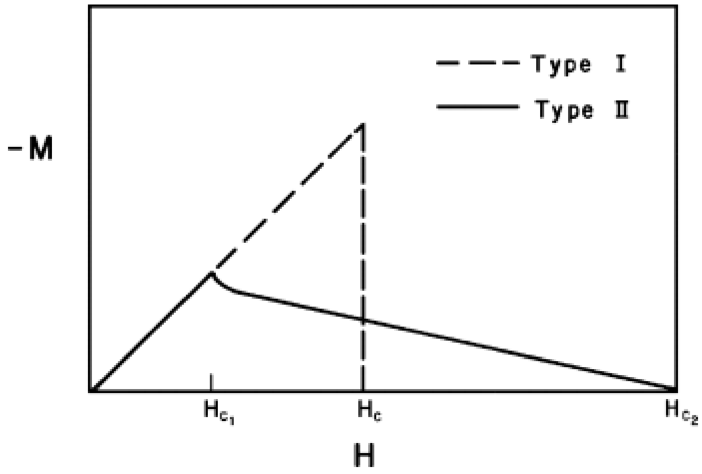

Fig. 2.1.2m1. Magnetization curve for Type-I and Type-II conductors

Type-I superconductor has one critical field, Hc. Type-II has two critical fields: H_{c1} and H_{c2} as shown above.

Type-I Superconductors are *perfectly diamagnetic*, i.e. magnetic field is expelled from a superconductor, as shown below:

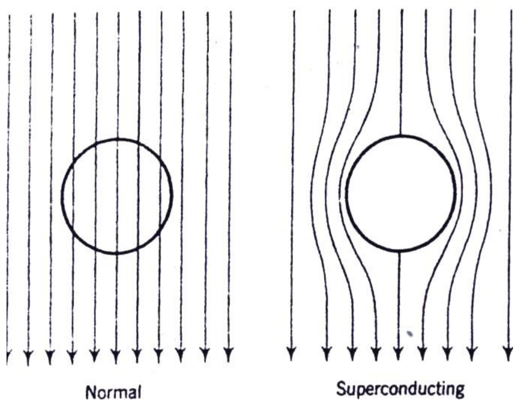

Fig. 2.1.2m2. Type-I Superconductor is perfectly diamagnetic

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Variation of critical field with temp:

This variation is parabolic:

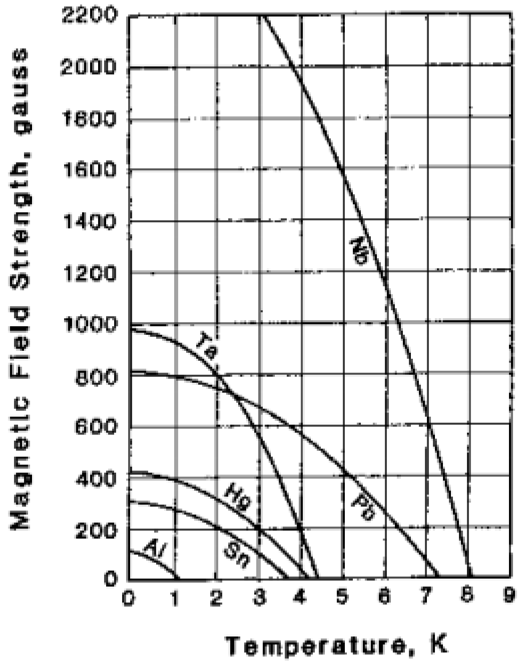

Fig. 2.1.2m3. Magnetic Field strength vs Temp for some Superconductors

The magnetic field-temperature characteristics of a Type I superconductor is given by an empirical relationship between the critical temperature and field,

$$H_c(T) = H_0\left[1 - \left(\frac{T}{T_c}\right)^2\right]$$

where H_0 is the threshold field at T = 0 K, and T_c is the transition temp at zero field.

Silsbee hypothesis [1]: "When the electric current flowing in a superconductor produces a magnetic field at the surface of the material which equals or exceeds the threshold field, the normal state is restored."

The current corresponding to the threshold field is called the *threshold current*.

For a long wire of diameter d, the magnetic field produced at the surface of the wire by an electric current I is: H = 0.4 * I / d; i.e. the *threshold current* is:

$I_T = 2.5 * H_T * d$

Here, H_T is in Gauss, d in cm, and I_T in Amps.

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Data (i.e. T_c and H_0) for some Type-I and Type-II superconductors are given below [9]:

Table 2.10 Critical temperature and critical field of Type I superconductors [30]

Material	T_c(K)	$\mu_0 H_0$(mT)
Aluminum	1.2	9.9
Cadmium	0.52	3.0
Gallium	1.1	5.1
Indium	3.4	27.6
Iridium	0.11	1.6
Lead	7.2	80.3
Mercury ∝	4.2	41.3
Mercury β	4.0	34.0
Osmium	0.7	6.3
Rhenium	1.7	20.1
Rhodium	0.0003	4.9
Ruthenium	0.5	6.6
Tantalum	4.5	83.0
Thalium	2.4	17.1
Thorium	1.4	16.2
Tin	3.7	30.6
Tungsten	0.016	0.12
Zinc	0.9	5.3
Zirconium	0.8	4.7

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Table 2.11 Critical temperature and upper critical field of common Type II superconductors [35]

Material	T_c(K)	$\mu_0 H_{c2}$(T)
Nb	9.3	0.29
V	5.4	0.7
NbTi	9.3	13
Nb_3 Sn	18	23
V_3Ga	15	23
Nb_3 Ge	20.5	41

Another class of materials that become superconducting are **'High Temp Superconductors (HTS)'**. These are Type-II superconductors that have a substantially higher T_c values:

Table 2.12 Critical properties of HTS materials. Two values of H_{c2} indicate anisotropic material property [34]

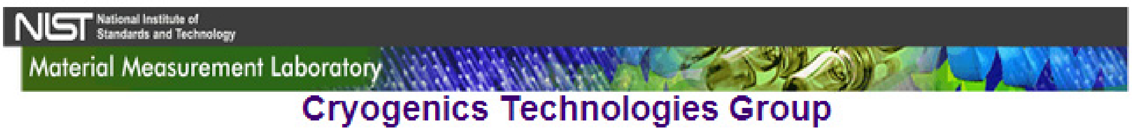
Superconductor	T_c(K)	$\mu_0 H_{c2}$(T)
MgB_2	39	16/2.5
LaSrCuO	40	50
YBCO	90	670/120
$Bi_2Sr_2CaCu_2O_8$	90	280/32
$Bi_2Sr_2Ca_2Cu_3O_{10}$	110	
$TlBaCaCuO_{10}$	110	
$TlBaCaCuO_{10}$	125	~120
$HgBa_2Ca_2Cu_3O_8$	133	~160

===

2.1.3 Cryogenic properties of materials from the National Institute of Standards and Technology Boulder, CO 80303, USA…NIST – Cryogenics website [11]:

As we enter this website viz. http://www.cryogenics.nist.gov/MPropsMAY/materialproperties.htm

We get:



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Material Properties

Aluminum 1100 (UNS A91100)

Aluminum 3003-F(UNS A93003)

Aluminum 5083-O (UNS A95083)

Aluminum 6061-T6 (UNS A96061)

Aluminum 6063-T5 (UNS A96063)

Apiezon N

Balsa

Beechwood/phenolic

Beryllium

Beryllium Copper

Brass (UNS C2600)

Copper (OFHC) (UNS C10100/ C10200)
* rev. 02/03/2010

Fiberglass Epoxy G-10

Glass Fabric/polyester

Glass mat/epoxy

Inconel 718 (UNS N107718)

Indium

Invar (Fe-36Ni) (UNS K93600)

Kevlar-49 Fiber

Kevlar-49 composite

Lead

Molybdenum

Nickel Steel Fe 2.25 Ni

Nickel Steel Fe 3.25 Ni (UNS S20103)

Nickel Steel Fe 5.0 Ni (UNS S20153)

Nickel Steel Fe 9.0 Ni (UNS S21800)

Platinum

Polyamide (Nylon)

Polyethylene Terephthalate (Mylar)

Polyimide (Kapton)

Polystyrene

Polyurethane

Polyvinyl Chloride (PVC)

Sapphire

Silicon

Stainless Steel 304 (UNS S30400)

Stainless Steel 304L (UNS S30403)

Stainless Steel 310 (UNS S31000)

Stainless Steel 316 (UNS S31600)

Teflon

Ti-6Al-4V (UNS R56400)

Titanium 15-3-3-3

Click on the desired material, and we get the properties:

One *great advantage* is that the properties are presented as logarithmic polynomial equations, which makes it easy to program in a computer. In some cases, graphs are also presented.

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2.1.3.1 As an example, in we click on 304 Stainless Steel, we get:

	Thermal Conductivity	Specific Heat
UNITS	W/(m-K)	J/(kg-K)
a	-1.4087	22.0061
b	1.3982	-127.5528
c	0.2543	303.647
d	-0.6260	-381.0098
e	0.2334	274.0328
f	0.4256	-112.9212
g	-0.4658	24.7593
h	0.1650	-2.239153
i	-0.0199	0
data range	4-300	4-300
equation range	1-300	4-300
curve fit % error relative to data	2	5

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Curve fit equation of the form:
$\log_{10} y = a+b(\log_{10}T) + c(\log_{10}T)^2 + d(\log_{10}T)^3 + e(\log_{10}T)^4 + f(\log_{10}T)^5 + g(\log_{10}T)^6 + h(\log_{10}T)^7 + i(\log_{10}T)^8$

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

Where: Coefficients a - *i* are summarized in the appropriate table and T is the temperature in K (x-axis), and y is the property to solve for.

	Young's Modulus	Young's Modulus	Linear expansion
Units	units: GPa	units: GPa	$[(L-L_{293})/L_{293}] \times 10^5$ unitless, eg. m/m
a	2.098145E2	2.100593E2	-2.9554E2
b	1.217019E-1	1.534883E-1	-3.9811E-1
c	-1.146999E-2	-1.617390E-3	9.2683E-3
d	3.605430E-4	5.117060E-6	-2.0261E-5
e	-3.017900E-6	-6.154600E-9	1.7127E-8
T_{low} (K)			23
f>			-300.04
data range (K)	5-65	48-293	4-300
equation range (K)	5-57	57-293	4-300
curve fit % error relative to data	1	1	5

equation of the form:

$$y = a + bT + cT^2 + dT^3 + eT^4 \quad >T \geq T_{low}$$

$$y = f \quad T < T_{low}$$

solves as expected: Where: Coefficients *a-e* are summarized in the appropriate table and *T* is the temperature in K (x-x- x-axis), and y is the property to solve for.

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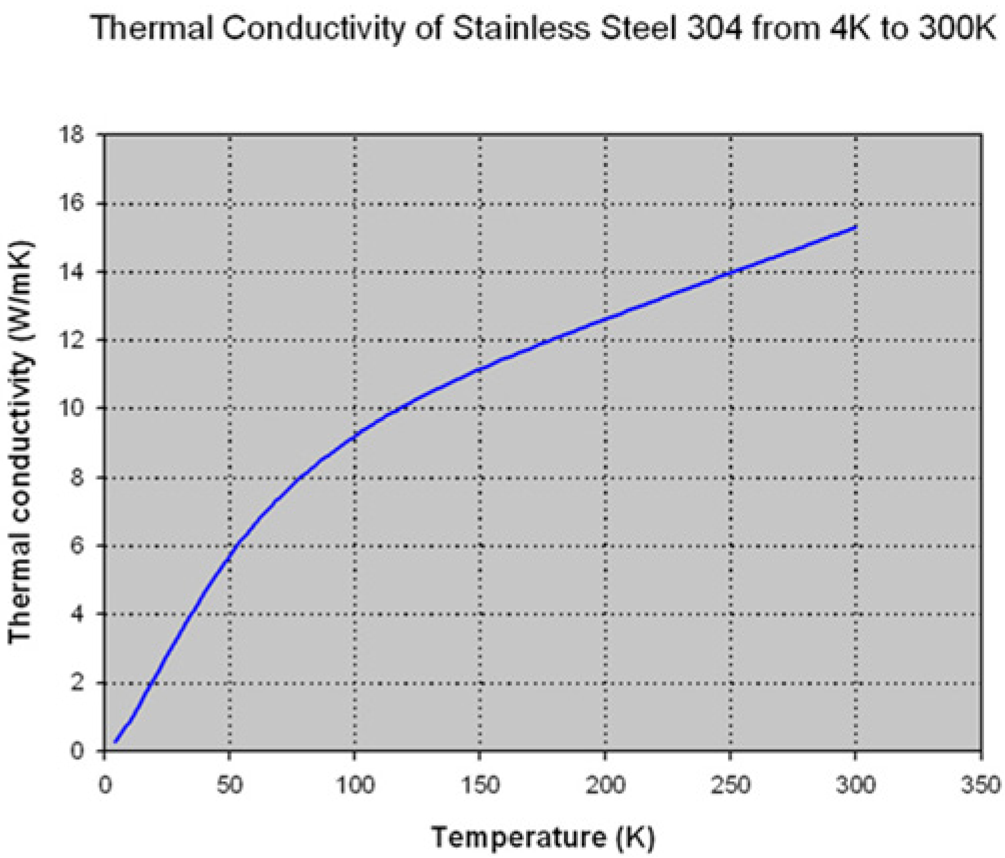
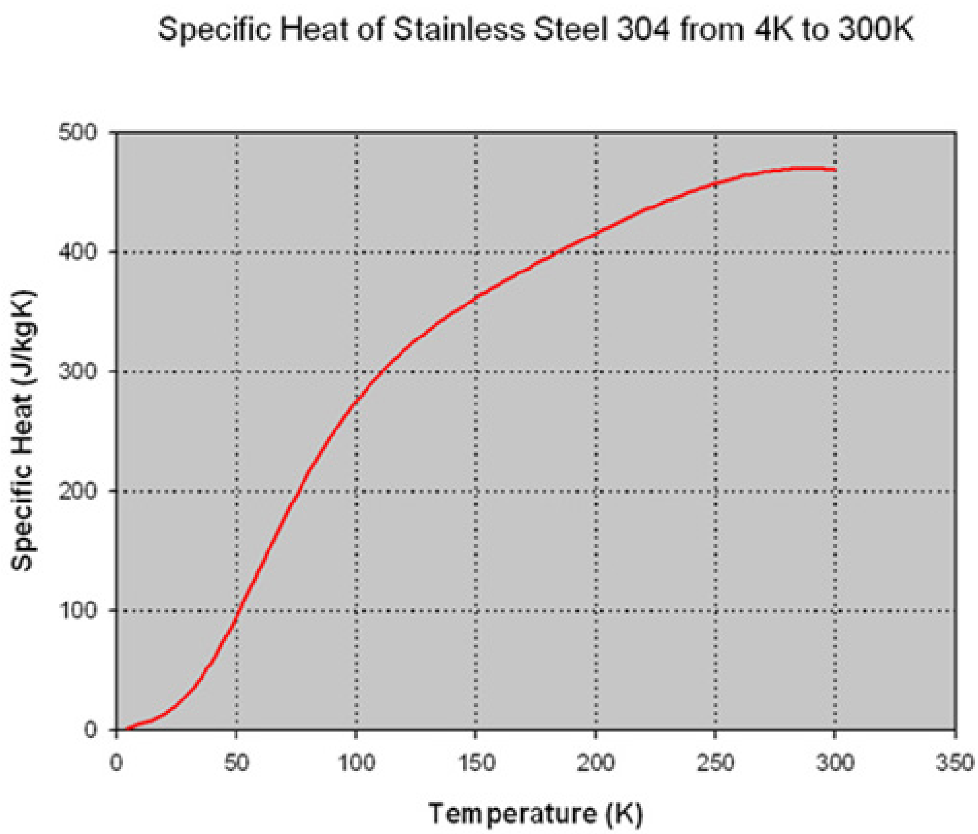
And, the plots:





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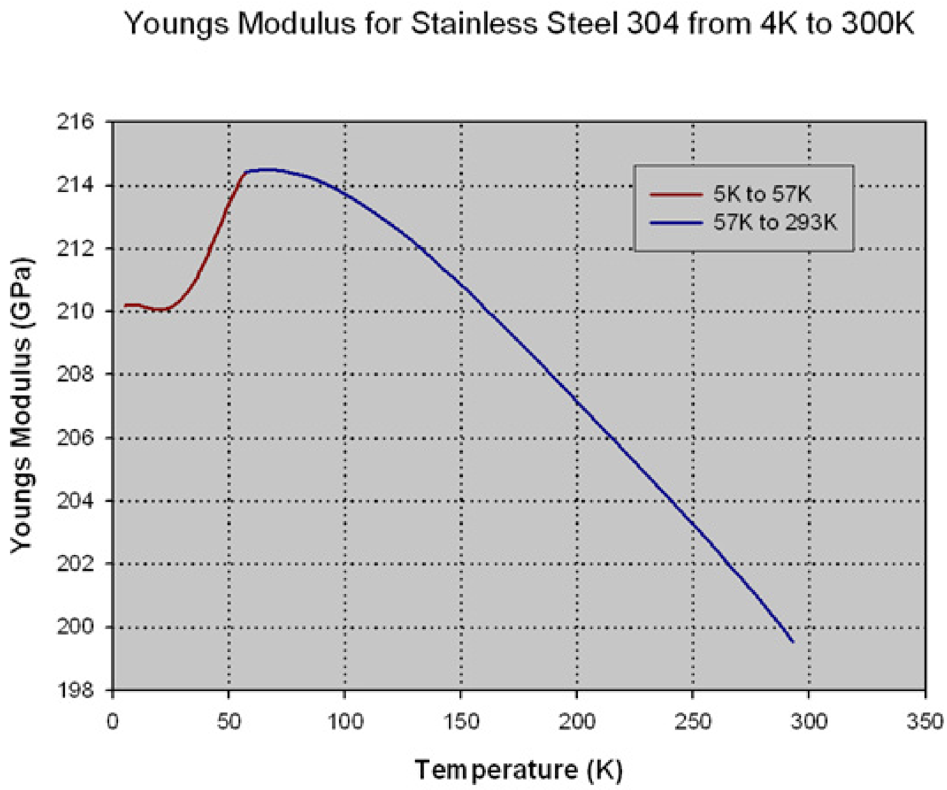

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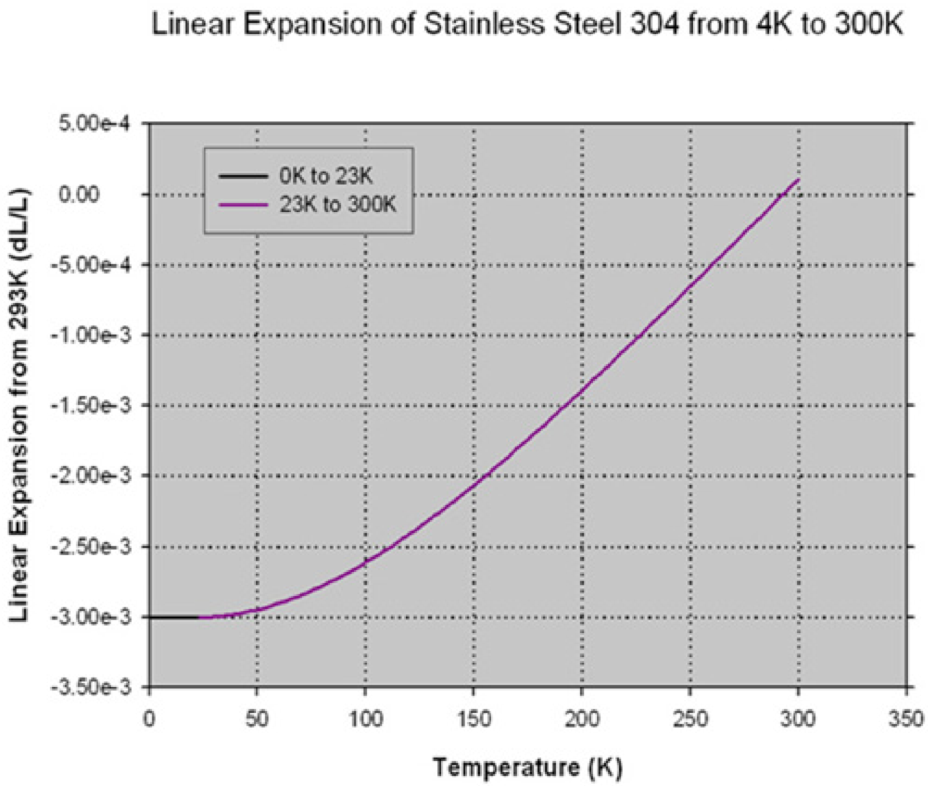

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2.1.3.2 For 6061-T6 Aluminum UNS A96061:

	Thermal Conductivity	Specific Heat
UNITS	W/(m-K)	J/(kg-K)
a	0.07918	46.6467
b	1.0957	-314.292
c	-0.07277	866.662
d	0.08084	-1298.3
e	0.02803	1162.27
f	-0.09464	-637.795
g	0.04179	210.351
h	-0.00571	-38.3094
i	0	2.96344
data range	4-300	4-300
equation range	1-300	4-300
curve fit % error relative to data	0.5	5

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Curve fit equation of the form:

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

Solves as:

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

Where: Coefficients a - *i* are summarized in the appropriate table and T is the temperature in K (x-axis), and y is the property to solve for.

	Young's Modulus	Linear expansion
UNITS	GPa	$[(L-L_{293})/L_{293}] \times 10^5$ unitless, eg. m/m
a	7.771221E1	-4.1277E2
b	1.030646E-2	-3.0389E-1
c	-2.924100E-4	8.7696E-3
d	8.993600E-7	-9.9821E-6
e	-1.070900E-9	0
T_{low} (K)		18
f>		-415.45
data range (K)	0-299	4-300
equation range (K)	2-295	4-300
curve fit % error relative to data	1	4

equation of the form:

$$y = a + bT + cT^2 + dT^3 + eT^4 \quad >T \geq T_{low}$$

$$y = f \quad T < T_{low}$$

solves as expected: Where: Coefficients *a-e* are summarized in the appropriate table and *T* is the temperature in K (x-axis), and y is the property to solve for.

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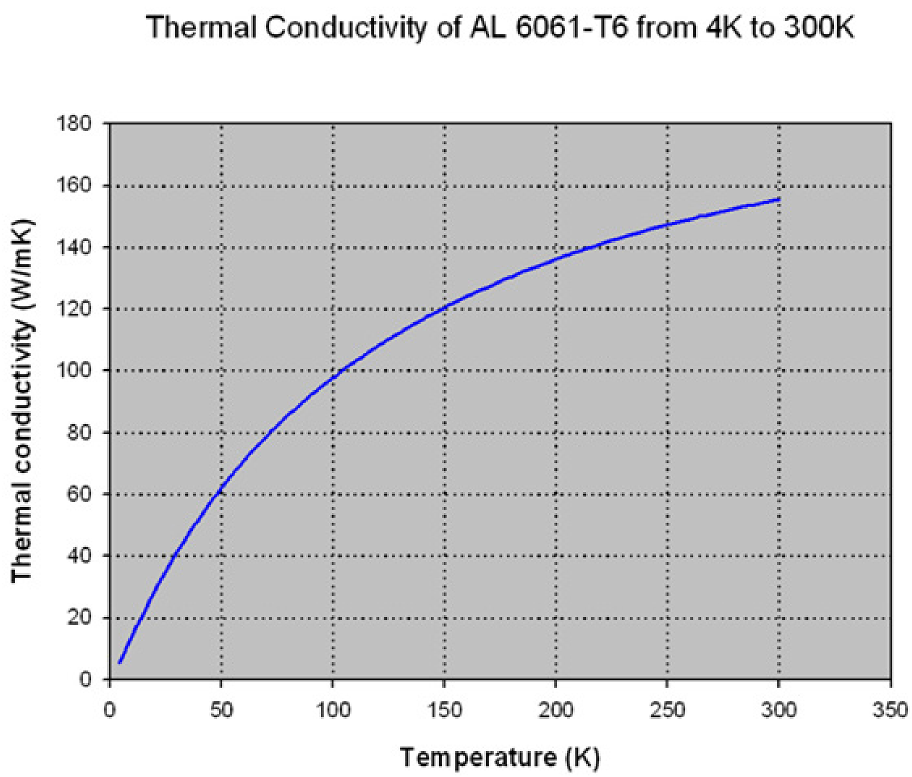

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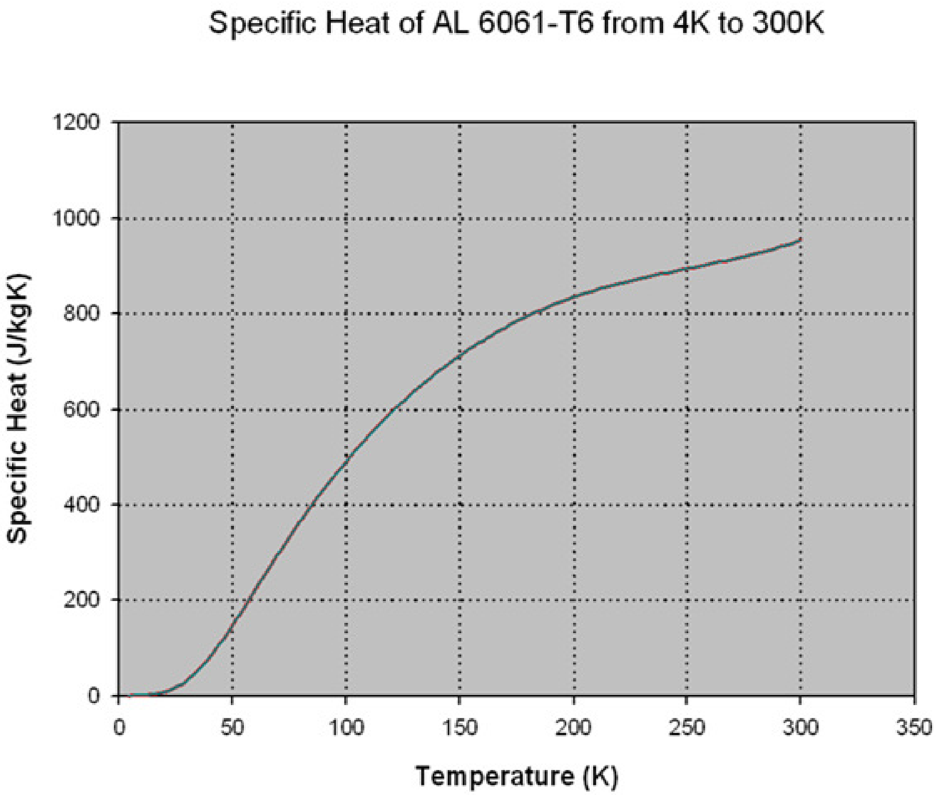

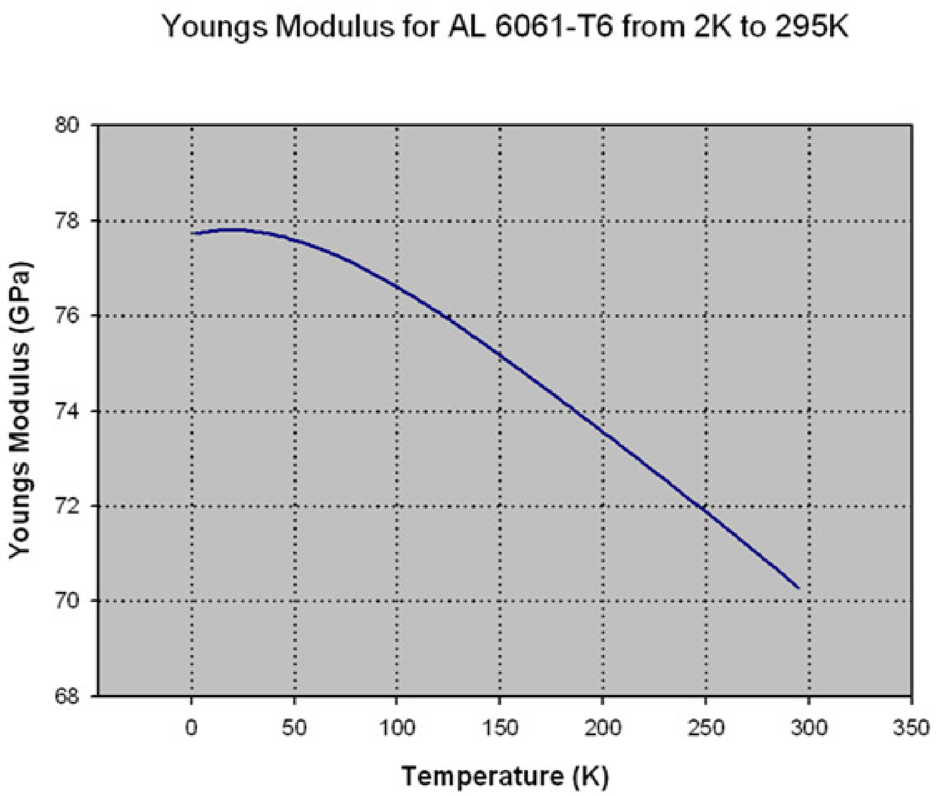

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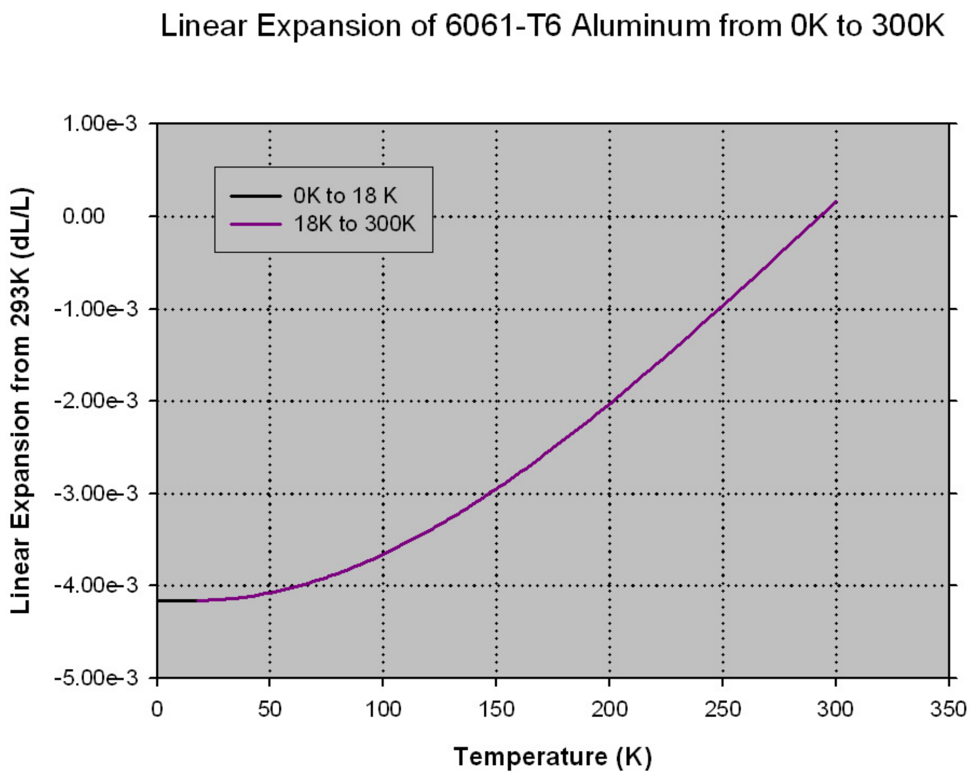

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2.1.3.3 For SS 304L:

	Thermal Conductivity	Specific Heat
UNITS	W/(m-K)	J/(kg-K)
a	-1.4087	-351.51
b	1.3982	3123.695
c	0.2543	-12017.28
d	-0.6260	26143.99
e	0.2334	-35176.33
f	0.4256	29981.75
g	-0.4658	-15812.78
h	0.1650	4719.64
i	-0.0199	-610.515
data range	4-300	4-20
equation range	1-300	4-23
curve fit % error relative to data	2	1

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Curve fit equation of the form:

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

Solves as:

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

Where: Coefficients a - *i* are summarized in the appropriate table and T is the temperature in K (x-axis), and y is the property to solve for.

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	Linear expansion
Units	$[(L-L_{293})/L_{293}] \times 10^{5}$ unitless, eg. m/m
a	-2.9554E2
b	-3.9811E-1
c	9.2683E-3
d	-2.0261E-5
e	1.7127E-8
T_{low} (K)	23
f>	-300.04
data range (K)	4-300
equation range (K)	4-300
curve fit % error relative to data	5

equation of the form:

$$y = a + bT + cT^2 + dT^3 + eT^4 \quad >T \geq T_{low}$$

$$y = f \quad T < T_{low}$$

solves as expected: Where: Coefficients *a-e* are summarized in the appropriate table and *T* is the temperature in K (x-axis), and y is the property to solve for.

===

2.1.3.4 For OFHC copper:

	Thermal Conductivity RRR = 50	Thermal Conductivity RRR = 100	Thermal Conductivity RRR = 150	Thermal Conductivity RRR = 300	Thermal Conductivity RRR = 500
UNITS	W/(m-K)	W/(m-K)	W/(m-K)	W/(m-K)	W/(m-K)
a	1.8743	2.2154	2.3797	1.357	2.8075
b	-0.41538	-0.47461	-0.4918	0.3981	-0.54074
c	-0.6018	-0.88068	-0.98615	2.669	-1.2777
d	0.13294	0.13871	0.13942	-0.1346	0.15362
e	0.26426	0.29505	0.30475	-0.6683	0.36444
f	-0.0219	-0.02043	-0.019713	0.01342	-0.02105
g	-0.051276	-0.04831	-0.046897	0.05773	-0.051727
h	0.0014871	0.001281	0.0011969	0.0002147	0.0012226
i	0.003723	0.003207	0.0029988	0	0.0030964
low range	4K	4K	4K	4K	4K
high range	300K	300K	300K	300K	300K
curve fit % error relative to data					

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For Thermal Conductivity only:
Curve fit equation of the form:
$\log_{10} k = (a + cT^{0.5} + eT + gT^{1.5} + iT^{2})/(1 + bT^{0.5} + dT + f\,T^{1.5} + hT^{2})$

solves as:
$k = 10^{(a + cT^{0.5} + eT + g\,T^{1.5} + iT^{2}) / (1+ bT^{0.5} + d\,T + f\,T^{1.5} + hT^{2})}$

	Specific Heat	Expansion Coefficient
UNITS	J/(kg-K)	10^{-6} * (1/K)
a	-1.91844	-17.9081289
b	-0.15973	67.131914
c	8.61013	-118.809316
d	-18.996	109.9845997
e	21.9661	-53.8696089
f	-12.7328	13.30247491
g	3.54322	-1,30843441
h	-0.3797	---
i	0	---
data range	4-300	4-300
equation range	4-300	4-300
curve fit % error relative to data		

For properties: specific heat and expansion coefficient curve fit equation of the form:
Curve fit equation of the form:
$\log_{10} y = a+b(\log_{10}T) + c(\log_{10}T)^{2} + d(\log_{10}T)^{3} + e(\log_{10}T)^{4} + f(\log_{10}T)^{5} + g(\log_{10}T)^{6} + h(\log_{10}T)^{7} + i(\log_{10}T)^{8}$

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

Where: Coefficients a - *i* are summarized in the appropriate table and T is the temperature in K (x-axis), and y is the property to solve for.

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2.1.3.5 For Teflon:

	Thermal Conductivity	Specific Heat
UNITS	W/(m-K)	J/(kg-K)
a	2.7380	31.88256
b	-30.677	-166.51949
c	89.430	352.01879
d	-136.99	-393.44232
e	124.69	259.98072
f	-69.556	-104.61429
g	23.320	24.99276
h	-4.3135	-3.20792
i	0.33829	0.16503
data range	4-300	4-300
equation range	4-300	4-300
curve fit % error relative to data		1.5

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Curve fit equation of the form:

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

Solves as:

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

Where: Coefficients a - *i* are summarized in the appropriate table and T is the temperature in K (x-axis), and y is the property to solve for.

	Linear expansion
Units	$[(L-L_{293})/L_{293}] \times 10^5$ unitless, eg. m/m
a	-2.125E3
b	-8.201E-1
c	6.161E-2
d	-3.171E-4
e	6.850E-7
T_{low} (K)	NA
f>	NA
data range (K)	4-300
equation range (K)	4-300
curve fit % error relative to data	2
data	

equation of the form:

$$y = a + bT + cT^2 + dT^3 + eT^4 \quad > T \geq T_{low}$$

$$y = f \quad T < T_{low}$$

solves as expected: Where: Coefficients *a-e* are summarized in the appropriate table and *T* is the temperature in K (x-axis), and y is the property to solve for.

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2.1.3.6 For Beryllium Copper:

	Thermal Conductivity
UNITS	W/(m•K)
a	-0.50015
b	1.93190
c	-1.69540
d	0.71218
e	1.27880
f	-1.61450
g	0.68722
h	-0.10501
i	0
data range	2-80
equation range	1-120
curve fit % error relative to data	2

Curve fit equation of the form:

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

Solves as:

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

Where: Coefficients a – *i* are summarized in the appropriate table and T is the temperature in K (x-axis), and y is the property to solve for.

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	Thermal Conductivity
UNITS	$[(L-L_{293})/L_{293}] \times 10^5$ unitless, eg. m/m
a	-3.1150E2
b	-4.4498E-1
c	1.0133E-2
d	-2.4718E-5
e	2.6277E-8
T_{low} (K)	24
f>	-316.68
data range (K)	4-300
equation range (K)	4-300
curve fit % error relative to data	1.5

equation of the form:

$$y = a + bT + cT^2 + dT^3 + eT^4 \quad > T \geq T_{low}$$

$$y = f \quad T < T_{low}$$

solves as expected: Where: Coefficients a-e are summarized in the appropriate table and T is the temperature in K (x-axis), and y is the property to solve for.

==

2.1.3.7 For 9% Ni Steel:

	Thermal Conductivity	Specific Heat
UNITS	W/(m-K)	J/(kg-K)
a	-0.0712785	15503.108
b	-3.48735	-37280.377
c	10.6547	26788.417
d	-12.9153	7010.0877
e	8.89066	-22731.651
f	-3.51482	15386.526
g	0.743643	-5175.7968
h	-0.0657884	896.97274
i	0	-64.055866
data range	4-300	60-300
equation range	4-300	55-300
curve fit % error relative to data	2	1.5

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Curve fit equation of the form:

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

Solves as:

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

Where: Coefficients a - *i* are summarized in the appropriate table and T is the temperature in K (x-axis), and y is the property to solve for.

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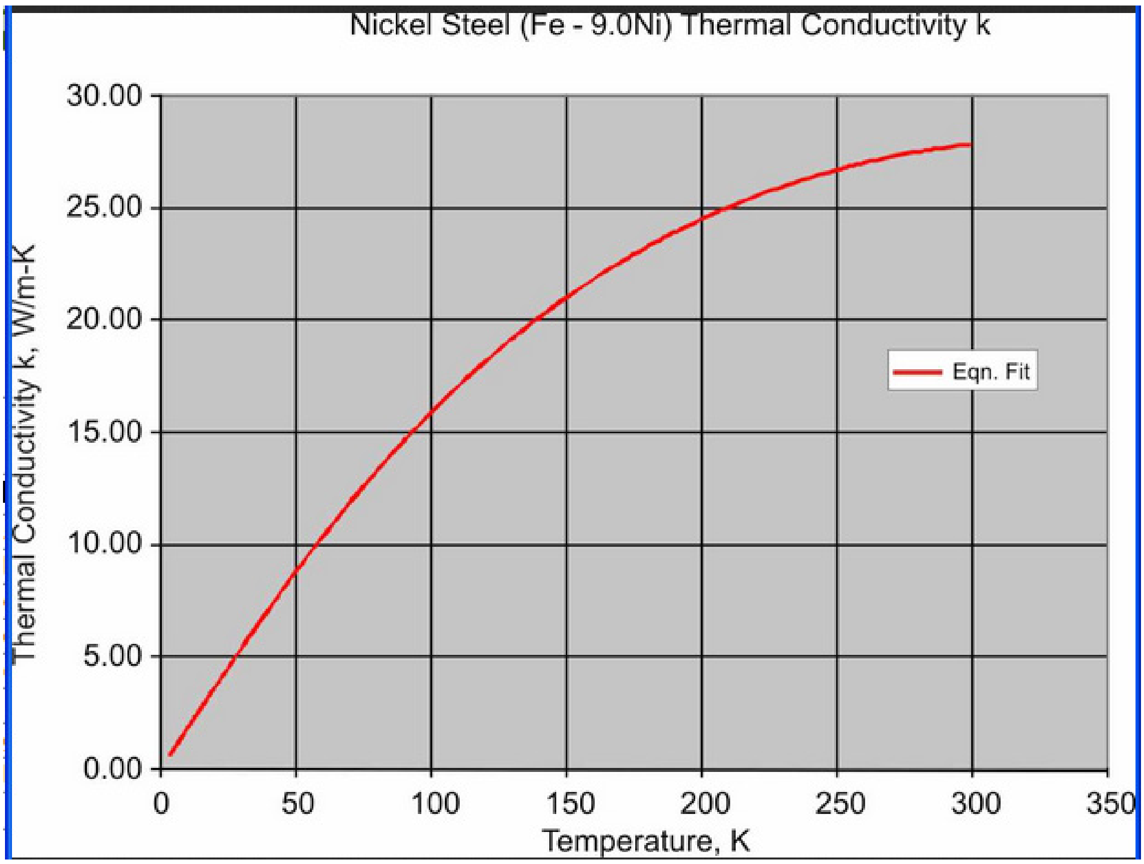
	Young's Modulus	Linear expansion
Units	GPa	$[(L-L_{293})/L_{293}] \times 10^5$ unitless, eg. m/m
a	2.05335E2	-2.104E2
b	1.74835E-2	-5.699E-2
c	-3.65760E-4	5.072E-3
d	8.71545E-7	-1.381E-5
e	-7.78130E-10	1.897E-8
T_{low} (K)		6
f>		-210.56
data range (K)	1-298	4-300
equation range (K)	1-298	4-265
curve fit % error relative to data	1	1.5

equation of the form:

$$y = a + bT + cT^2 + dT^3 + eT^4 \quad T \geq T_{low}$$

$$y = f \quad T < T_{low}$$

solves as expected: Where: Coefficients a-e are summarized in the appropriate table and T is the temperature in K (x-axis), and y is the property to solve for.



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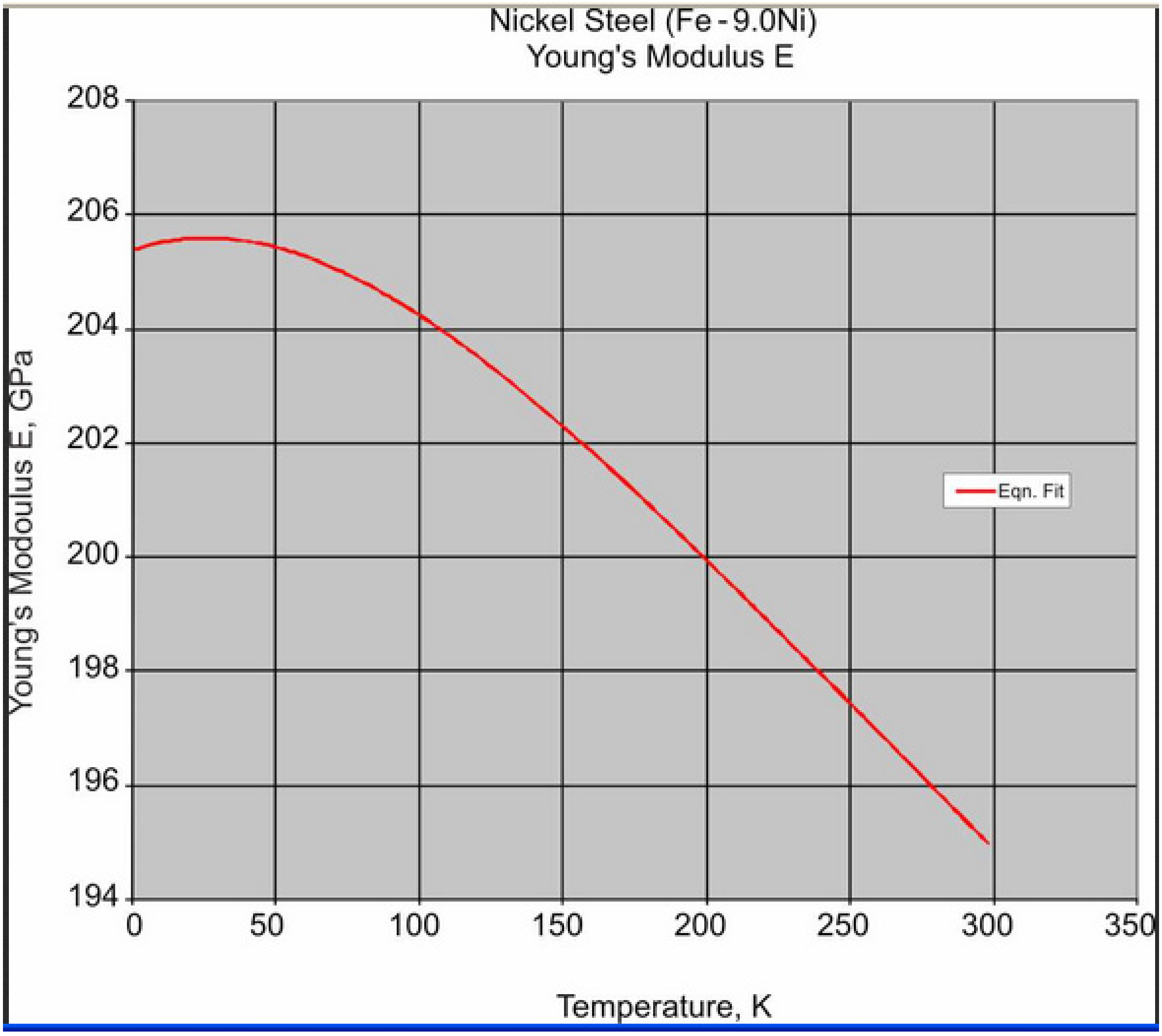

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2.1.3.8 For Invar:

	Thermal Conductivity	Specific Heat
UNITS	W/(m-K)	J/(kg-K)
a	-2.7064	28.08
b	8.5191	-228.23
c	-15.923	777.587
d	18.276	-1448.423
e	-11.9116	1596.567
f	4.40318	-1040.294
g	-0.86018	371.2125
h	0.068508	-56.004
i	0	0
data range	4-300	4-20
equation range	4-300	4-27
curve fit % error relative to data	2	2

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Curve fit equation of the form:

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

Solves as:

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

Where: Coefficients a - *i* are summarized in the appropriate table and T is the temperature in K (x-axis), and y is the property to solve for.

	Young's Modulus	Linear expansion
Units	GPa	$[(L-L_{293})/L_{293}] \times 10^5$ unitless, eg. m/m
a	1.41565E2	-5.265E1
b	2.54435E-2	1.009E-1
c	-1.00842E-3	8.395E-4
d	6.72797E-6	-1.973E-6
e	-1.08230E-8	8.794E-11
T_{low} (K)		80
f>		-40
data range (K)	1-298	4-300
equation range (K)	3-298	4-300
curve fit % error relative to data	1	5

equation of the form:

$$y = a + bT + cT^2 + dT^3 + eT^4 \quad >T \geq T_{low}$$

$$y = f \quad T < T_{low}$$

solves as expected: Where: Coefficients a-e are summarized in the appropriate table and T is the temperature in K (x-axis), and y is the property to solve for.

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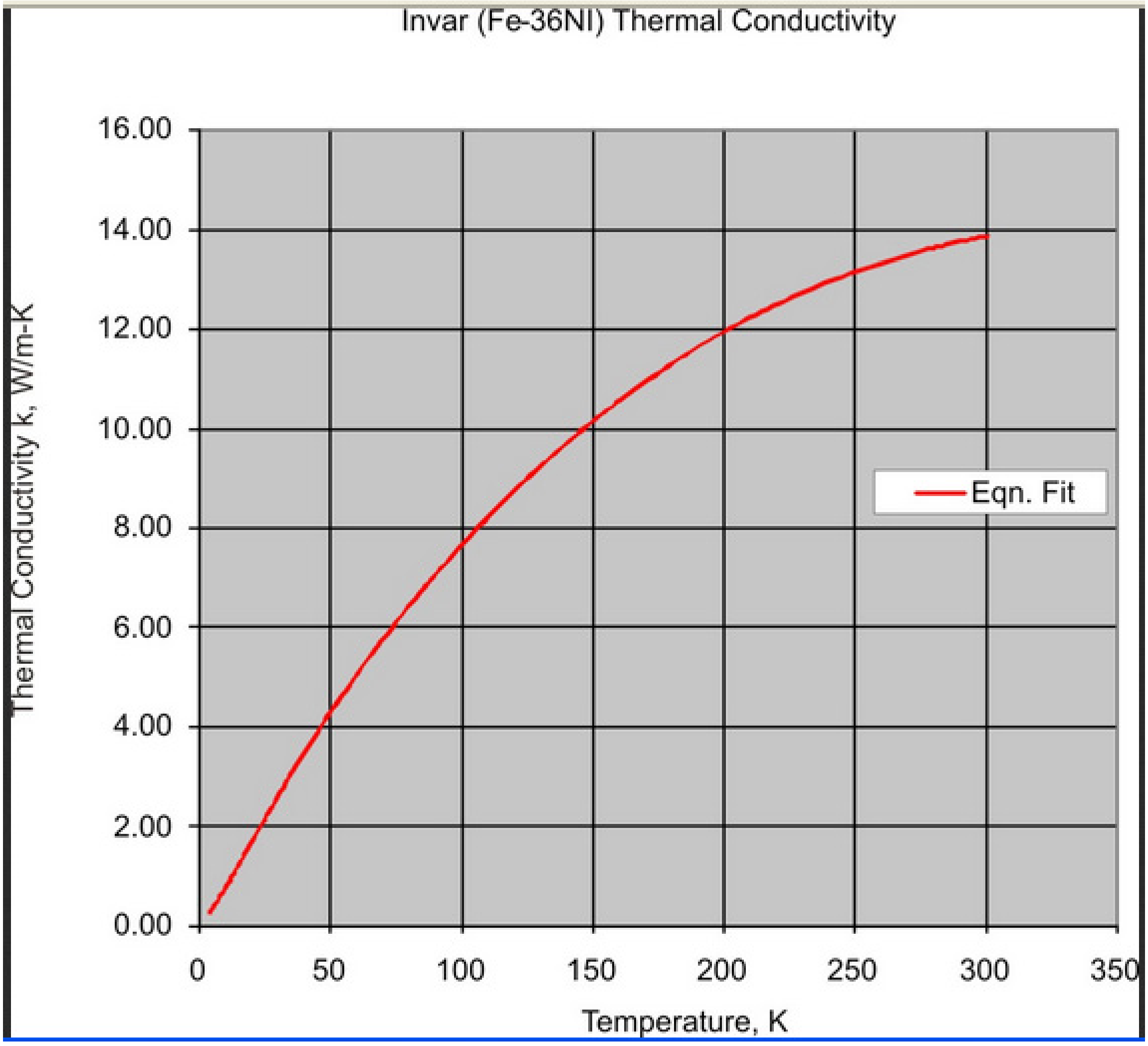

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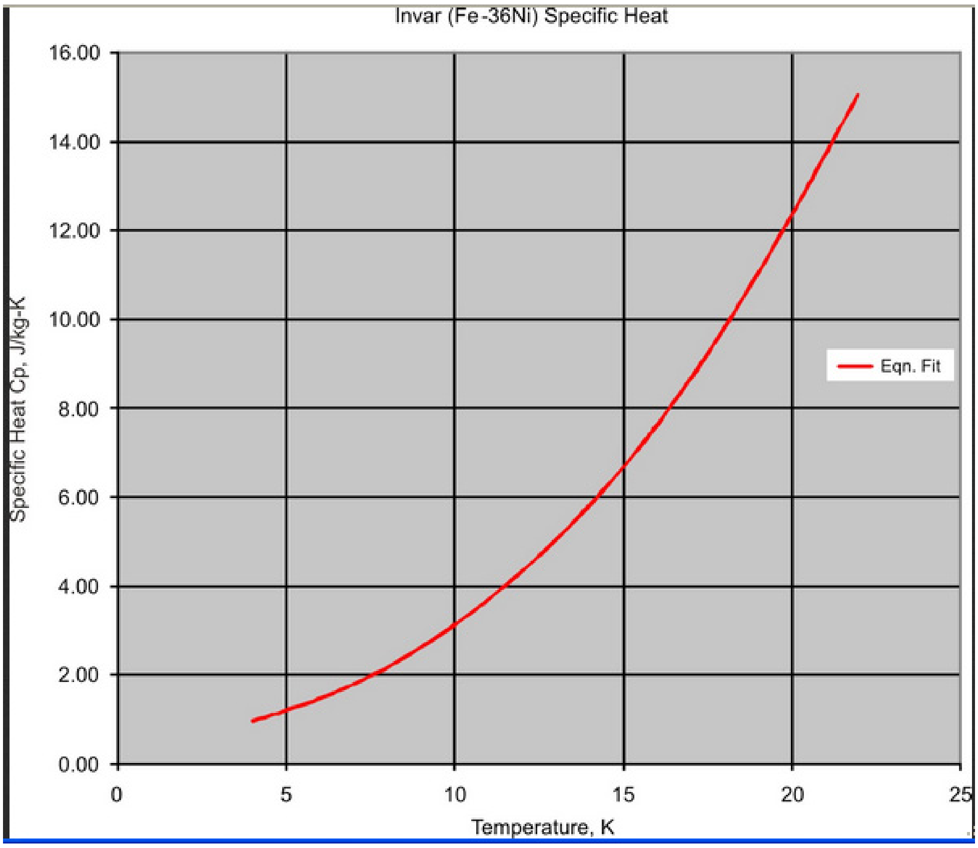

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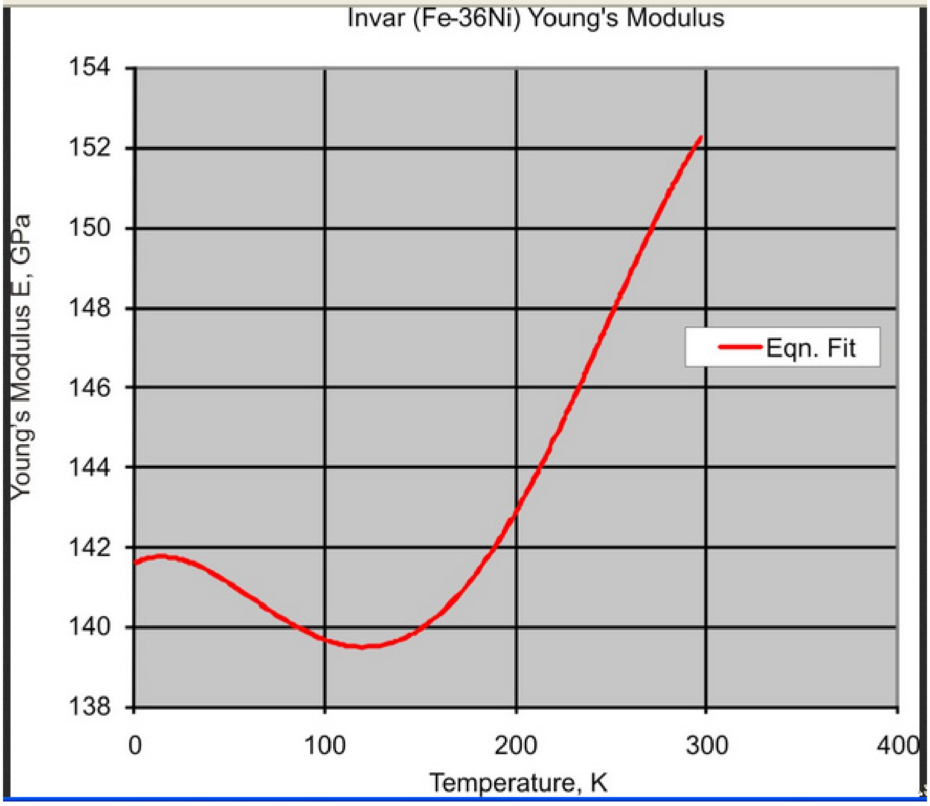

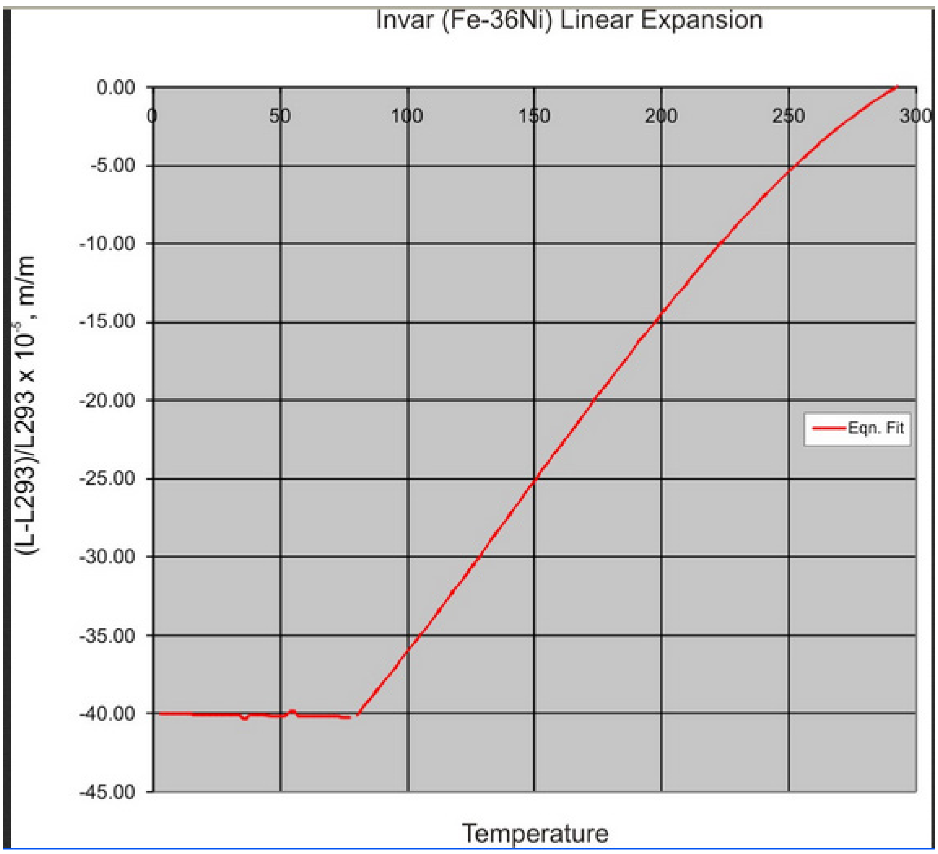

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2.1.3.9 For Brass (UNS C26000):

	Thermal Conductivity
UNITS	W/(m•K)
a	0.021035
b	-1.01835
c	4.54083
d	-5.03374
e	3.20536
f	-1.12933
g	0.174057
h	-0.0038151
i	0
data range	5-116
equation range	5-110
curve fit % error relative to data	1.5

Curve fit equation of the form:

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

Solves as:

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

Where: Coefficients a - *i* are summarized in the appropriate table and T is the temperature in K (x-axis), and y is the property to solve for.

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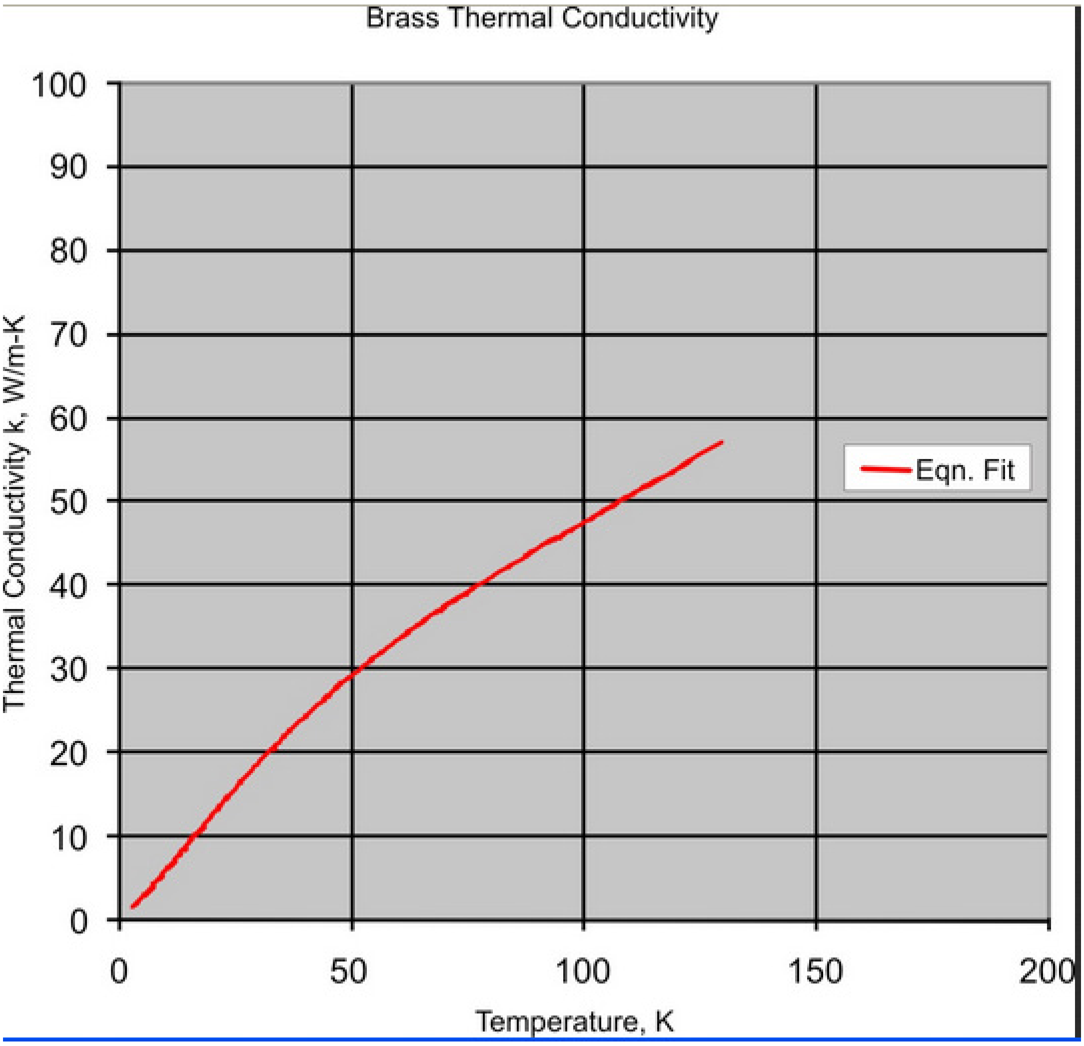

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2.1.3.10 For Polyamide (Nylon):

	Thermal Conductivity	Specific Heat
UNITS	W/(m-K)	J/(kg-K)
a	-2.6135	-5.2929
b	2.3239	25.301
c	-4.7586	-54.874
d	7.1602	71.061
e	-4.9155	-52.236
f	1.6324	21.648
g	-0.2507	-4.7317
h	0.0131	0.42518
i	0	0
data range	4-300	4-300
equation range	1-300	4-300
curve fit % error relative to data	2	4

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Curve fit equation of the form:

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

Solves as:

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

Where: Coefficients a - *i* are summarized in the appropriate table and T is the temperature in K (x-axis), and y is the property to solve for.

	Linear expansion
Units	$[(L-L_{293})/L_{293}] \times 10^5$ unitless, eg. m/m
a	-1.389E3
b	-1.561E-1
c	2.988E-2
d	-7.948E-5
e	1.181E-7
T_{low} (K)	NA
f>	NA
data range (K)	4-300
equation range (K)	4-300
curve fit % error relative to data	1

equation of the form:

$$y = a + bT + cT^2 + dT^3 + eT^4 \quad >T \geq T_{low}$$

$$y = f \quad T < T_{low}$$

solves as expected: Where: Coefficients a-e are summarized in the appropriate table and T is the temperature in K (x-axis), and y is the property to solve for.

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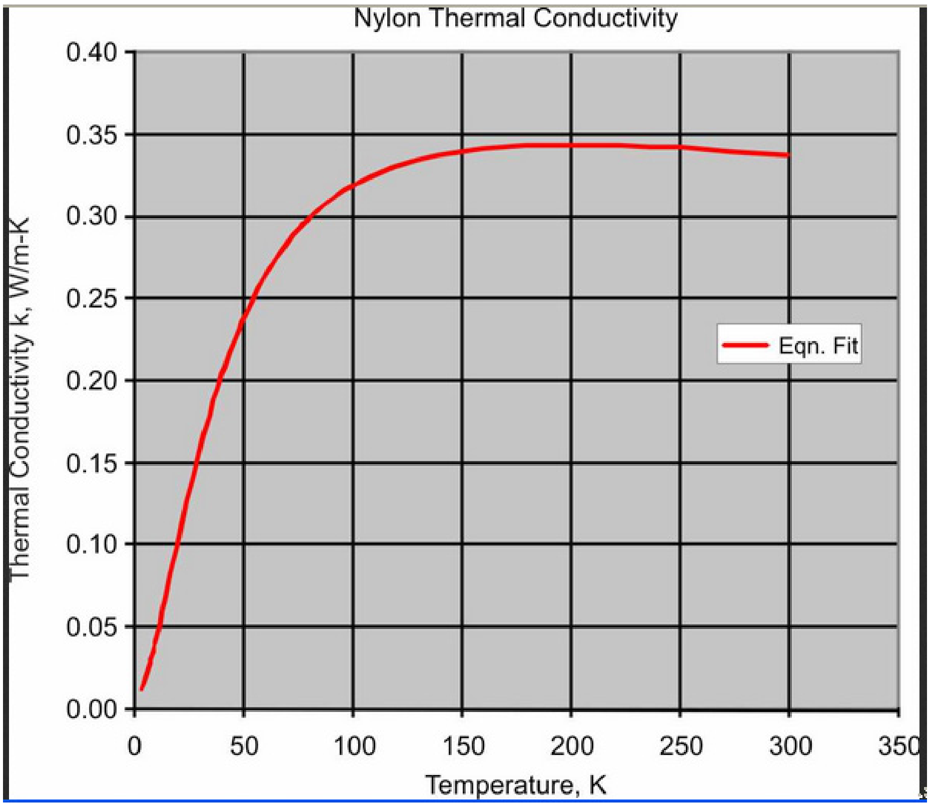

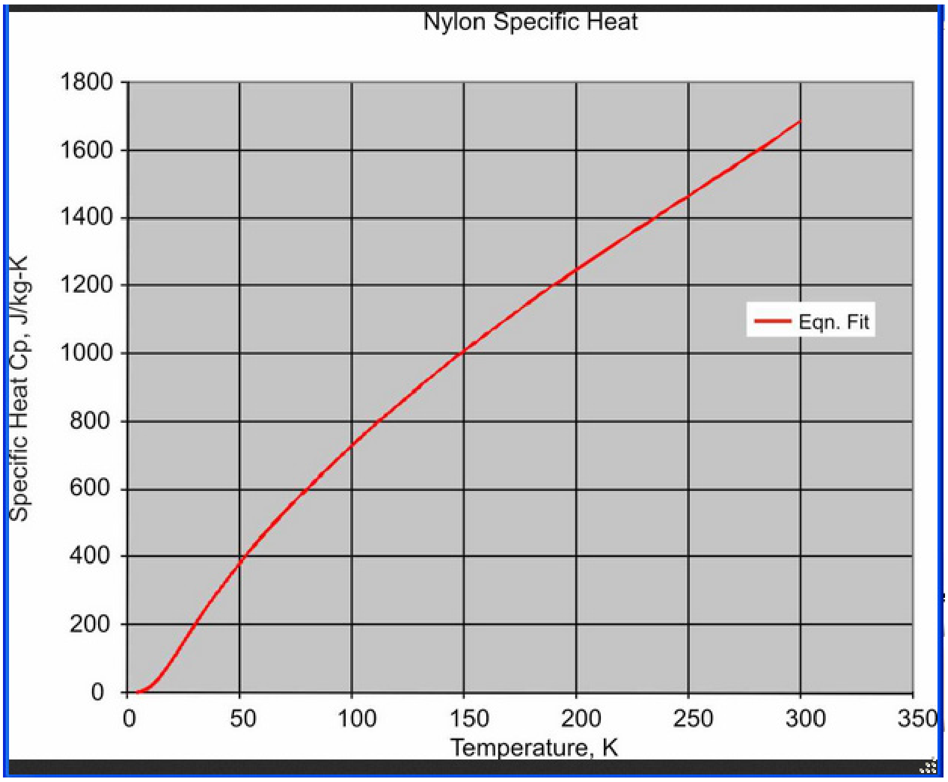

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2.1.3.11 For Platinum:

	Thermal Conductivity	Specific Heat
UNITS	W/(m-K)	J/(kg-K)
a	-7.33450054	-1.6135538
b	80.8550484	0.95823584
c	-268.441084	1.4317770
d	481.629105	-3.5963989
e	-503.890454	5.1299735
f	314.812622	-2.4186452
g	-115.699394	-0.12560841
h	23.0957119	0.34342394
i	-1.93361717	-0.06198179
data range	3-298	1-296
equation range	4-295	1-295
curve fit % error relative to data	3	3

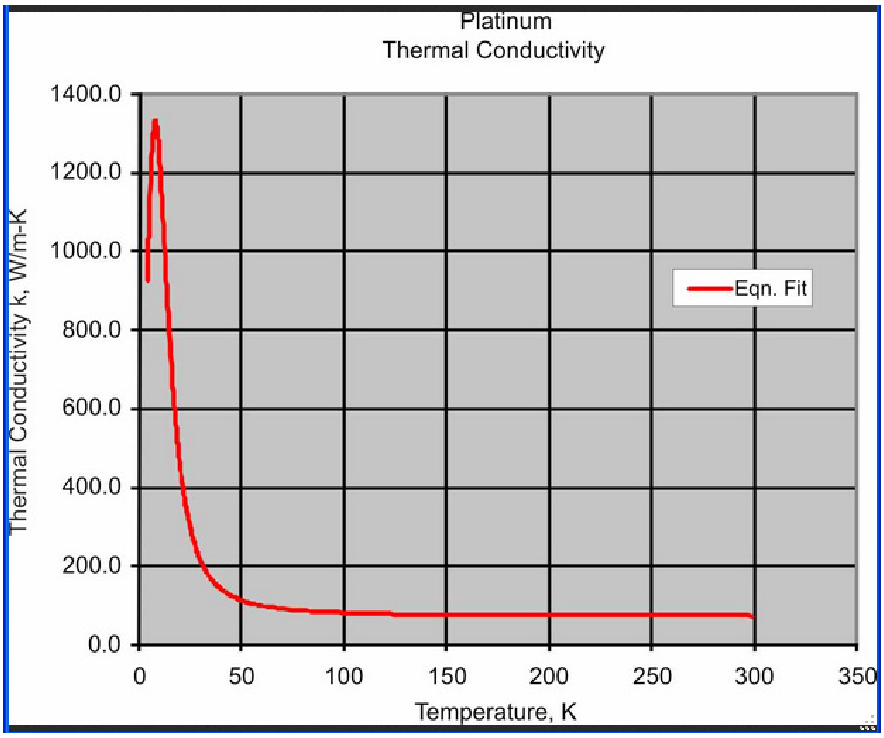
Curve fit equation of the form:

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

Solves as:

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

Where: Coefficients a - *i* are summarized in the appropriate table and T is the temperature in K (x-axis), and y is solve for.



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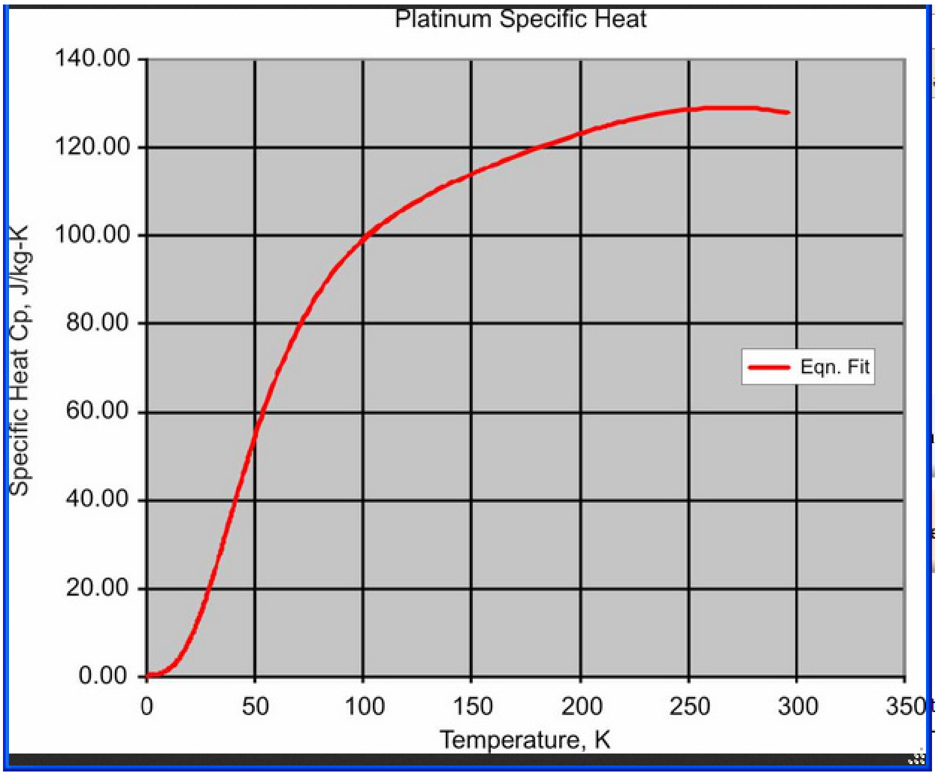

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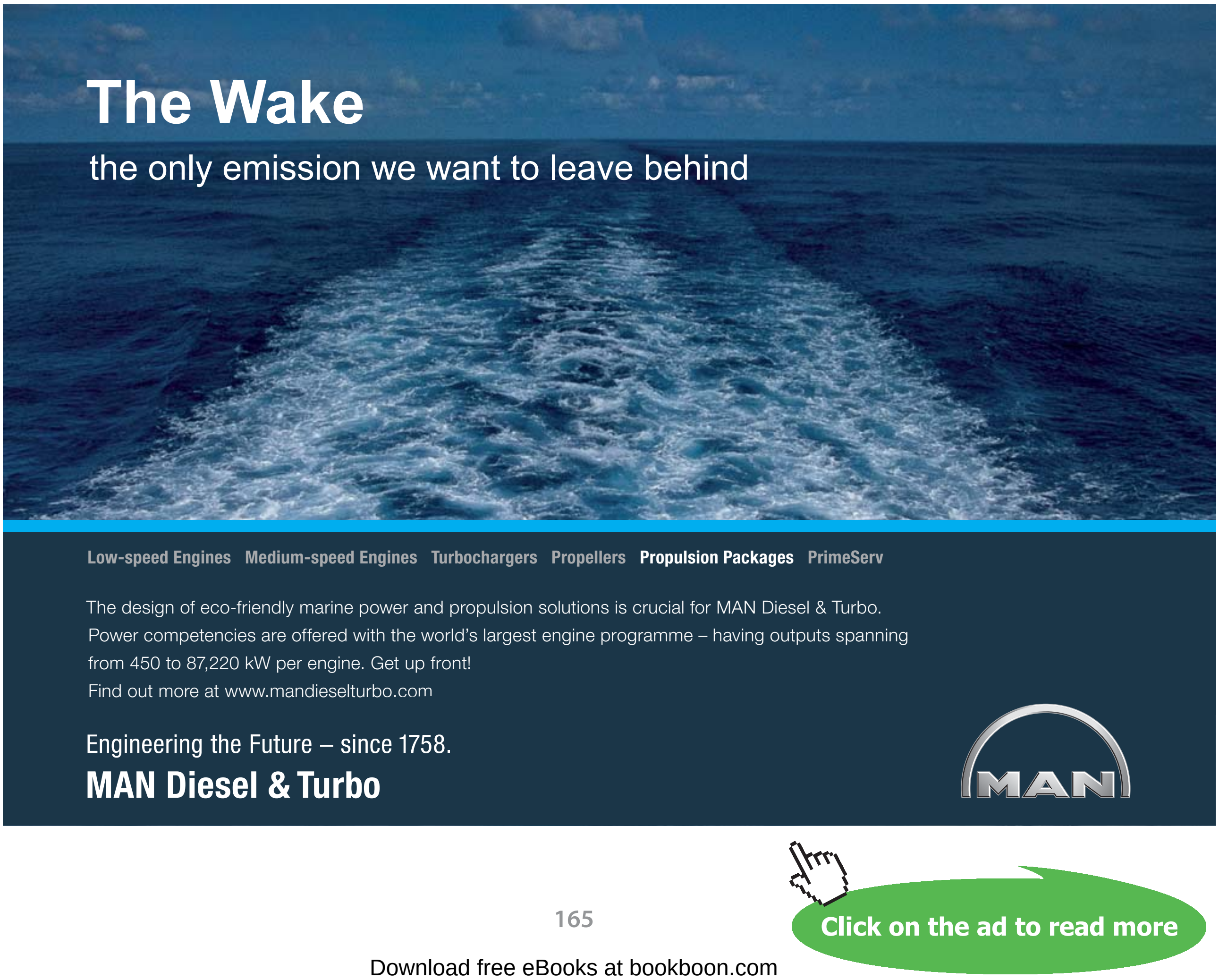

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2.1.3.12 For Titanium 15-3-3-3:

Composition: Bal Ti, 14.88% V, 3.13 Cr, 2.88 Sn, 3.00 Al,

	Thermal Conductivity
UNITS	W/(m-K)
a	-2.398794842
b	8.970743802
c	-29.19286973
d	54.87139779
e	-59.67137228
f	38.89321714
g	-14.94175848
h	3.111616089
i	-0.270452768
data range	1.4-300
equation range	1.4-300
curve fit % error relative to data	3

Curve fit equation of the form:

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

Solves as:

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

Where: Coefficients a - *i* are summarized in the appropriate table and T is the temperature in K (x-axis), and y is the property to solve for.

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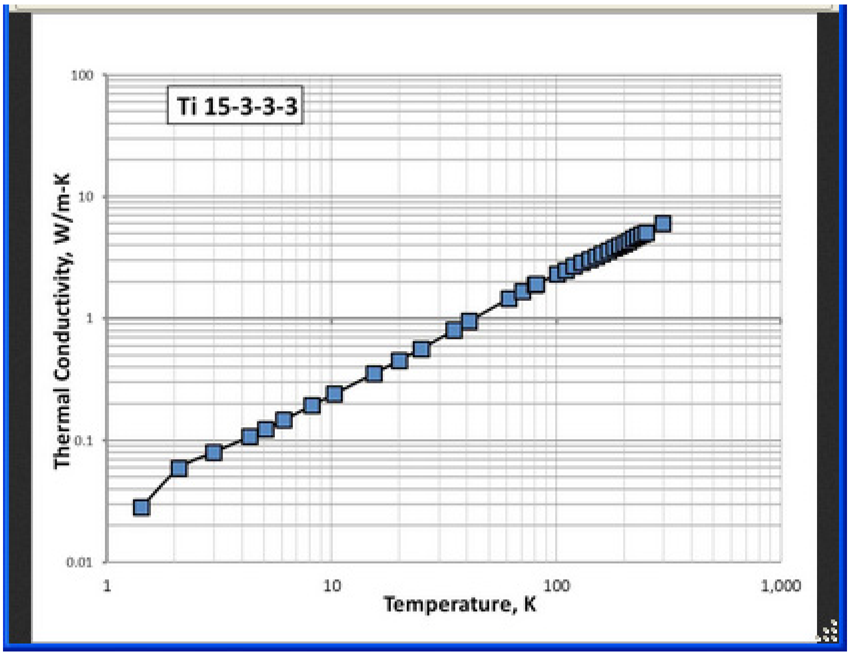

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2.1.3.13 For Lead:

	Thermal Conductivity
UNITS	W/(m-K)
a	38.963479
b	-221.40505
c	597.56622
d	-900.93831
e	816.40461
f	-455.08342
g	152.94025
h	-28.451163
i	2.2516244
data range	4-296
equation range	5-295
curve fit % error relative to data	2

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Curve fit equation of the form:

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

Solves as:

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

Where: Coefficients a – *i* are summarized in the appropriate table and T is the temperature in K (x-axis), and y is the property to solve for.

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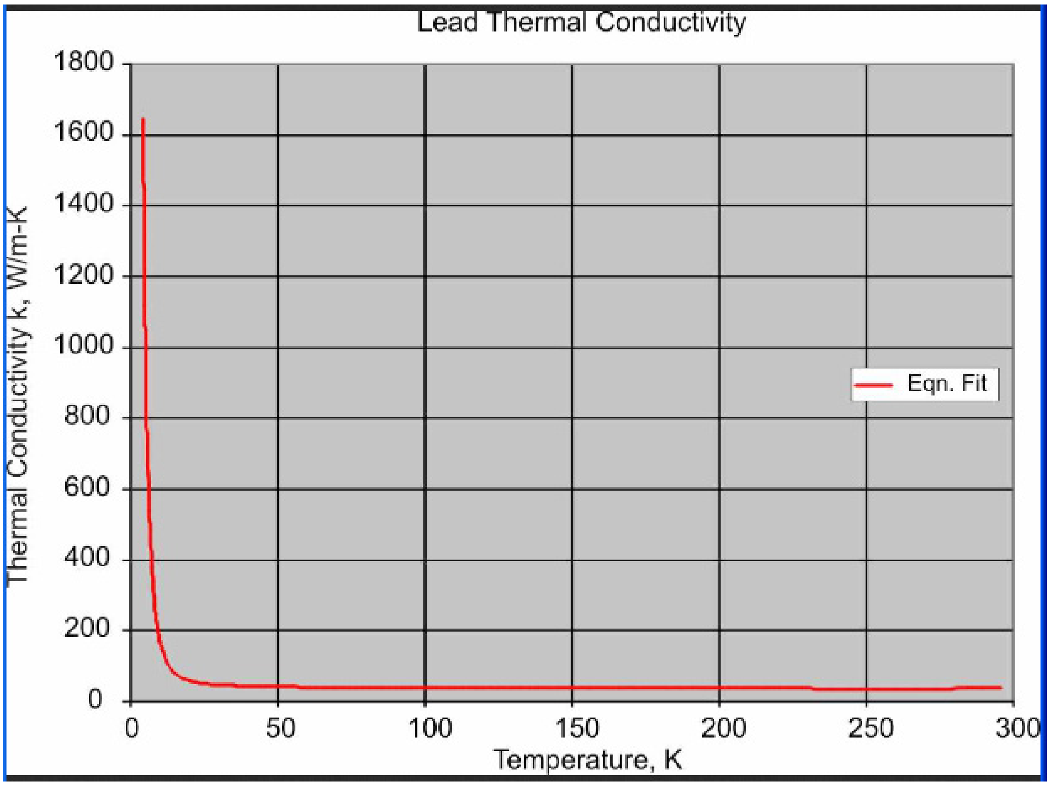

===

2.1.3.14For Molybdenum:

	Thermal Conductivity
UNITS	W/(m-K)
a	10.78259
b	-72.13065
c	228.57351
d	-384.50447
e	381.43825
f	-228.83783
g	81.26658
h	-15.69097
i	1.26814
data range	2-373
equation range	4-300
curve fit % error relative to data	3

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Curve fit equation of the form:

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

Solves as:

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

Where: Coefficients a – *i* are summarized in the appropriate table and T is the temperature in K (y-axis)

	Linear Expansion
UNITS	$[(L-L_{293})/L_{293}] \times 10^{-5}$ unitless, eg. m/m
a	-90.912613
b	-0.127173
c	0.00266801
d	-5.0432E-06
e	3.5183E-09
T_{low} (K)	NA
f>	NA
data range (K)	20-500K
equation range (K)	20-350K
curve fit % error relative to data	4

equation of the form:

$$x = a + bT + cT^2 + dT^3 + eT^4 \quad >T \geq T_{low}$$

$$x = f \quad T < T_{low}$$

solves as expected: Where: Coefficients a-e are summarized in the appropriate table and T is the temperature in K (x-axis), and y is the property to solve for.

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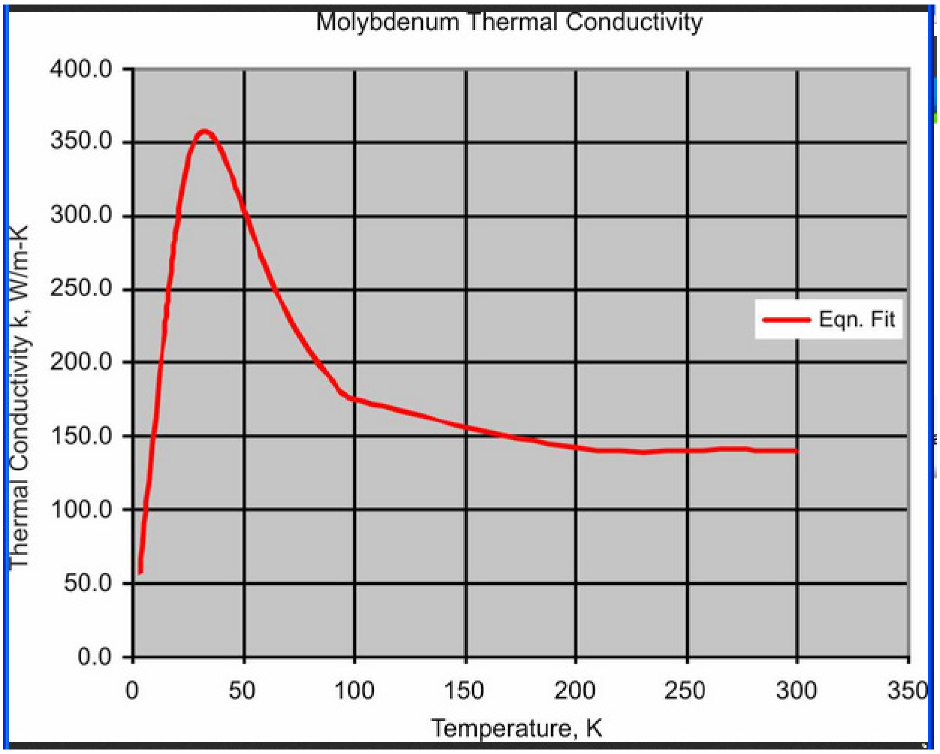

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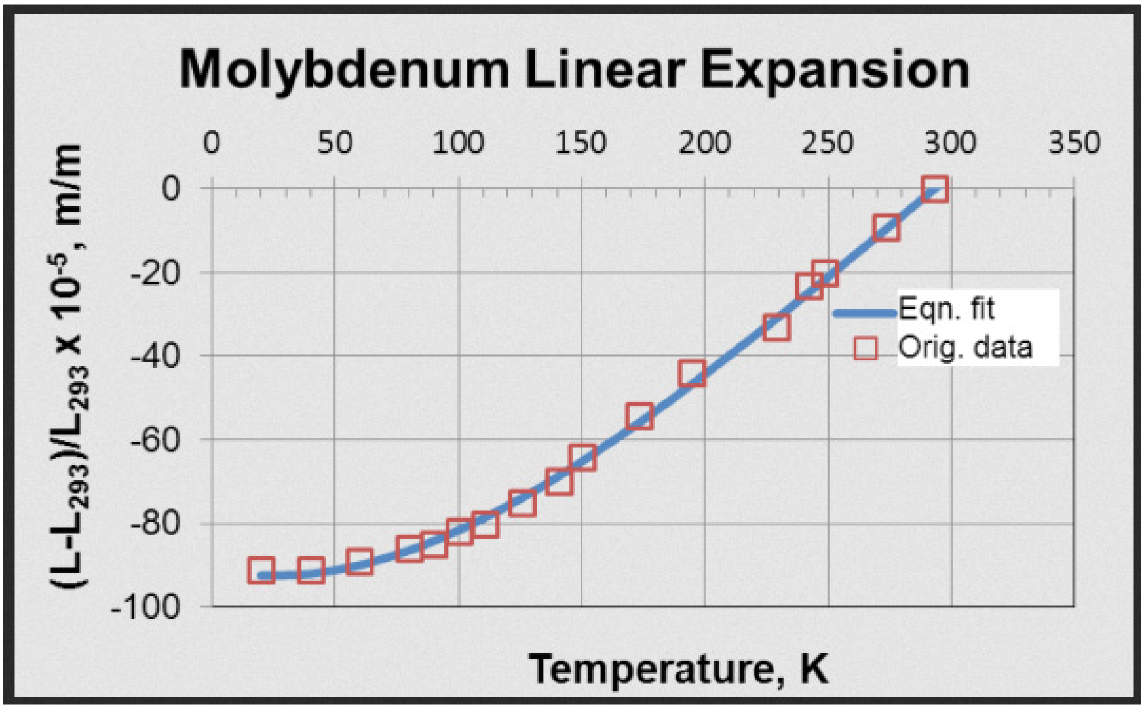

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2.1.3.15 For Polyimide (Kapton):

	Thermal Conductivity	Specific Heat
UNITS	W/(m-K)	J/(kg-K)
a	5.73101	-1.3684
b	-39.5199	0.65892
c	79.9313	2.8719
d	-83.8572	0.42651
e	50.9157	-3.0088
f	-17.9835	1.9558
g	3.42413	-0.51998
h	-0.27133	0.051574
i	0	0
data range	4-300	4-300
equation range	4-300	4-300
curve fit % error relative to data	2	3

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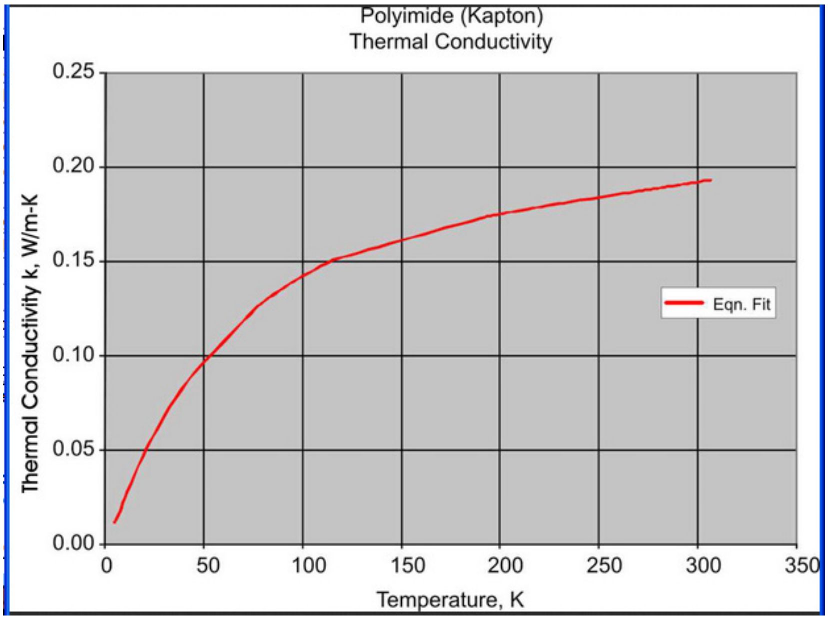
Curve fit equation of the form:

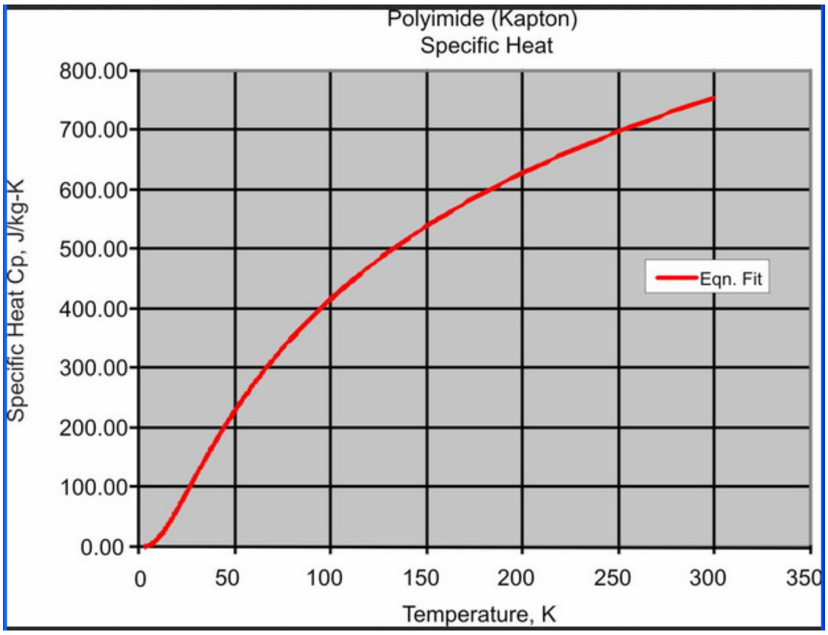
$\log_{10} y = a+b(\log_{10}T) + c(\log_{10}T)^2 + d(\log_{10}T)^3 + e(\log_{10}T)^4 + f(\log_{10}T)^5 + g(\log_{10}T)^6 + h(\log_{10}T)^7 + i(\log_{10}T)^8$

Solves as:

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

Where: Coefficients a – *i* are summarized in the appropriate table and T is the temperature in K (x-axis), and y is the property to solve for.





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2.1.3.15 And, summary of coefficients for a few materials

And, summary of coefficients for a few materials is given by E.D. Marquardt, J.P. Le, and Ray Radebaugh in a paper presented 11th Intl. cryo-cooler conference in year 2000 at Keystone, Co. USA.[12]

Thermal cond (k, W/m.K):

The general form of the equation for thermal conductivity, *k*, is given in eqn.(1) below:

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

where *a*, *b*, *c*, *d*, *e*, *f*, *g*, *h*, and *i* are the fitted coefficients, and *T* is the temperature (K). These are common logarithms.

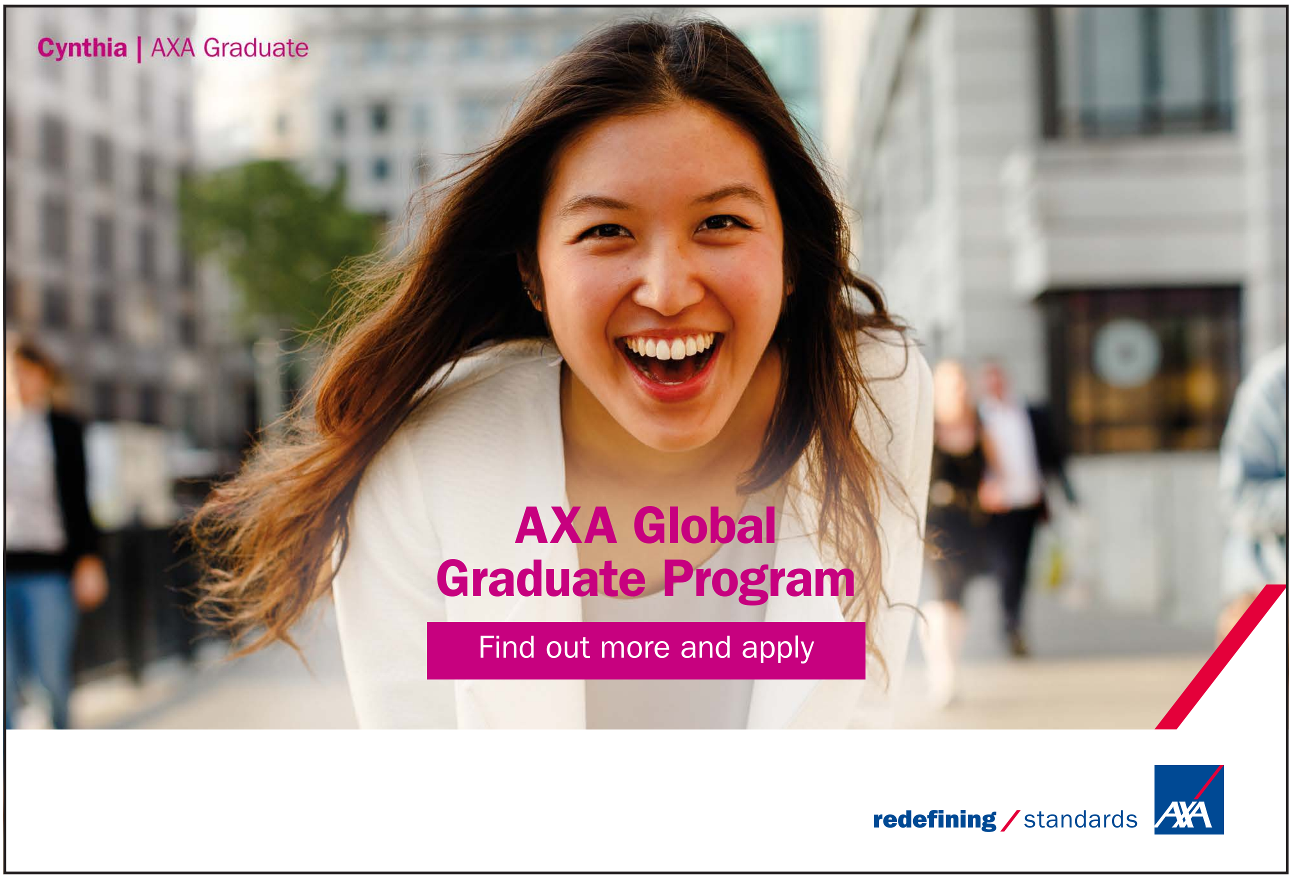

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Table 1A. Coefficients for thermal conductivity for metals.

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

For Oxygen-free copper:

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

Note: Above eqn should be used with caution since k of oxygen-free copper depends on RRR.

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For Specific heat:

The general form of the equation is the same as Equation 1.

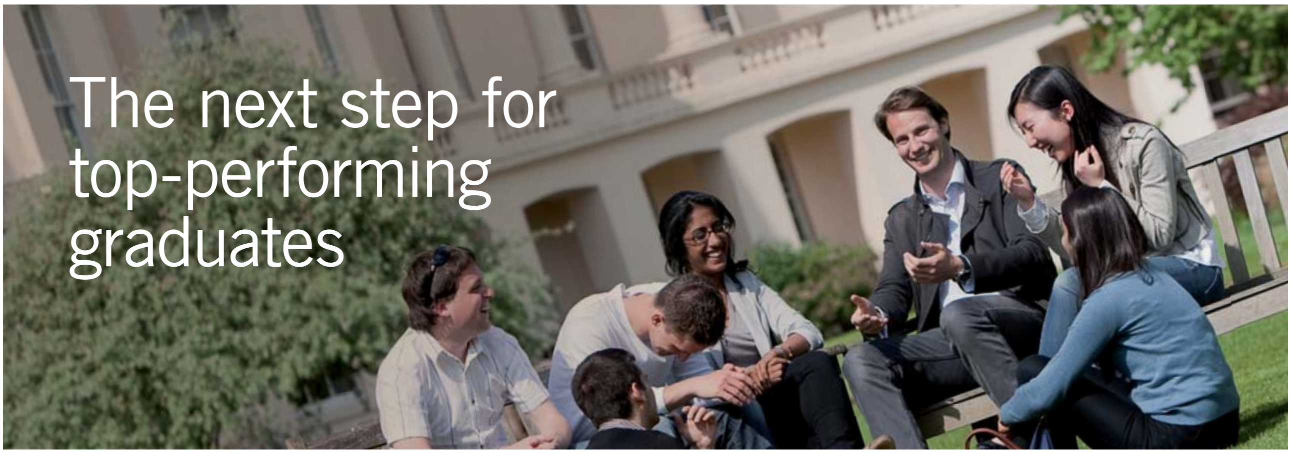
Table 2 shows the coefficients for the specific heat (cp, J/kg.K):

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

Note: We have written Functions for thermal and mechanical properties of many materials in EES, EXCEL and Mathcad. See below.

==



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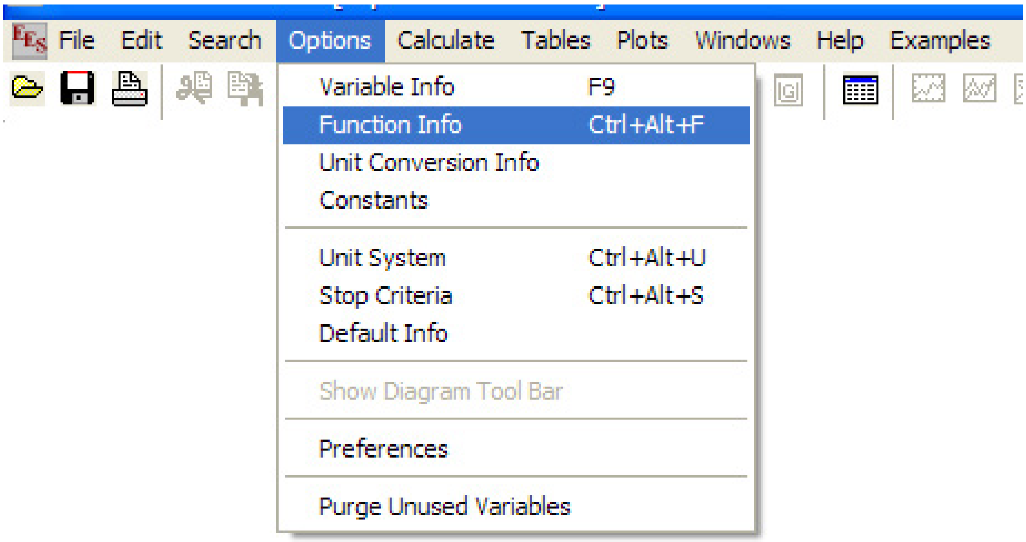
2.1.4 Properties of materials from built-in functions in EES:

One of the main advantages of EES is that it has built-in functions for properties of a large number of materials and fluids.

Following is the procedure to access these properties:

1. In the EES Menu, go to Options-Function Info. We get:



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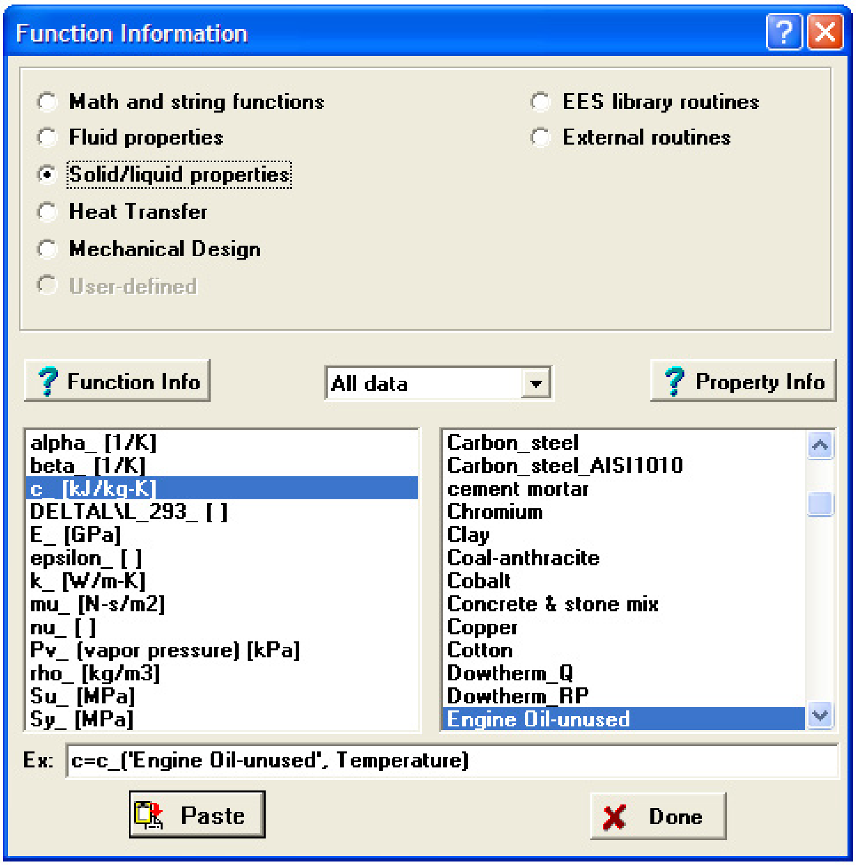
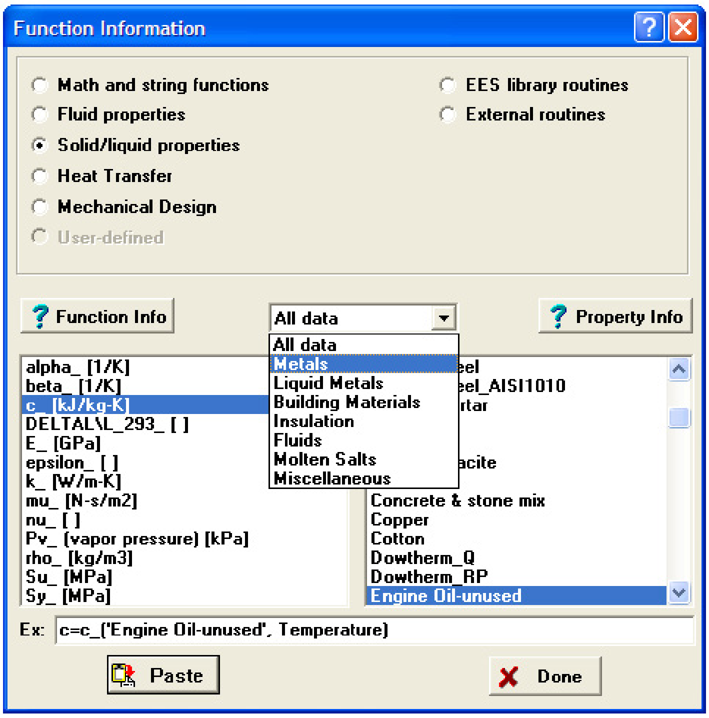
2. Click on Function Info. We get the following window. Here, select the Solid/liquid fluid properties radio button, and we see:



3. In the 'All data' drop down menu, we can choose any of the following:



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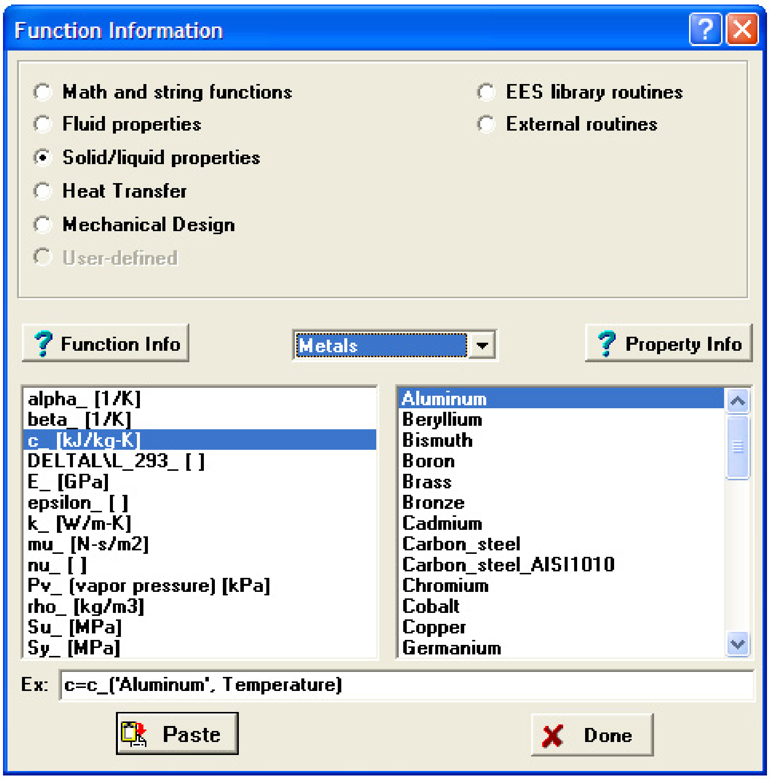
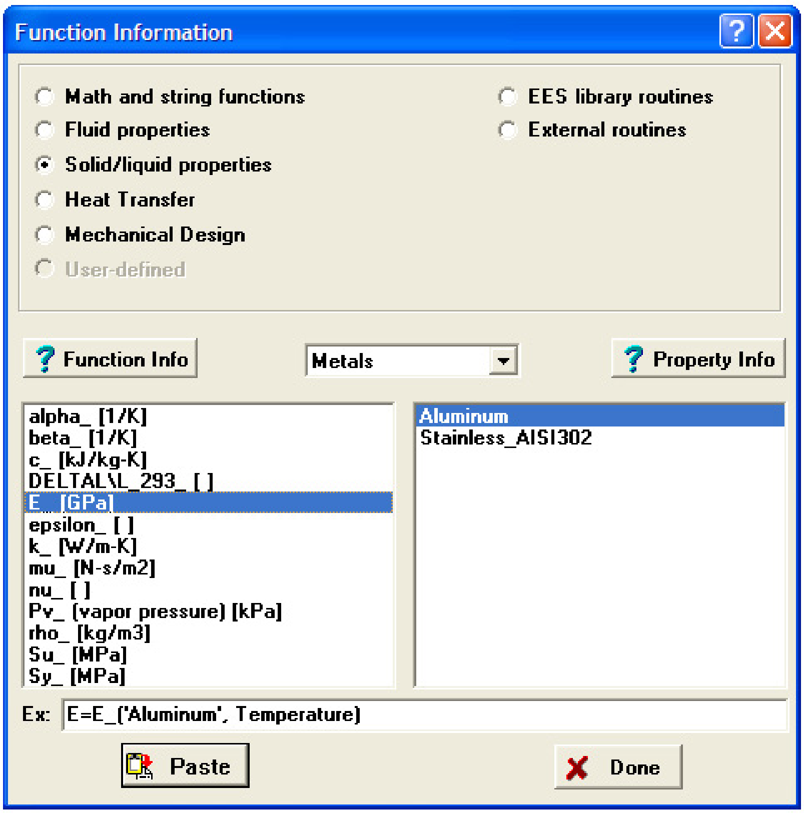
4. If we choose 'Metals', we get:



5. One problem with EES is that all cryogenic properties are not available for all materials of interest. For example, if we need Young's Modulus, E, and select E in the LHS, we get:



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i.e. E is available only for Aluminum and SS=AISI 302.

Also, for many materials, properties may be available only down to 100 K and not below.

Further, EES is primarily an equation solver and not a ‘cryogenic specific’ software.

Therefore, first preference should be to use the equations/graphs from NIST-Cryogenics data, and if any data is not available there, then check with EES.

==

2.2 Problems solved with EES:

Prob.2.2.1 Write EES Functions to determine the thermal conductivities of SS-304L, OFHC copper, 6061- T6-Aluminium, Beryllium copper, SS-304, Brass, Invar, Lead, Nylon and Teflon, using the data from NIST-Cryogenics website.

EES Functions:

```
FUNCTION k_ss304L(T)

"Thermal cond. of SS-304L. Ref: NIST-Cryogenics.

k in W/m.K, and, T in K"

{Finds Th. cond. in the range: T = 1 – 300 K:}

IF (T < 1) or (T > 300) THEN

    CALL ERROR('Temp. must be between 1 and 300 K !')

ENDIF

a := -1.4087; b := 1.3982; c := 0.2543; d := -0.6260; e := 0.2334; f := 0.4256; g := -0.4658; h := 0.1650;
i := -0.0199

k_ss304L = 10^(a+b*(log10(T)) + c*(log10(T))^ 2 + d*(log10(T))^ 3 + e*(log10(T))^ 4 + f*(log10(T))^
5 + g*(log10(T))^ 6 + h*(log10(T))^ 7 + i*(log10(T))^ 8)

END
```

==

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```
FUNCTION k_OFHC_copper(T)

"Thermal cond. of OFHC copper (RRR = 500). Ref: NIST-Cryogenics.

k in W/m.K, T in K"

{ Finds Th. cond. in the range: T = 4 – 300 K:}

IF (T < 4) or (T > 300) THEN

        CALL ERROR('Temp. must be between 4 and 300 K !')

ENDIF

a := 2.8075; b := -0.54074; c := -1.2777; d := 0.15362; e := 0.36444; f := -0.02105; g := -0.051727; h := 0.0012226; i := 0.0030964

k_OFHC_copper = 10^((a+c * T^0.5 + e * T + g * T^1.5+ i * T^2) / (1 + b * T^0.5 + d * T + f * T^1.5 + h * T^2))

END

"=========================================================================="
```

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```
FUNCTION k_AL_6061_T6(T)

"Thermal cond. of Aluminium-6061-T6. Ref: NIST-Cryogenics.

k in W/m.K, T in K"

{ Finds Th. cond. in the range: T = 1 – 300 K:}

IF (T < 1) or (T > 300) THEN

        CALL ERROR('Temp. must be between 1 and 300 K !')

ENDIF

a := 0.07918; b := 1.0957; c := -0.07277; d := 0.08084; e := 0.02803; f := -0.09464; g := 0.04179; h := -0.00571; i := 0.0

k_AL_6061_T6 = 10^(a+b*(log10(T)) + c*(log10(T))^ 2 + d*(log10(T))^ 3 + e*(log10(T))^ 4 + f*(log10(T))^ 5 + g*(log10(T))^ 6 + h*(log10(T))^ 7 + i*(log10(T))^ 8)

END

"=================================================================="
```

For Beryllium copper:

Original graph from Ref.[1] were digitized using the PlotDigitizer [Ref: 13]. The resulting data tables were transferred to EES as a Lookup Table. Then, the EES Function is written using the built-in Function 'Interpolate1' for linear interpolation. Following are the results:

```
FUNCTION k_BeCu(T)

"Thermal cond. and sp. heat of Beryllium copper. Ref: Barron …digitized and put in Lookup Table of EES.

k in W/m.K,"

{ Finds Th. cond. in the range: T = 1 – 400 K:}

IF (T < 1) or (T > 400) THEN

        CALL ERROR('Temp. must be between 1 and 400 K !')
```


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```
ENDIF

k_BeCu =interpolate1('k_BeCu', 'Temp', 'k', Temp = T)

END

"=================================================================="

FUNCTION k_SS_304(T)

"Thermal cond. and sp. heat of SS-304 . Ref: Barron…digitized and put in Lookup Table of EES.

k in W/m.K,"

{ Finds Th. cond. in the range: T = 4.2 – 420 K:}

IF (T < 4.2) or (T > 420) THEN

        CALL ERROR('Temp. must be between 4.2 and 420 K !')

ENDIF

k_SS_304 =interpolate1('k_SS304', 'Temp', 'k', Temp = T)

END

"=================================================================="

FUNCTION k_Brass(T)

"Thermal cond. of Brass. Ref: NIST-Cryogenics.

k in W/m.K,"

{ Finds Th. cond. in the range: T = 5 – 110 K:}

IF (T < 5) or (T > 110) THEN

        CALL ERROR('Temp. must be between 5 and 110 K !')

ENDIF
```


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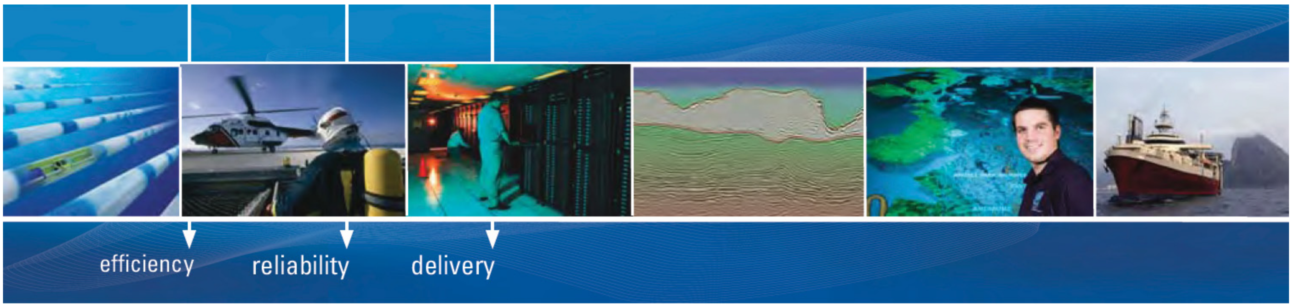
```
a := 0.021035; b := -1.01835; c :=4.54083; d :=-5.03374; e :=3.20536; f := -1.12933; g := 0.174057; h := -0.0038151; i := 0

k_Brass = 10^(a+b*(log10(T)) + c*(log10(T))^ 2 + d*(log10(T))^ 3 + e*(log10(T))^ 4 + f*(log10(T))^ 5 + g*(log10(T))^ 6 + h*(log10(T))^ 7 + i*(log10(T))^ 8)

END
"======================================================================"

FUNCTION k_Invar(T)

"Thermal cond. of Invar. Ref: NIST-Cryogenics.

k in W/m.K,"

{ Finds Th. cond. in the range: T = 4 – 300 K:}

IF (T < 4) or (T > 300) THEN

        CALL ERROR('Temp. must be between 4 and 300 K !')

ENDIF
```



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```
a := -2.7064; b := 8.5191; c :=-15.923; d :=18.276; e := -11.9116; f := 4.40318;
g := -0.86018; h := 0.068508; i := 0

k_Invar = 10^(a+b*(log10(T)) + c*(log10(T))^ 2 + d*(log10(T))^ 3 + e*(log10(T))^ 4 +

f*(log10(T))^ 5 + g*(log10(T))^ 6 + h*(log10(T))^ 7 + i*(log10(T))^ 8)

END

"================================================================="

FUNCTION k_Lead(T)

"Thermal cond. of Lead. Ref: NIST-Cryogenics.

k in W/m.K,"

{Finds Th. cond. in the range: T = 5 – 295 K:}

IF (T < 5) or (T > 295) THEN

        CALL ERROR('Temp. must be between 5 and 295 K !')

ENDIF

a :=38.963479; b := -221.40505; c :=597.56622; d :=-900.93831; e := 816.40461;
f := -455.08342; g := 152.94025; h := -28.451163; i := 2.2516244

k_Lead = 10^(a+b*(log10(T)) + c*(log10(T))^ 2 + d*(log10(T))^ 3 + e*(log10(T))^ 4 + f*(log10(T))^
5 + g*(log10(T))^ 6 + h*(log10(T))^ 7 + i*(log10(T))^ 8)

END

"================================================================="

FUNCTION k_Nylon(T)

"Thermal cond. of Nylon. Ref: NIST-Cryogenics.

k in W/m.K,"

{ Finds Th. cond. in the range: T = 1 – 300 K:}
```


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```
IF (T < 1) or (T > 300) THEN

        CALL ERROR('Temp. must be between 1 and 300 K !')

ENDIF

a := -2.6135; b := 2.3239; c :=-4.7586; d :=7.1602; e := -4.9155; f := 1.6324; g := -0.2507;
h := 0.0131; i := 0

k_Nylon = 10^(a+b*(log10(T)) + c*(log10(T))^ 2 + d*(log10(T))^ 3 + e*(log10(T))^ 4 + f*(log10(T))^
5 + g*(log10(T))^ 6 + h*(log10(T))^ 7 + i*(log10(T))^ 8)

END

"====================================================================="

FUNCTION k_Teflon(T)

"Thermal cond. of Teflon. Ref: NIST-Cryogenics.

k in W/m.K,"

{ Finds Th. cond. in the range: T = 4 – 300 K:}

IF (T < 4) or (T > 300) THEN

        CALL ERROR('Temp. must be between 4 and 300 K !')

ENDIF

a := 2.7380; b := -30.677; c := 89.43; d := -136.99; e := 124.69; f := -69.556; g := 23.320; h := -4.3135; i
:= 0.33829

k_Teflon = 10^(a+b*(log10(T)) + c*(log10(T))^ 2 + d*(log10(T))^ 3 + e*(log10(T))^ 4 + f*(log10(T))^
5 + g*(log10(T))^ 6 + h*(log10(T))^ 7 + i*(log10(T))^ 8)

END

"====================================================================="
```


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```
FUNCTION k_pyrex(T)

"Thermal cond. of pyrex glass. Ref: Barron…digitized ans put in Lookup Table of EES.

k in W/m.K,"

{ Finds Th. cond. in the range: T = 4.0 – 300 K:}

IF (T < 4.0) or (T > 300) THEN

        CALL ERROR('Temp. must be between 4.0 and 300 K !')

ENDIF

k_pyrex =interpolate1('k_pyrex', 'Temp', 'k', Temp = T)

END

"======================================================================="
```

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"**Prob.2.2.2** Find out Strength to conductivity ratios at a temp of 80 K, for: (i) SS-304L (ii) 6061 T6-Al (iii) OFHC copper, and, (iv) Teflon"

EES Solution:

Temperature = 80 "K"

"Yield strengths from the Table under section 2.1.2:"

sigma_y_304L = 1300"MPa … yield strength for SS 304L"
sigma_y_Al6061T6 = 332"MPa … yield strength for 6061 T6 Al"
sigma_y_OFHC_copper = 88"MPa … yield strength for OFHC copper"
sigma_y_Teflon = 65"MPa … yield strength for Teflon"

"Thermal conductivities from the EES functions written by us above:"

k_304L = k_ss304L(Temperature)"W/m-K"
k_Al6061T6 =k_AL_6061_T6(Temperature)"W/m-K"
k_OFHC_copper = k_OFHC_copper(Temperature) "W/m-K"
k_Teflon = k_Teflon(Temperature)"W/m-K"

"Therefore, their strength-to-conductivity ratios:"

Ratio_304L = sigma_y_304L / k_304L "MPa/(W/m-K)"
Ratio_Al6061T6 = sigma_y_Al6061T6/k_Al6061T6"MPa/(W/m-K)"
Ratio_OFHC_copper = sigma_y_OFHC_copper/k_OFHC_copper"MPa/(W/m-K)"
Ratio_Teflon = sigma_y_Teflon /k_Teflon"MPa/(W/m-K)"

Results:

Unit Settings: SI K MPa J mass deg

k_{304L} = 8.114 [W/m-K]

$k_{Al6061T6}$ = 85.56 [W/m-K]

$k_{OFHC,copper}$ = 558 [W/m-K]

k_{Teflon} = 0.2341 [W/m-K]

$Ratio_{304L}$ = 160.2 [MPa-m-K/W]

$Ratio_{Al6061T6}$ = 3.88 [MPa-m-K/W]

$Ratio_{OFHC,copper}$ = 0.1577 [MPa-m-K/W]

$Ratio_{Teflon}$ = 277.7 [MPa-m-K/W]

$\sigma_{y,304L}$ = 1300 [MPa]

$\sigma_{y,Al6061T6}$ = 332 [MPa]

$\sigma_{y,OFHC,copper}$ = 88 [MPa]

$\sigma_{y,Teflon}$ = 65 [MPa]

Temperature = 80 [K]

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Thus:

Strength-to-conductivity ratios are:

For SS 304L: 160.2 MPa-m-K/W …. Ans.

For 6061-T6-Aluminium: 3.88 MPa-m-K/W …. Ans.

For OFHC copper (RRR = 500): 0.1577 MPa-m-K/W …. Ans.

For Teflon: 277.7 MPa-m-K/W …. Ans.

==

Prob.2.2.3 A strut, 3 mm in dia and 5 cm in length is to support two vessels in a cryostat. If the two ends of the strut are at 80 K and 5 K, find out the heat transferred, if the material of strut is (i) SS 304L, (ii) SS 304, (iii) Beryllium copper (iv) Invar, (v) Nylon, and (vi) Teflon, (vii) Pyrex glass. Take the variation of thermal conductivity with temp in to account.

EES Solution:

"Data:"

```
d = 0.003"m"
L = 0.05"m"
T1 = 5"K"
T2 = 80"K"
```

"Calculations:"

"We will use the built-in EES Function 'Integral' to get the Thermal conductivity integrals:"

```
A = pi * d^2 / 4 "m^2 …. area of cross-section of the strut"
Q_SS304L = (A/L) * integral(k_SS304L(T),T,T1,T2) "W…. heat transfer for SS304L"
Q_SS304 = (A/L) * integral(k_SS_304(T),T,T1,T2) "W…. heat transfer for SS304"
Q_BeCu = (A/L) * integral(k_BeCu(T),T,T1,T2) "W…. heat transfer for BeCu"
Q_Invar = (A/L) * integral(k_Invar(T),T,T1,T2) "W…. heat transfer for Invar"
Q_Nylon = (A/L) * integral(k_Nylon(T),T,T1,T2) "W…. heat transfer for Nylon"
Q_Teflon = (A/L) * integral(k_Teflon(T),T,T1,T2) "W…. heat transfer for Teflon"
Q_pyrex = (A/L) * integral(k_pyrex(T),T,T1,T2) "W…. heat transfer for pyrex glass"
```


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Results:

Unit Settings: SI K MPa J mass deg

A = 0.000007069 [m²]

d = 0.003 [m]

L = 0.05 [m]

Q_{BeCu} = 0.1583 [W]

Q_{Invar} = 0.03742 [W]

Q_{Nylon} = 0.002003 [W]

Q_{pyrex} = 0.002837 [W]

Q_{SS304} = 0.04581 [W]

Q_{SS304L} = 0.04946 [W]

Q_{Teflon} = 0.001947 [W]

T = 80 [K]

T1 = 5 [K]

T2 = 80 [K]

Thus:

Heat transfer from 80 K to 5 K:

For SS304L = Q_SS304L = 0.04946 W …. Ans.

For SS304 = Q_SS304 = 0.04582 W …. Ans.

For BeCu = Q_BeCu = 0.1583 W …. Ans.

For Invar = Q_Invar = 0.03742 W …. Ans.

For Nylon = Q_Nylon = 0.002003 W …. Ans.

For Teflon = Q_Teflon = 0.001947 W …. Ans.

For Pyrex = Q_pyrex = 0.002837 W …. Ans.

==

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"**Prob.2.2.4** Given that thermal conductivity of Stainless Steel 304 varies as: k(T) = 1.5 T^0.4 (W/m.K), find out the heat transferred in a rod of 10 mm dia and 100 mm length, if the two ends are maintained at 80 K and 300 K, respectively. [9]"

EES Solution:

"Data:"

d = 0.010"m"
L = 0.100"m"
T1 = 80"K"
T2 = 300"K"

"Calculations:"

"We will use the built-in EES Function 'Integral' to get the Thermal conductivity integrals:"

A = pi * d^2 / 4 "m^2…area of cross-section of the rod"

Q_SS304 = (A/L) * integral(1.5*T^(0.4),T,T1,T2) "W…heat transfer for SS304 from 300 K to 80 K"

Results:

Unit Settings: SI K MPa J mass deg

A = 0.00007854 [m^2]	d = 0.01 [m]	L = 0.1 [m]
Q_{SS304} = 2.083 [W]	T = 300 [K]	T1 = 80 [K]
T2 = 300 [K]		

Thus:

Heat transferred = Q_SS304 = 2.083 W …. Ans.

"=="

Prob.2.2.5 Write an EES Function to determine (cv/R) when (T/θ_D) is known. Here, θ_D is the Debye temp of the material.

EES Function:

Under Section 2.1.2, we have given the Table of (cv/R) vs (T/θ_D) from Ref.[1].

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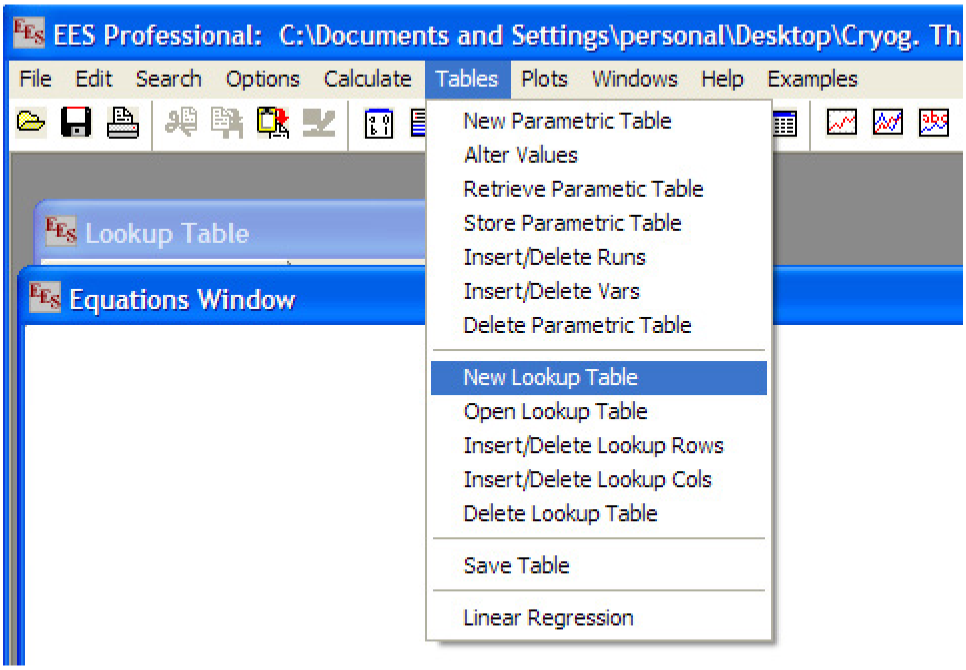
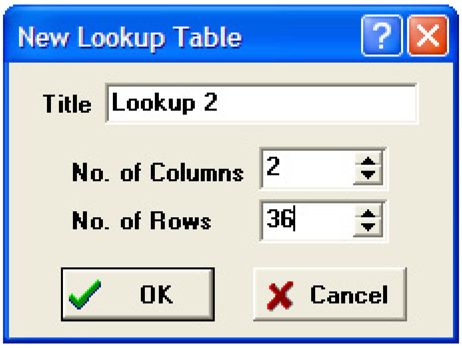
Now, enter it as a Lookup Table in EES:

To do this, go to EES – Tables – New LookupTable:



Clicking on New Lookup Table brings up the following:



In our Table, there are 2 columns and 36 rows. Fill up as shown above and click OK. We get a blank Table. Fill it up with data as shown below. Name the Table and the two columns.

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Only part of the Table is shown, to conserve space:

Lookup Table

CvbyR_vs_TbyThetaD

	TbyThetaD	CvbyR
Row 1	0.05	0.1191
Row 2	0.09	0.1682
Row 3	0.1	0.2275
Row 4	0.12	0.3733
Row 5	0.14	0.5464
Row 6	0.16	0.7334
Row 7	0.18	0.9228
Row 8	0.2	1.106
Row 9	0.25	1.509
Row 10	0.3	1.823
Row 11	0.35	2.06
Row 12	0.4	2.238
Row 13	0.45	2.373
Row 14	0.5	2.476
Row 15	0.6	2.621
Row 16	0.7	2.715
Row 17	0.8	2.748
Row 18	0.9	2.823
Row 19	1	2.855
Row 20	1.1	2.88
Row 21	1.2	2.898
Row 22	1.3	2.913
Row 23	1.4	2.925

Now, we can use the built-in EES Function '**Interpolate**' to get the value of (Cv/R) at any (T/Theta_D) (or vice versa). Following is the desired EES Function:

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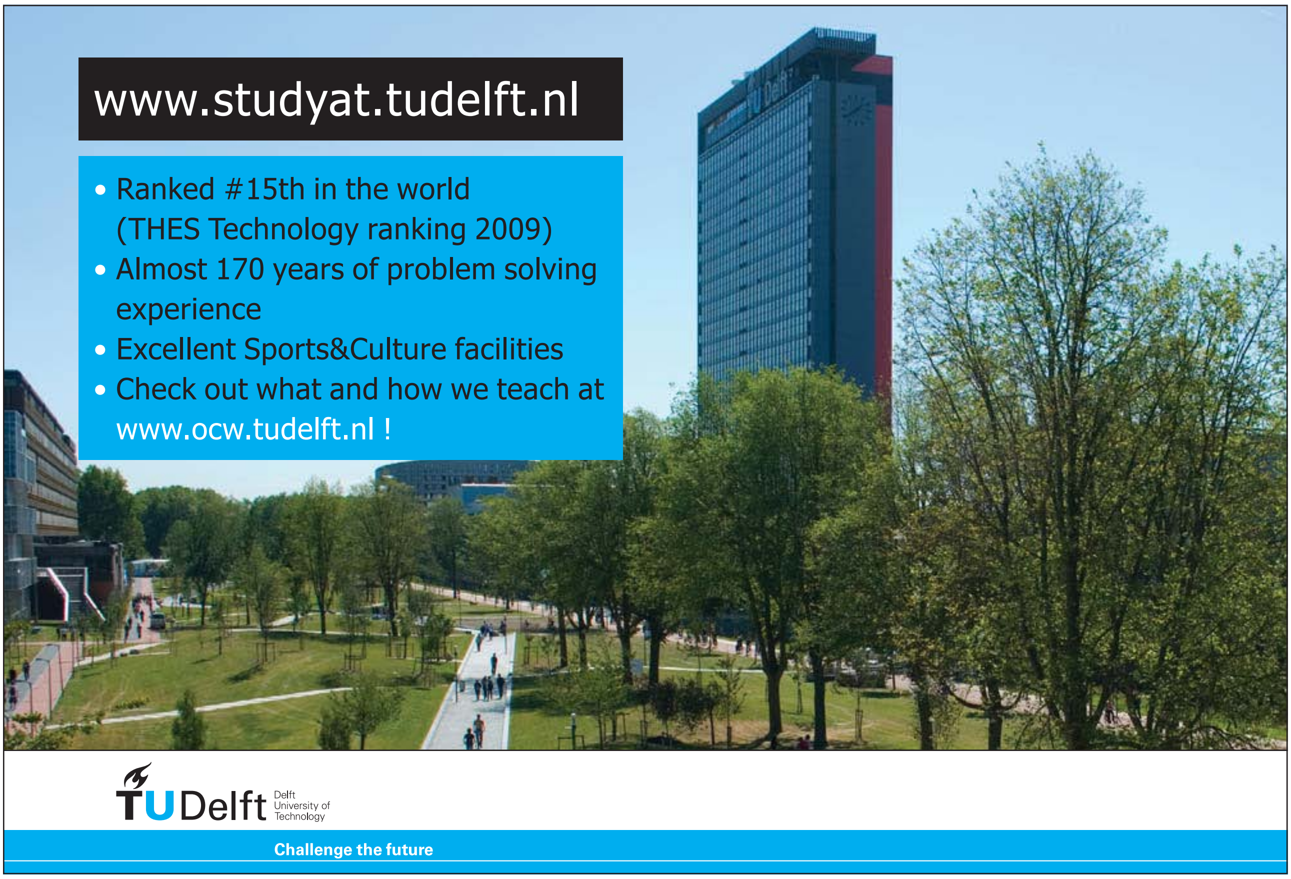
```
FUNCTION CvbyR(TbyThetaD)

{ Finds Cv/R for given T/ThetaD…from Debye Theory…from Lookup Table, by cubic interpolation.

Use Interploate1 for linear interpolation.}

IF (TbyThetaD < (1/12)) THEN

        CVbyR = 233.78 * (TbyThetaD)^3

ELSE

        CvbyR = interpolate('CvbyR_vs_TbyThetaD','TbyThetaD','CvbyR','TbyThetaD' = TbyThetaD)

ENDIF

END

"=========================================================================="
```



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Prob.2.2.6 Use the above written EES Function to get sp. heat of Aluminium, copper, Niobium, Chromium and Silver at a temp of 25 K.

EES Solution:

"Data:"

"Debye Temps:"

Theta_D_Al = 385"K …. Aluminium"
Theta_D_Cu = 310"K …. copper"
Theta_D_Nb= 265"K … Niobium"
Theta_D_Ag = 220"K …. silver"
Theta_D_Cr = 430"K …. Chromium"

"Mol. weights: [Ref: http://www.lenntech.com/calculators/molecular/molecular-weight-calculator.htm]

M_Al = 26.98
M_Cu = 63.55
M_Nb = 92.91
M_Ag = 107.87
M_Cr = 52

T = 25"K"
R_u = 8314.47 "J/kg.K"

"Calculations:"

"(T / Theta_D) ratios:"

TbyTheta_D_Al = T/Theta_D_Al "…for Al"
TbyTheta_D_Cu = T/Theta_D_Cu "…for Cu"
TbyTheta_D_Nb = T/Theta_D_Nb "…for Nb"
TbyTheta_D_Ag = T/Theta_D_Ag "…for Ag"
TbyTheta_D_Cr = T/Theta_D_Cr "…for Cr"

"Therefore, sp.heats:"

cv_Al = (R_u/M_Al) * CvbyR(TbyTheta_D_Al)"J/kg.K ….. cv for Al"
cv_Cu = (R_u/M_Cu) * CvbyR(TbyTheta_D_Cu)"J/kg.K ….. cv for Cu"

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cv_Nb = (R_u/M_Nb) * CvbyR(TbyTheta_D_Nb)"J/kg.K ….. cv for Nb"

cv_Ag = (R_u/M_Ag) * CvbyR(TbyTheta_D_Ag)"J/kg.K ….. cv for Ag"

cv_Cr = (R_u/M_Cr) * CvbyR(TbyTheta_D_Cr)"J/kg.K ….. cv for Cr"

Results:

Unit Settings: SI K MPa J mass deg

cv_{Ag} = 24.93 [J/kg-K]	cv_{Al} = 19.73 [J/kg-K]	cv_{Cr} = 7.346 [J/kg-K]
cv_{Cu} = 16.04 [J/kg-K]	cv_{Nb} = 17.22 [J/kg-K]	M_{Ag} = 107.9
M_{Al} = 26.98	M_{Cr} = 52	M_{Cu} = 63.55
M_{Nb} = 92.91	R_u = 8314 [J/kg-mol-K]	T = 25 [K]
$TbyTheta_{D,Ag}$ = 0.1136	$TbyTheta_{D,Al}$ = 0.06494	$TbyTheta_{D,Cr}$ = 0.05814
$TbyTheta_{D,Cu}$ = 0.08065	$TbyTheta_{D,Nb}$ = 0.09434	$\theta_{D,Ag}$ = 220 [K]
$\theta_{D,Al}$ = 385 [K]	$\theta_{D,Cr}$ = 430 [K]	$\theta_{D,Cu}$ = 310 [K]
$\theta_{D,Nb}$ = 265 [K]		

Thus, at 25 K:

Sp. heat of Aluminium = 19.73 J/kg.K … Ans.

Sp. heat of copper= 16.04 J/kg.K … Ans.

Sp. heat of Niobium = 17.22 J/kg.K … Ans.

Sp. heat of Chromium = 7.346 J/kg.K … Ans.

Sp. heat of Silver = 24.93 J/kg.K … Ans.

==

"**Prob.2.2.7** Write EES Functions for sp. heat of various materials used in Cryogenics."

FUNCTION cp_ss304(T)

"Sp. heat. of SS-304. Ref: NIST-Cryogenics.

cp in J/kg.K, and, T in K"

{ Finds cp in the range: T = 4 – 300 K:}

IF (T < 4) or (T > 300) THEN

CALL ERROR('Temp. must be between 4 and 300 K !')

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```
ENDIF

a := 22.0061; b := -127.5528; c := 303.647; d := -381.0098; e := 274.0328; f := -112.9212; g := 24.7593; h := -2.239153; i := 0

cp_ss304 = 10^(a+b*(log10(T)) + c*(log10(T))^ 2 + d*(log10(T))^ 3 + e*(log10(T))^ 4 + f*(log10(T))^ 5 + g*(log10(T))^ 6 + h*(log10(T))^ 7 + i*(log10(T))^ 8)

END

"==================================================================="

FUNCTION cp_ss304L(T)

{ Finds Sp. heat in the range T = 4 – 23 K:}

IF (T < 4) or (T > 23) THEN

        CALL ERROR('Temp. must be between 4 and 23 K !')

ENDIF

a1 := -351.51; b1 := 3123.695; c1 := -12017.28; d1 := 26143.99; e1 := -35176.33; f1 := 29981.75; g1 := -15812.78; h1 := 4719.64; i1 := -610.515

cp_ss304L = 10^(a1+b1*(log10(T)) + c1*(log10(T))^ 2 + d1*(log10(T))^ 3 + e1*(log10(T))^ 4 + f1*(log10(T))^ 5 + g1*(log10(T))^ 6 + h1*(log10(T))^ 7 + i1 *(log10(T))^ 8)

END

"==================================================================="

FUNCTION cp_AL_6061_T6(T)

"Sp. heat of Aluminium-6061-T6. Ref: NIST-Cryogenics.

cp in J/kg.K, T in K"

{ Finds sp. heat in the range: T = 4 – 300 K:}
```


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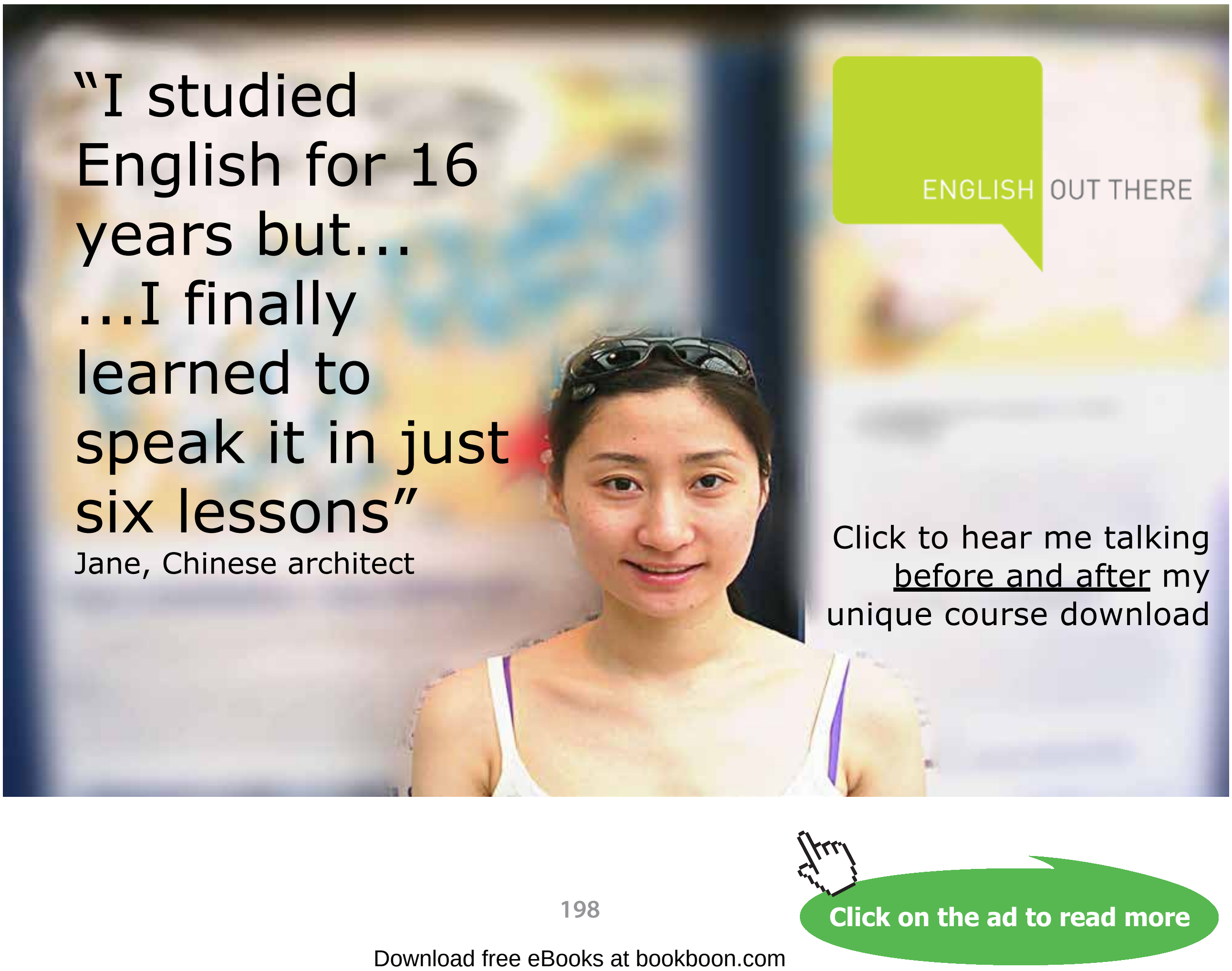
```
IF (T < 4) or (T > 300) THEN

        CALL ERROR('Temp. must be between 4 and 300 K !')

ENDIF

a := 46.6467; b := -314.292; c := 866.662; d := -1298.3; e := 1162.27; f := -637.795; g := 210.351; h :=
-38.3094; i := 2.96344

cp_AL_6061_T6 = 10^(a+b*(log10(T)) + c*(log10(T))^ 2 + d*(log10(T))^ 3 + e*(log10(T))^ 4 +
f*(log10(T))^ 5 + g*(log10(T))^ 6 + h*(log10(T))^ 7 + i*(log10(T))^ 8)

END

"=========================================================================="

FUNCTION cp_OFHC_copper(T)

"Sp. heat of OFHC-copper. Ref: NIST-Cryogenics.
```



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```
cp in J/kg.K, T in K”

{ Finds sp. heat in the range: T = 4 – 300 K:}

IF (T < 4) or (T > 300) THEN

      CALL ERROR(‘Temp. must be between 4 and 300 K !’)

ENDIF

a := -1.91844; b := -0.15973; c := 8.61013; d := -18.99640; e := 21.96610; f := -12.7328; g := 3.54322; h
:= -0.37970; i := 0

cp_OFHC_copper = 10^(a+b*(log10(T)) + c*(log10(T))^ 2 + d*(log10(T))^ 3 + e*(log10(T))^ 4 +
f*(log10(T))^ 5 + g*(log10(T))^ 6 + h*(log10(T))^ 7 + i*(log10(T))^ 8)

END

“===================================================================”

FUNCTION cp_Nylon(T)

“Sp. heat of Nylon. Ref: NIST-Cryogenics.

cp in J/kg.K, T in K”

{ Finds sp. heat in the range: T = 4 – 300 K:}

IF (T < 4) or (T > 300) THEN

      CALL ERROR(‘Temp. must be between 4 and 300 K !’)

ENDIF

a := -5.2929; b := 25.301; c := -54.874; d := 71.061; e := -52.236; f := 21.648; g := -4.7317; h := 0.42518; i := 0

cp_Nylon = 10^(a+b*(log10(T)) + c*(log10(T))^ 2 + d*(log10(T))^ 3 + e*(log10(T))^ 4 + f*(log10(T))^
5 + g*(log10(T))^ 6 + h*(log10(T))^ 7 + i*(log10(T))^ 8)
```


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```
END

"======================================================================="

FUNCTION cp_Teflon(T)

"Sp. heat of Teflon. Ref: NIST-Cryogenics.

cp in J/kg.K, T in K"

{ Finds sp. heat in the range: T = 4 – 300 K:}

IF (T < 4) or (T > 300) THEN

        CALL ERROR('Temp. must be between 4 and 300 K !')

ENDIF

a := 31.88256; b := -166.51949; c := 352.01879; d := -393.44232; e := 259.98072; f := -104.61429; g :=
24.99276; h := -3.20792; i := 0.16503

cp_Teflon = 10^(a+b*(log10(T)) + c*(log10(T))^ 2 + d*(log10(T))^ 3 + e*(log10(T))^ 4 + f*(log10(T))^
5 + g*(log10(T))^ 6 + h*(log10(T))^ 7 + i*(log10(T))^ 8)

END

"======================================================================="

FUNCTION cp_Brass_65_35(T)

"Sp. heat of Brass. Ref: Digitized and used in a Lookup Table in EES-linear interpolation.

cp in J/kg.K, T in K"

{ Finds sp. heat in the range: T = 20 – 300 K:}

IF (T < 2) or (T > 305) THEN

        CALL ERROR('Temp. must be between 2 and 305 K !')
```


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ENDIF

cp_Brass_65_35 = interpolate1('cp-Brass65/35', 'Temp', 'cp', Temp = T)

END

"=="

FUNCTION cp_pyrex(T)

"Sp. heat of Pyrex. Ref: CERN Accel. School-2013. Put in Lookup Table in EES- and- linear interpolation.

cp in J/kg.K, T in K"

{ Finds sp. heat in the range: T = 1 – 300 K:}

IF (T < 1) or (T > 300) THEN

CALL ERROR('Temp. must be between 1 and 300 K !')

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```
ENDIF

cp_pyrex= interpolate1('cp_pyrex', 'Temp', 'cp', Temp = T)

END

"=================================================================="

FUNCTION cp_Lead(T)

"Sp. heat of Lead. Ref: BNL Selected Cryogenic Data Notebook – 1980- Put in Lookup Table in EES- and- linear interpolation.

cp in J/kg.K, T in K"

{ Finds sp. heat in the range: T = 1 – 310 K:}

IF (T < 1) or (T > 310) THEN

        CALL ERROR('Temp. must be between 1 and 310 K !')

ENDIF

        cp_Lead= interpolate1('cp_Lead', 'Temp', 'cp', Temp = T)

END

"=================================================================="
```

"**Prob.2.2.8** Find the sp. heats at 25 K for the following materials, using the EES Functions written above: (i) SS304 (ii) 6061-T6 Al (iii) OFHC copper (iv) Brass (v) Teflon (vi) Nylon, and (vii) Pyrex"

EES Solution:

"Data:"

T = 25"K"

"Calculations:"

cp_SS304 = cp_ss304(T) "J/kg.K … sp. heat of SS 304"
cp_Al = cp_AL_6061_T6(T) "J/kg.K … sp. heat of Aluminium"

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cp_OFHC_Cu = cp_OFHC_copper(T) "J/kg.K … sp. heat of OFHC-copper"
cp_Brass = cp_Brass_65_35(T) "J/kg.K … sp. heat of Brass"
cp_Teflon = cp_Teflon(T) "J/kg.K … sp. heat of Teflon"
cp_Nylon = cp_Nylon(T) "J/kg.K … sp. heat of Nylon"
cp_Pyrex = cp_pyrex(T) "J/kg.K … sp. heat of Pyrex"

Results:

Unit Settings: SI K MPa J mass deg

cp_{Al} = 18.28 [J/kg-K]	cp_{Brass} = 18.36 [J/kg-K]
cp_{Nylon} = 150 [J/kg-K]	$cp_{OFHC,Cu}$ = 15.22 [J/kg-K]
cp_{Pyrex} = 44.3 [J/kg-K]	cp_{SS304} = 20.63 [J/kg-K]
cp_{Teflon} = 102 [J/kg-K]	T = 25 [K]

Thus:
At 25 K:
Sp. heat of SS304 = 20.63 J/kg.K …. Ans.
Sp. heat of Aluminium 6061-T6 = 18.28 J/kg.K …. Ans.
Sp. heat of OFHC copper = 15.22 J/kg.K …. Ans.
Sp. heat of Brass = 18.36 J/kg.K …. Ans.
Sp. heat of Teflon = 102 J/kg.K …. Ans.
Sp. heat of Nylon = 150 J/kg.K …. Ans.
Sp. heat of Pyrex = 44.3 J/kg.K …. Ans.

==

"**Prob.2.2.9** Find the amount of heat to be removed for 1 kg of following materials to be cooled from 300 to 77 K, taking in to account the variation of sp. heats with temp. (i) SS304 (II) 6061-T6 Al (iii) OFHC copper (iv) Brass (v) Teflon (vi) Nylon (vii) Pyrex (viii) Lead"

EES Solution:

"Data:"

T1 = 77 "K"
T2 = 300"K"
m = 1 "kg"

"Calculations:"

Q_SS304 = m * integral(cp_ss304(T) ,T, T1, T2) "J … heat to be removed for 1 kg of SS 304"
Q_Al = m * integral(cp_AL_6061_T6(T) ,T, T1, T2) "J … heat to be removed for 1 kg of Al-6061-T6"

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Q_OFHC_Cu = m * integral(cp_OFHC_copper(T),T, T1, T2) "J … heat to be removed for 1 kg of OFHC copper"
Q_Brass = m * integral(cp_Brass_65_35(T),T, T1, T2) "J … heat to be removed for 1 kg of Brass"
Q_Teflon = m * integral(cp_Teflon(T) ,T, T1, T2) "J … heat to be removed for 1 kg of Teflon"
Q_Nylon = m * integral(cp_Nylon(T) ,T, T1, T2) "J … heat to be removed for 1 kg of Nylon"
Q_Pyrex = m * integral(cp_pyrex(T) ,T, T1, T2) "J … heat to be removed for 1 kg of Pyrex"
Q_Lead = m * integral(cp_Lead(T) ,T, T1, T2) "J … heat to be removed for 1 kg of Lead"

Results:

Unit Settings: SI K MPa J mass deg

m = 1 [kg]	Q_{Al} = 168854 [J]	Q_{Brass} = 81661 [J]
Q_{Lead} = 27626 [J]	Q_{Nylon} = 254014 [J]	$Q_{OFHC,Cu}$ = 74142 [J]
Q_{Pyrex} = 111292 [J]	Q_{SS304} = 86575 [J]	Q_{Teflon} = 153726 [J]
T = 300 [K]	T1 = 77 [K]	T2 = 300 [K]

Thus:
For 1 kg of material, amount of heat to be removed, while cooling from 300 K to 77K:
For SS304 = 86574 J …. Ans.
For Aluminium 6061-T6 = 168854 J …. Ans.

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For OFHC copper = 74142 J …. Ans.

For Brass = 81661 J …. Ans.

For Teflon = 153726 J …. Ans.

For Nylon = 254014 J …. Ans.

For Pyrex = 111293 J …. Ans.

For Lead = 27626 J …. Ans.

==

"**Prob.2.2.10** Write EES Functions for Yield stress of various materials used in Cryogenics."

Original graphs from Ref.[1] were digitized using the PlotDigitizer [Ref: 13]. The resulting data tables were transferred to EXCEL and plotted. The **'Trendline'** menu was used to fit the plot to a 4^{th} order polynomial. Then, the EES Functions are written using these curve-fit equations. Following are the results:

For SS-304	
T(K)	Yield stress (MPA)
0	1347.933
50.05241	1327.601
99.60644	1307.235
148.0599	1286.834
197.6278	1255.509
248.3032	1218.74
298.9924	1171.012
350	1128.763

For 2024-T4 Aluminium	
T(K)	Yield stress (MPA)
0	526.0093
50.0801	434.447
99.68258	375.7258
150.358	338.9562
198.8114	318.5554
249.4453	314.6614
298.9854	305.2535
350	323.2765

For Teflon	
T(K)	Yield stress (MPA)
0	142.4609
50.5231	83.77415
100.0841	57.92856
150.7387	37.59671
199.1783	28.15445
249.8121	24.26039
299.3385	25.81112
350	27.43078

For Be-Cu	
T(K)	Yield stress (MPA)
0	947.9815
49.58172	828.9539
99.19804	759.2742
149.8873	711.5461
199.4482	685.7005
248.9884	676.2927
299.6153	677.8779
350	690.4216

For Ti	
T(K)	Yield stress (MPA)
0	1824.629
48.68187	1541.258
99.56491	1340.111
149.2989	1177.283
198.9983	1041.853
248.6769	922.8596
299.4492	809.3803
350	712.3387

For 9% Ni Steel, Invar-36	
T(K)	Yield stress (MPA)
0	1134.242
50.49541	976.9285
100.1671	863.4147
149.7973	782.7765
199.4067	718.5761
250.089	676.3272
299.6638	639.5231
350	608.2327

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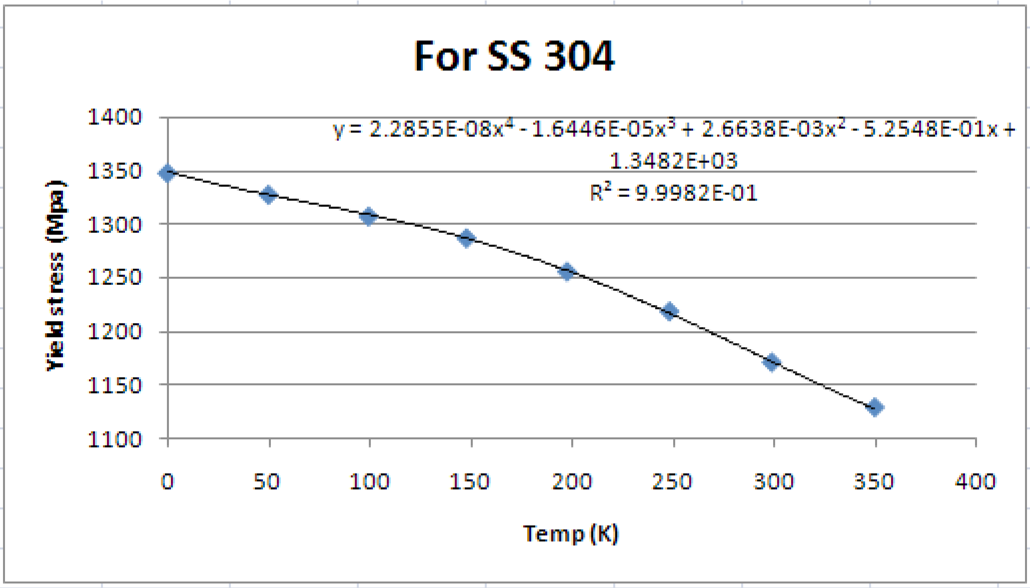
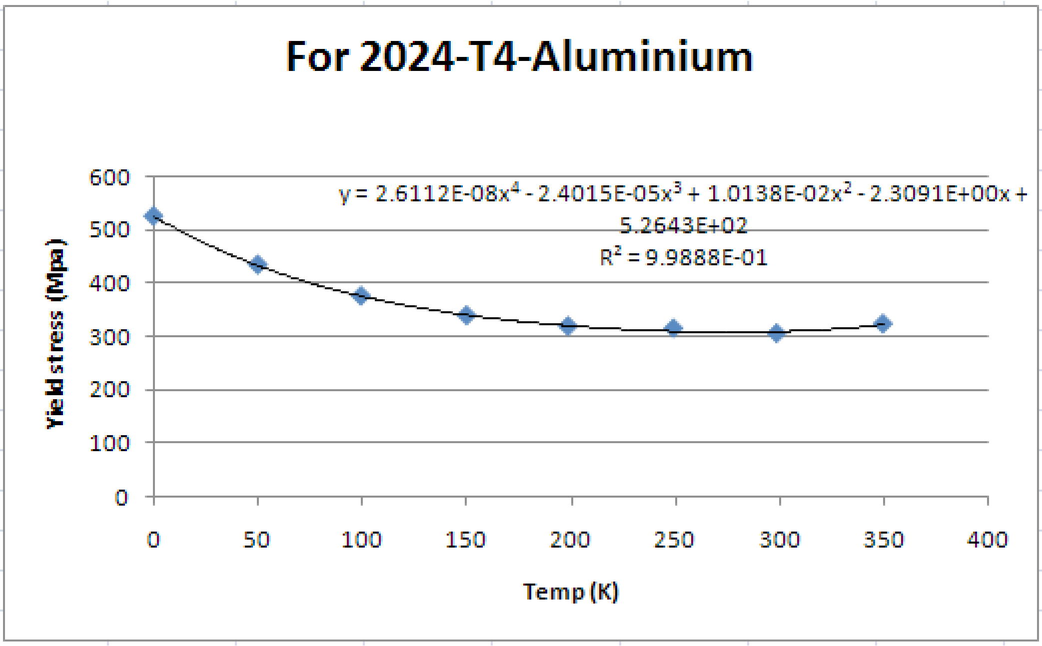
For K-Monel			For C1020-C steel	
T(K)	Yield stress (MPA)		T(K)	Yield stress (MPA)
0	1090.408		0	712.3042
50.44004	1020.763		49.8932	582.3871
100.0494	956.5622		99.52338	501.7489
149.6242	919.7581		150.2264	443.0622
198.0915	888.3988		199.822	389.8203
249.8606	857.1429		249.3968	353.0162
300.5013	847.7695		298.9578	327.1706
350	849.3203		350	295.8802





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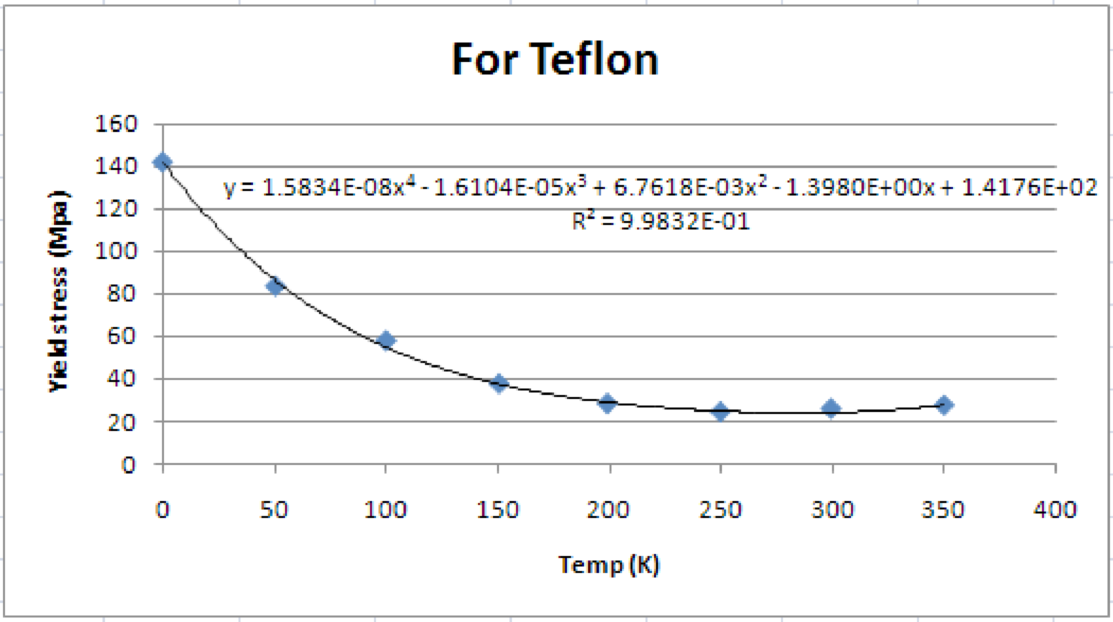

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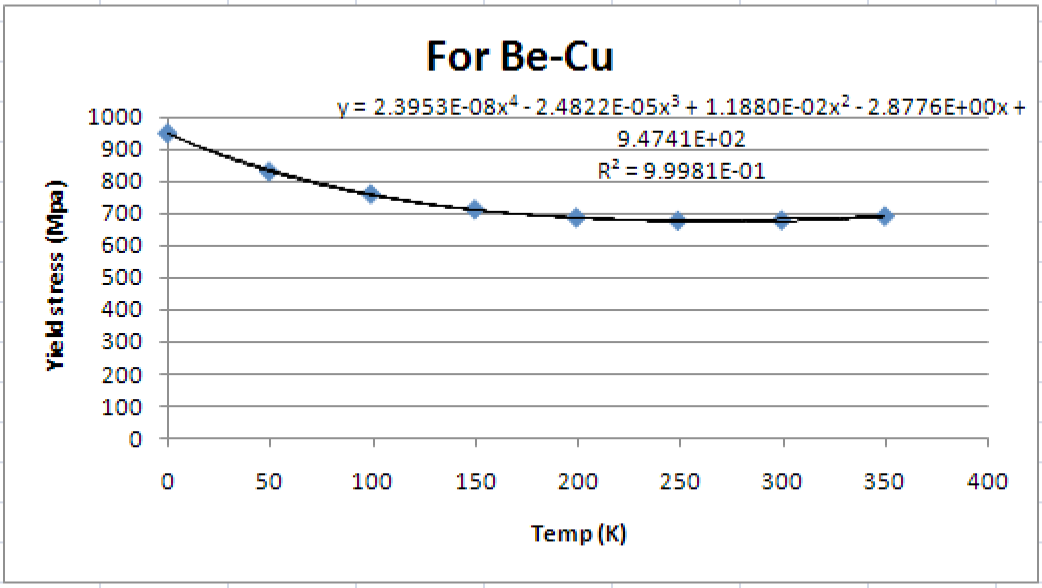

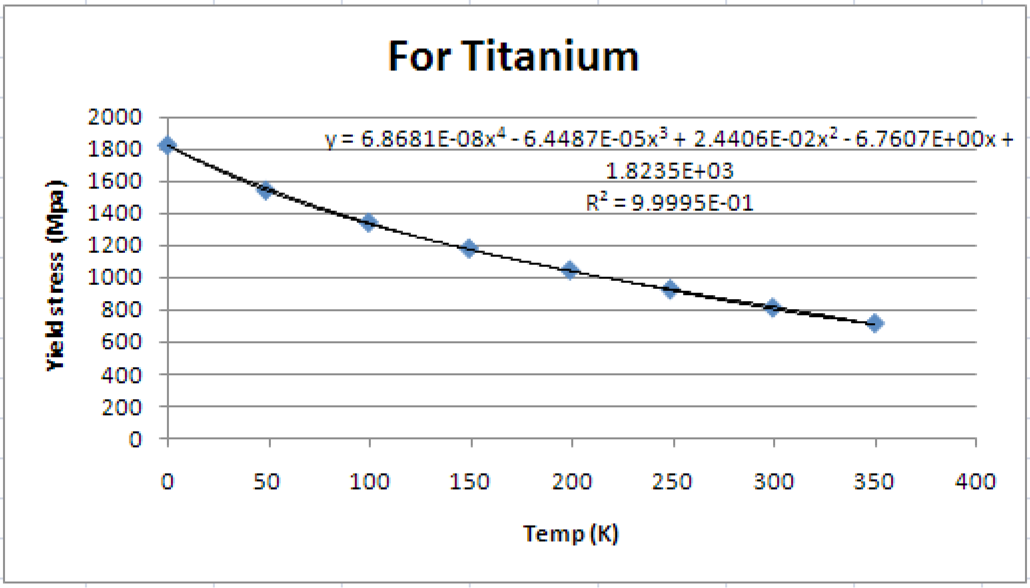

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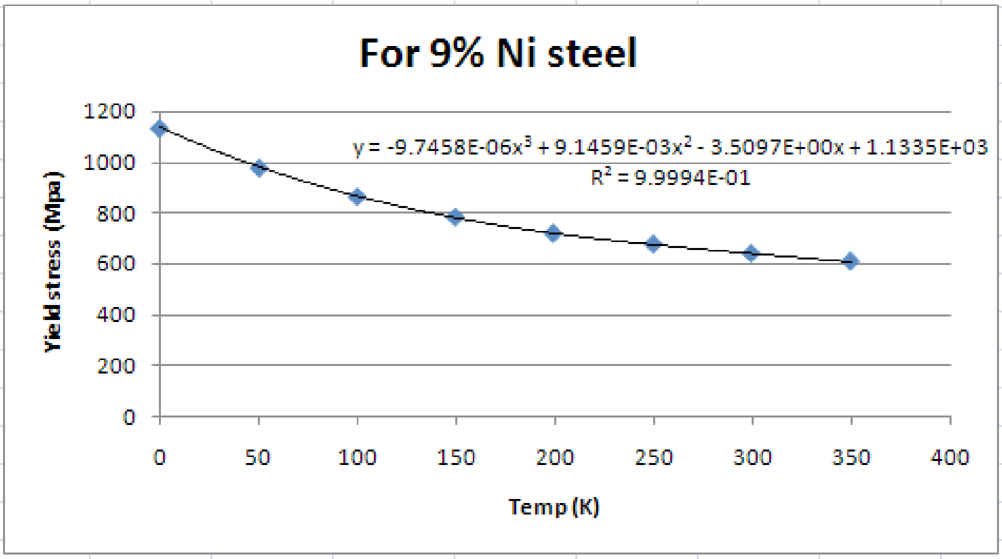

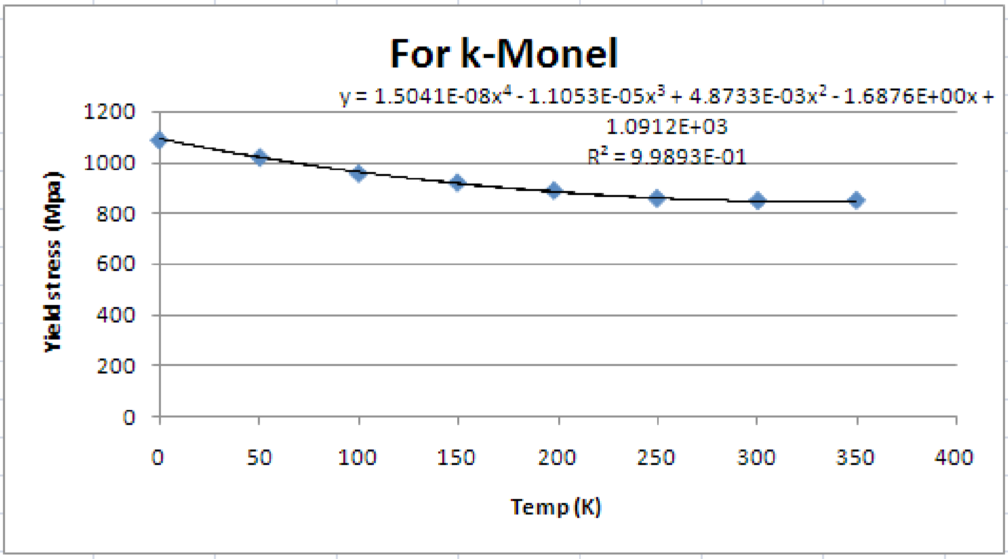

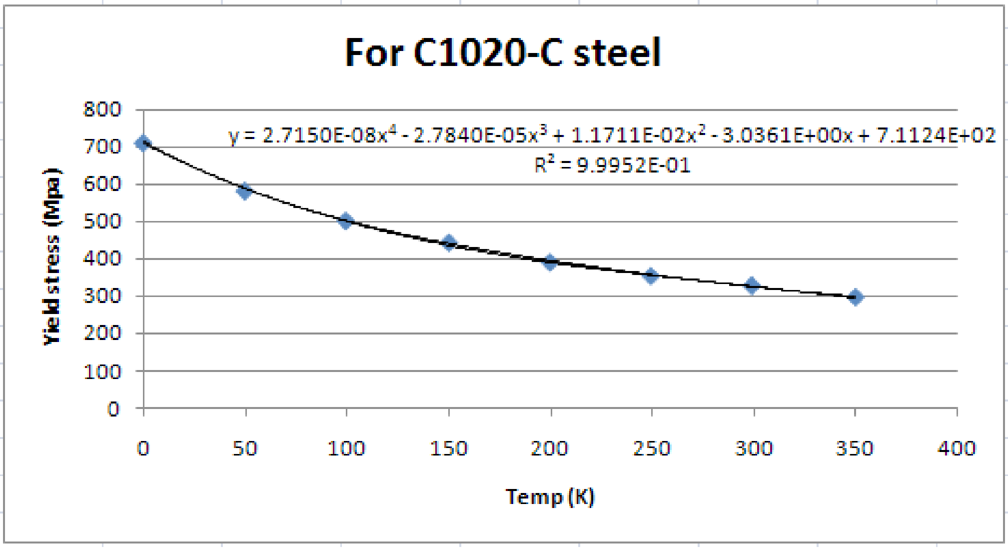

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Now, the EES Functions:

```
FUNCTION Yield_stress_SS304(T)

"Yield stress of SS304. Ref: Cryogenics Systems by Barron.

Yield stress in MPa, T in K"

{ Finds Yield stress in the range: T = 0 – 350 K:}

IF (T < 0) or (T > 350) THEN

        CALL ERROR('Temp. must be between 0 and 350 K !')

ENDIF

Yield_stress_SS304 = 2.2855E-08 * T^4 – 1.6446E-05*T^3 + 2.6638E-03*T^2 – 5.2548E-01*T + 1.3482E+03

END

"=================================================================="
```

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```
FUNCTION Yield_stress_AL_2024_T4(T)

"Yield stress of 2024-T4-Aluminium. Ref: Cryogenics Systems by Barron.

Yield stress in MPa, T in K"

{ Finds Yield stress in the range: T = 0 – 350 K:}

IF (T < 0) or (T > 350) THEN

        CALL ERROR('Temp. must be between 0 and 350 K !')

ENDIF

Yield_stress_AL_2024_T4 = 2.6112E-08* T^4 – 2.4015E-05 * T^3 + 1.0138E-02* T^2 – 2.3091E+00*T
+ 5.2643E+02

END

"=================================================================================="

FUNCTION Yield_stress_Teflon(T)

"Yield stress of Teflon. Ref: Cryogenics Systems by Barron.

Yield stress in MPa, T in K"

{ Finds Yield stress in the range: T = 0 – 350 K:}

IF (T < 0) or (T > 350) THEN

        CALL ERROR('Temp. must be between 0 and 350 K !')

ENDIF

Yield_stress_Teflon = 1.5834E-08 * T^4 – 1.6104E-05 * T^3 + 6.7618E-03 * T^2 – 1.3980E+00 * T +
1.4176E+02

END

"=================================================================================="
```


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```
FUNCTION Yield_stress_BeCu(T)

"Yield stress of Berylium copper. Ref: Cryogenics Systems by Barron.

Yield stress in MPa, T in K"

{ Finds Yield stress in the range: T = 0 – 350 K:}

IF (T < 0) or (T > 350) THEN

        CALL ERROR('Temp. must be between 0 and 350 K !')

ENDIF

Yield_stress_BeCu = 2.3953E-08 * T^4 – 2.4822E-05 * T^3 + 1.1880E-02 * T^2 – 2.8776E+00 * T +
9.4741E+02

END

"=================================================================="

FUNCTION Yield_stress_Ti(T)

"Yield stress of Titanium. Ref: Cryogenics Systems by Barron.

Yield stress in MPa, T in K"

{ Finds Yield stress in the range: T = 0 – 350 K:}

IF (T < 0) or (T > 350) THEN

        CALL ERROR('Temp. must be between 0 and 350 K !')

ENDIF

Yield_stress_Ti = 6.8681E-08 * T^4 – 6.4487E-05 * T^3 + 2.4406E-02 * T^2 – 6.7607E+00 * T +
1.8235E+03

END

"=================================================================="
```


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```
FUNCTION Yield_stress_9%NiSteel(T)

"Yield stress of 9% Ni Steel. Ref: Cryogenics Systems by Barron.

Yield stress in MPa, T in K"

{ Finds Yield stress in the range: T = 0 – 350 K:}

IF (T < 0) or (T > 350) THEN

        CALL ERROR('Temp. must be between 0 and 350 K !')

ENDIF

Yield_stress_9%NiSteel = -9.7458E-06 * T^3 + 9.1459E-03 * T^2 – 3.5097E+00 * T + 1.1335E+03

END

"=====================================================================”
```

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```
FUNCTION Yield_stress_kMonel(T)

"Yield stress of k-Monel. Ref: Cryogenics Systems by Barron.

Yield stress in MPa, T in K"

{ Finds Yield stress in the range: T = 0 – 350 K:}

IF (T < 0) or (T > 350) THEN

        CALL ERROR('Temp. must be between 0 and 350 K !')

ENDIF

Yield_stress_kMonel = 1.5041E-08 * T^4 – 1.1053E-05 * T^3 + 4.8733E-03 * T^2 – 1.6876E+00 * T + 1.0912E+03

END

"===================================================================="

FUNCTION Yield_stress_C1020CSteel(T)

"Yield stress of C1020-CSteel. Ref: Cryogenics Systems by Barron.

Yield stress in MPa, T in K"

{ Finds Yield stress in the range: T = 0 – 350 K:}

IF (T < 0) or (T > 350) THEN

        CALL ERROR('Temp. must be between 0 and 350 K !')

ENDIF

Yield_stress_C1020CSteel= 2.7150E-08 * T^4 – 2.7840E-05 * T^3 + 1.1711E-02 * T^2 – 3.0361E+00 * T + 7.1124E+02

END

"===================================================================="
```


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"**Prob.2.2.11** Find the Yield stress to density ratios of following materials, at a temp of 20 K: (i) 2024-T4_Aluminium (rho = 2740.31 kg/m^3) (ii) 304 SS (rho = 7805.73 kg/m^3) (iii) Monel (rho = 8885.25 kg/m^3) (iv) Beryllium copper (rho = 8303.97 kg/m^3) (v) Teflon (rho = 2297.43 kg/m^3)"

"EES Solution:"

```
T= 20 "K"

sigma_y_Al = Yield_stress_AL_2024_T4(T)"MPa"
sigma_y_SS304= Yield_stress_SS304(T)"MPa"
sigma_y_KMonel= Yield_stress_kMonel(T)"MPa"
sigma_y_BeCu = Yield_stress_BeCu(T)"MPa"
sigma_y_Teflon = Yield_stress_Teflon(T)"MPa"

rho_Al = 2740.31"kg/m^3"
rho_SS304 = 7805.73 "kg/m^3"
rho_KMonel = 8885.25"kg/m^3"
rho_BeCu = 8303.97"kg/m^3"
rho_Teflon = 2297.43"kg/m^3"

"Therefore:"

Stressbyrho_Al = sigma_y_Al / rho_Al"MPa.m^3/kg"
Stressbyrho_SS304 = sigma_y_SS304 / rho_SS304"MPa.m^3/kg"
Stressbyrho_KMonel = sigma_y_KMonel / rho_KMonel"MPa.m^3/kg"
Stressbyrho_BeCu = sigma_y_BeCu / rho_BeCu"MPa.m^3/kg"
Stressbyrho_Teflon = sigma_y_Teflon / rho_Teflon"MPa.m^3/kg"
```

Results:

Unit Settings: SI K MPa J mass deg

ρ_{Al} = 2740 [kg/m^3]

ρ_{BeCu} = 8304 [kg/m^3]

ρ_{KMonel} = 8885 [kg/m^3]

ρ_{SS304} = 7806 [kg/m^3]

ρ_{Teflon} = 2297 [kg/m^3]

$\sigma_{y,Al}$ = 484.1 [MPa]

$\sigma_{y,BeCu}$ = 894.4 [MPa]

$\sigma_{y,KMonel}$ = 1059 [MPa]

$\sigma_{y,SS304}$ = 1339 [MPa]

$\sigma_{y,Teflon}$ = 116.4 [MPa]

$Stressbyrho_{Al}$ = 0.1767 [MPa-m^3/kg]

$Stressbyrho_{BeCu}$ = 0.1077 [MPa-m^3/kg]

$Stressbyrho_{KMonel}$ = 0.1192 [MPa-m^3/kg]

$Stressbyrho_{SS304}$ = 0.1715 [MPa-m^3/kg]

$Stressbyrho_{Teflon}$ = 0.05066 [MPa-m^3/kg]

T = 20 [K]

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Thus:

Strength to density ratios:

For 2024-T4_Al = 0.1767 MPa-m^3/kg …. Ans.

For SS 304 = 0.1715 MPa-m^3/kg …. Ans.

For KMonel = 0.1192 MPa-m^3/kg …. Ans.

For Beryllium copper = 0.1077 MPa-m^3/kg …. Ans.

For Teflon = 0.05066 MPa-m^3/kg …. Ans.

==

"**Prob.2.2.12** Using the EES Functions written above, find the Yield stress to conductivity ratios of following materials, at a temp of 30 K: (i) SS-304 (ii) Beryllium copper, and (iii) Teflon"

EES Solution:

"Data:"

T = 30 "K"

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"Calculations:"

sigma_y_SS304 = Yield_stress_SS304(T)"MPa… Yield stress of SS304"
sigma_y_BeCu = Yield_stress_BeCu(T)"MPa… Yield stress of BeCu"
sigma_y_Teflon = Yield_stress_Teflon(T)"MPa… Yield stress of Teflon"
k_SS304 = k_SS_304(T)"W/m.K….th. cond. of SS 304"
k_BeCu= k_BeCu(T)"W/m.K….th. cond. of BeCu"
k_Teflon= k_Teflon(T)"W/m.K….th. cond. of Teflon"
Ratio_SS304 = sigma_y_SS304/k_SS304"MPa-m-K/W …. ratio for SS304"
Ratio_BeCu = sigma_y_BeCu/k_BeCu"MPa-m-K/W …. ratio for BeCu"
Ratio_Teflon = sigma_y_Teflon/k_Teflon"MPa-m-K/W …. ratio for Teflon"

Results:

Unit Settings: SI K MPa J mass deg

k_{BeCu} = 12.02 [W/m-K]	k_{SS304} = 3.16 [W/m-K]
k_{Teflon} = 0.1738 [W/m-K]	$Ratio_{BeCu}$ = 72.49 [MPa-m-K/W]
$Ratio_{SS304}$ = 422.2 [MPa-m-K/W]	$Ratio_{Teflon}$ = 606.8 [MPa-m-K/W]
$\sigma_{y,BeCu}$ = 871.1 [MPa]	$\sigma_{y,SS304}$ = 1334 [MPa]
$\sigma_{y,Teflon}$ = 105.5 [MPa]	T = 30 [K]

Thus:

Strength to conductivity ratios:

For SS 304 = 422.2 MPa-m-K/W…. Ans.

For BeCu = 72.49 MPa-m-K/W…. Ans.

For Teflon = 606.8 MPa-m-K/W…. Ans.

==

"**Prob.2.2.13** Write EES Functions to determine Young's Modulus for important materials used in Cryogenics."

Original graphs from Ref.[1] were digitized using the PlotDigitizer [Ref: 13]. The resulting data tables were transferred to EXCEL and plotted. The **'Trendline'** menu was used to fit the plot to a 3rd/4th order polynomial. Then, the EES Functions are written using these curve-fit equations. Following are the results:

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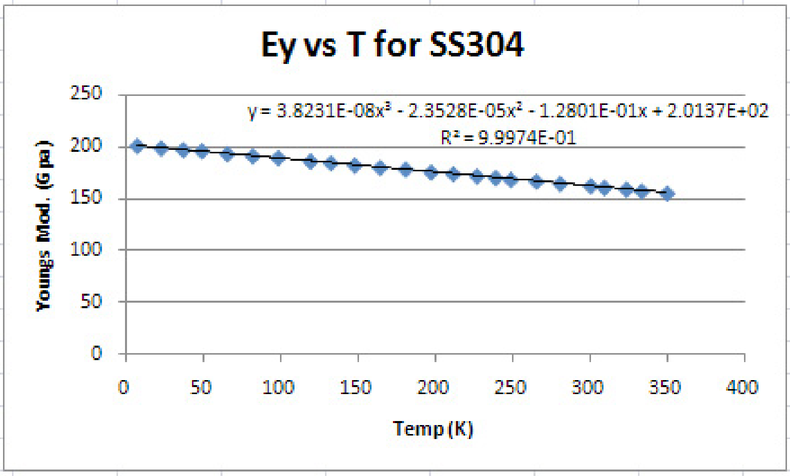
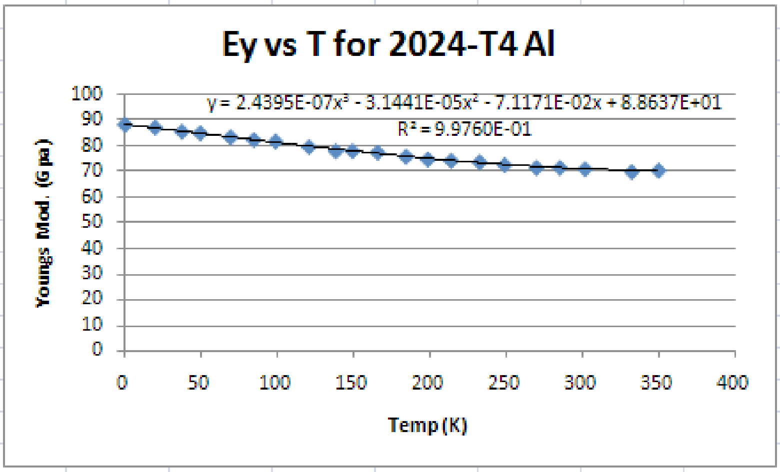
For SS 304:

Temp (K)	E (GPa)
7.65625	200.362
22.9688	198.19
37.1875	196.561
49.2188	195.475
65.625	192.76
82.0313	190.588
98.4375	188.959
119.219	185.701
132.344	184.072
147.656	181.9
164.063	179.729
180.469	178.1
196.875	175.385
211.094	173.756
226.406	171.584
238.438	169.955
248.281	168.326
264.688	166.697
280	164.525
299.688	162.353
308.438	160.724
322.656	159.095
332.5	157.466
348.906	155.294



For Aluminium 2024-T4:

Temp (K)	E (GPa)
0	88.5068
19.6875	87.4208
37.1875	85.7919
49.2188	85.2489
68.9063	83.6199
84.2188	82.5339
98.4375	81.991
120.313	79.819
137.813	78.1901
148.75	78.1901
165.156	77.6471
183.75	76.0181
197.969	74.9321
213.281	74.3891
231.875	73.8462
248.281	72.7602
269.063	71.6742
284.375	71.6742
300.781	71.1312
331.406	70.0453
348.906	70.5882



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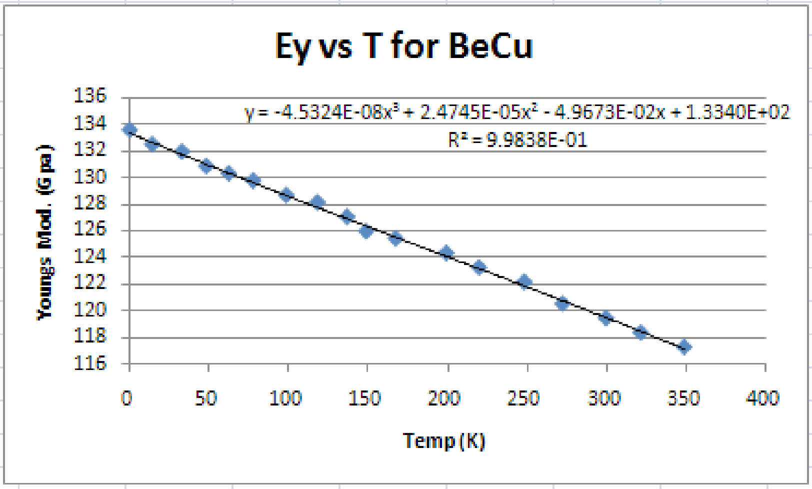
For Beryllium copper:

Temp (K)	E (GPa)
0	133.575
14.2188	132.489
32.8125	131.946
48.125	130.86
62.3438	130.317
77.6563	129.774
98.4375	128.688
118.125	128.145
136.719	127.059
148.75	125.973
167.344	125.43
199.063	124.344
219.844	123.258
248.281	122.172
272.344	120.543
299.688	119.457
321.563	118.371
348.906	117.285



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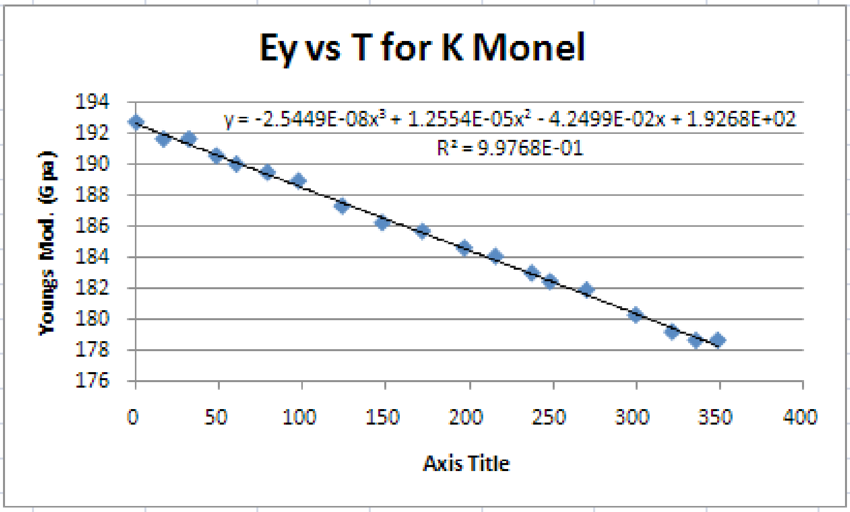
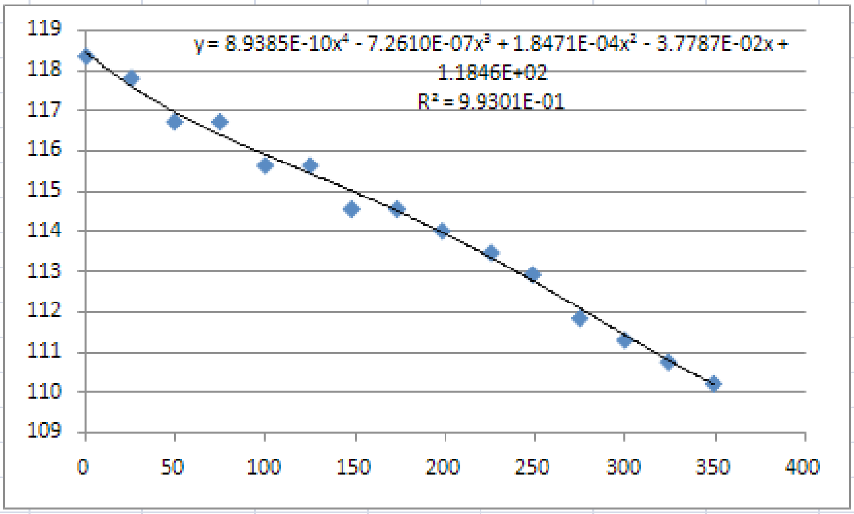
For K Monel:

Temp (K)	E (GPa)
0	192.76
16.4063	191.674
31.7188	191.674
48.125	190.588
60.1563	190.045
78.75	189.502
97.3438	188.959
123.594	187.33
147.656	186.244
171.719	185.701
196.875	184.615
215.469	184.072
237.344	182.986
248.281	182.443
270.156	181.9
299.688	180.272
321.563	179.186
335.781	178.643
348.906	178.643



For Titanium:

Temp (K)	E (Gpa)
0	118.371
25.1563	117.828
49.2188	116.742
74.375	116.742
99.5313	115.656
124.688	115.656
147.656	114.57
172.813	114.57
197.969	114.027
225.313	113.484
248.281	112.941
274.531	111.855
299.688	111.312
323.75	110.769
348.906	110.226



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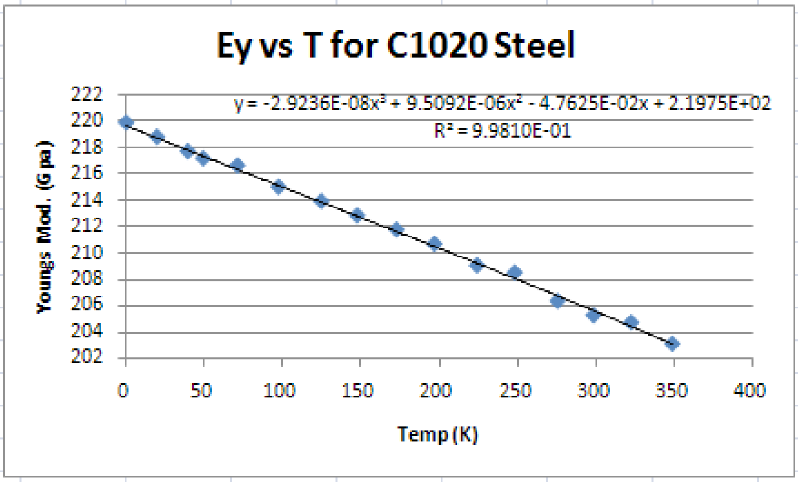
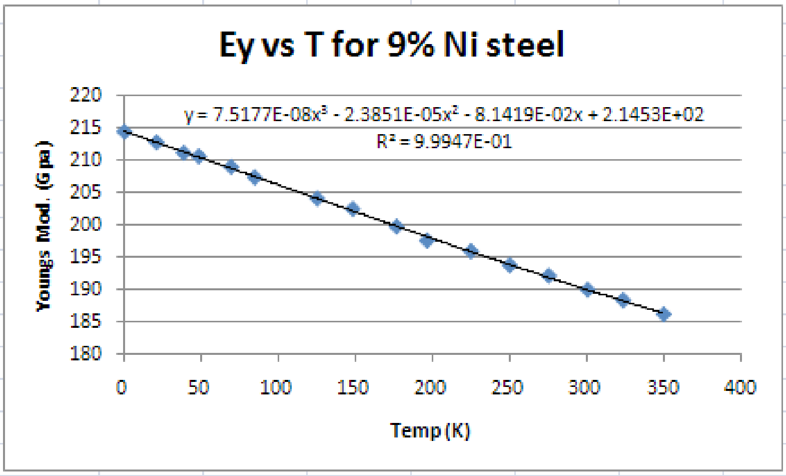
For C1020 C steel:

Temp (K)	E (GPa)
0	219.91
19.6875	218.824
39.375	217.738
49.2188	217.195
71.0938	216.652
97.3438	215.023
124.688	213.937
147.656	212.851
172.813	211.765
196.875	210.679
224.219	209.05
248.281	208.507
275.625	206.335
298.594	205.249
322.656	204.706
348.906	203.077



For 9 % Ni steel:

Temp (K)	E (GPa)
0	214.48
20.7813	212.851
38.2813	211.222
48.125	210.679
68.9063	209.05
84.2188	207.421
124.688	204.163
147.656	202.534
176.094	199.819
195.781	197.647
224.219	196.018
249.375	193.846
274.531	192.217
299.688	190.045
322.656	188.416
348.906	186.244



Now, write EES Functions, using the curve fit equations obtained above:

EES Functions:

FUNCTION Youngs_Modulus_SS304(T)

"E_y for SS304. Ref: Cryogenics Systems by Barron.

Ey in GPa, T in K"

{ Finds E_y in the range: T = 0 – 350 K:}

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```
IF (T < 0) or (T > 350) THEN

        CALL ERROR('Temp. must be between 0 and 350 K !')

ENDIF

Youngs_Modulus_SS304= 3.8231E-08 * T^3 – 2.3528E-05 * T^2 – 1.2801E-01 * T + 2.0137E+02

END

"=================================================================="

FUNCTION Youngs_Modulus_AL_2024_T4(T)

"E_y for Aluminium 2024-T4. Ref: Cryogenics Systems by Barron.

Ey in GPa, T in K"

{ Finds E_y in the range: T = 0 – 350 K:}

IF (T < 0) or (T > 350) THEN

        CALL ERROR('Temp. must be between 0 and 350 K !')

ENDIF

Youngs_Modulus_AL_2024_T4= 2.4395E-07 * T^3 – 3.1441E-05 * T^2 – 7.1171E-02 * T + 8.8637E+01

END

"=================================================================="

FUNCTION Youngs_Modulus_BeCu(T)

"E_y for Beryllium copper. Ref: Cryogenics Systems by Barron.

Ey in GPa, T in K"

{ Finds E_y in the range: T = 0 – 350 K:}
```


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```
IF (T < 0) or (T > 350) THEN

        CALL ERROR('Temp. must be between 0 and 350 K !')

ENDIF

Youngs_Modulus_BeCu= -4.5324E-08 * T^3 + 2.4745E-05 * T^2 – 4.9673E-02 * T + 1.3340E+02

END

"========================================================================"

FUNCTION Youngs_Modulus_KMonel(T)

"E_y for K-Monel. Ref: Cryogenics Systems by Barron.

Ey in GPa, T in K"

{ Finds E_y in the range: T = 0 – 350 K:}
```

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```
IF (T < 0) or (T > 350) THEN

        CALL ERROR('Temp. must be between 0 and 350 K !')

ENDIF

Youngs_Modulus_KMonel= -2.5449E-08 * T^3 + 1.2554E-05 * T^2 – 4.2499E-02 * T + 1.9268E+02

END

"=================================================================="

FUNCTION Youngs_Modulus_Titanium(T)

"E_y for Titanium. Ref: Cryogenics Systems by Barron.

Ey in GPa, T in K"

{ Finds E_y in the range: T = 0 – 350 K:}

IF (T < 0) or (T > 350) THEN

        CALL ERROR('Temp. must be between 0 and 350 K !')

ENDIF

Youngs_Modulus_Titanium= 8.9385E-10 * T^4 – 7.2610E-07 * T^3 + 1.8471E-04 * T^2 – 3.7787E-02
* T + 1.1846E+02

END

"=================================================================="

FUNCTION Youngs_Modulus_C1020_Steel(T)

"E_y for Titanium. Ref: Cryogenics Systems by Barron.

Ey in GPa, T in K"
```


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```
{ Finds E_y in the range: T = 0 – 350 K:}

IF (T < 0) or (T > 350) THEN

        CALL ERROR('Temp. must be between 0 and 350 K !')

ENDIF

Youngs_Modulus_C1020_Steel= -2.9236E-08 * T^3 + 9.5092E-06 * T^2 – 4.7625E-02 * T + 2.1975E+02

END

"======================================================================="

FUNCTION Youngs_Modulus_9%Ni_Steel(T)

"E_y for Titanium. Ref: Cryogenics Systems by Barron.

Ey in GPa, T in K"

{ Finds E_y in the range: T = 0 – 350 K:}

IF (T < 0) or (T > 350) THEN

        CALL ERROR('Temp. must be between 0 and 350 K !')

ENDIF

Youngs_Modulus_9%Ni_Steel= 7.5177E-08 * T^3 – 2.3851E-05 * T^2 – 8.1419E-02 * T + 2.1453E+02

END

"======================================================================="
```

"**Prob.2.2.14** Using the above written EES Functions, determine Young's Modulus at 20 K for: (i) AL-2024-T (ii) SS 304 (iii) Beryllium copper (iv) k Monel (v) Titanium (vi) C1020 Steel (vii) 9% Ni Steel."

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EES Solution:

T = 20 "K"

E_y_AL2024T4 = Youngs_Modulus_AL_2024_T4(T) "GPa…. Young's Mod. for AL-2024-T4"
E_y_SS304 = Youngs_Modulus_SS304(T) "GPa…. Young's Mod. for SS304"
E_y_BeCu = Youngs_Modulus_BeCu(T) "GPa…. Young's Mod. for BeCu"
E_y_KMonel = Youngs_Modulus_KMonel(T) "GPa…. Young's Mod. for KMonel"
E_y_Titanium = Youngs_Modulus_Titanium(T) "GPa…. Young's Mod. for Titanium"
E_y_C1020Steel = Youngs_Modulus_C1020_Steel(T) "GPa…. Young's Mod. for C1020 Steel"
E_y_9%NiSteel = Youngs_Modulus_9%Ni_Steel(T) "GPa…. Young's Mod. for 9% Ni Steel"

Results:

Unit Settings: SI K MPa J mass deg

$E_{y,9\%NiSteel}$ = 212.9 [GPa]	$E_{y,AL2024T4}$ = 87.2 [GPa]
$E_{y,BeCu}$ = 132.4 [GPa]	$E_{y,C1020Steel}$ = 218.8 [GPa]
$E_{y,KMonel}$ = 191.8 [GPa]	$E_{y,SS304}$ = 198.8 [GPa]
$E_{y,Titanium}$ = 117.8 [GPa]	T = 20 [K]

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Thus:

Young's Modulus values at 20 K:

For Aluminium 2024-T4: 87.2 GPa … Ans.

For SS 304: 198.8 GPa … Ans.

For Beryllium copper: 132.4 GPa … Ans.

For K Monel: 191.8 GPa … Ans.

For Titanium: 117.8 GPa … Ans.

For C1020 Steel: 218.8 GPa … Ans.

For 9% Ni Steel: 212.9 GPa … Ans.

===

Prob.2.2.15 Using the above written EES Functions, determine Young's Modulus, Bulk Modulus and Shear Modulus at 20 K for: (i) AL-2024-T (ii) SS 304 (iii) Beryllium copper (iv) Titanium

(b) Plot the variation of Bulk Modulus and Shear Modulus for these materials as the temp varies from 5 K to 300 K.

EES Solution:

"Data:"

T = 25 "K"

nu_AL = 0.32 "Poisson's rtio for AL2024-T4"
nu_SS304 = 0.305 "Poisson's rtio for SS 304"
nu_Titanium = 0.32 "Poisson's rtio for Titanium"
nu_BeCu = 0.285 "Poisson's rtio for BeCu"

"Calculations:"

"Young's Moduli:"

E_y_AL2024T4 = Youngs_Modulus_AL_2024_T4(T) "GPa…. Young's Mod. for AL-2024-T4"
E_y_SS304 = Youngs_Modulus_SS304(T) "GPa…. Young's Mod. for SS304"
E_y_BeCu = Youngs_Modulus_BeCu(T) "GPa…. Young's Mod. for BeCu"
E_y_Titanium = Youngs_Modulus_Titanium(T) "GPa…. Young's Mod. for Titanium"

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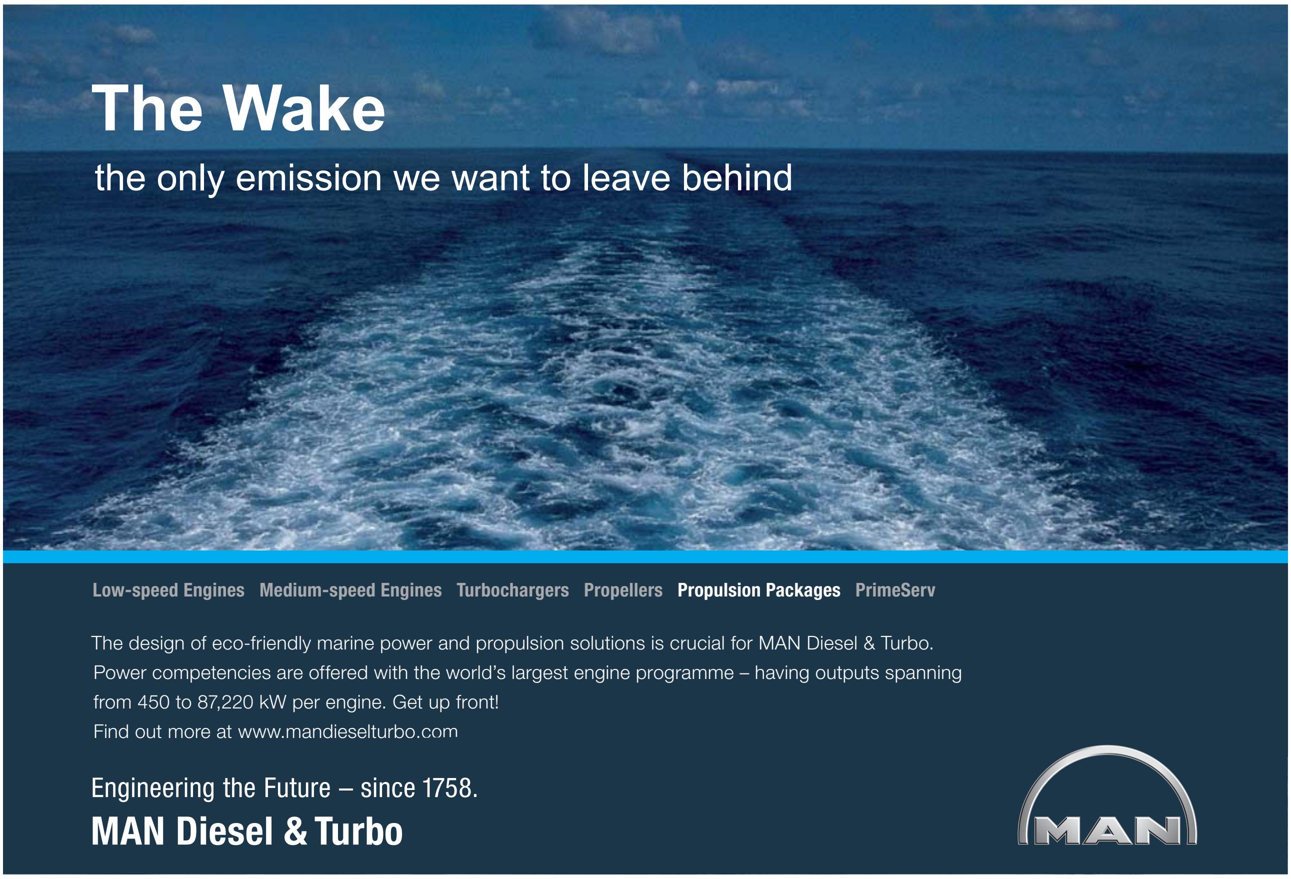
"Bulk Moduli:"

B_AL2024T4 = E_y_AL2024T4 / (3 * (1 – 2 * nu_AL)) "GPa…. Bulk Mod. for AL-2024-T4"
B_SS304 = E_y_SS304 / (3 * (1 – 2 * nu_SS304)) "GPa…. Bulk Mod. for SS 304"
B_Titanium = E_y_Titanium / (3 * (1 – 2 * nu_Titanium)) "GPa…. Bulk Mod. for Titanium"
B_BeCu = E_y_BeCu / (3 * (1 – 2 * nu_BeCu)) "GPa…. Bulk Mod. for BeCu"

"Shear Moduli:"

G_AL2024T4 = E_y_AL2024T4 / (2 * (1+ nu_AL)) "GPa…. Shear Mod. for AL-2024-T4"
G_SS304 = E_y_SS304 / (2 * (1 + nu_SS304)) "GPa…. Shear Mod. for SS 304"
G_Titanium = E_y_Titanium / (2 * (1+ nu_Titanium)) "GPa…. Shear Mod. for Titanium"
G_BeCu = E_y_BeCu / (2 * (1+ nu_BeCu)) "GPa…. Shear Mod. for BeCu"



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Results:

Unit Settings: SI K MPa J mass deg

$B_{AL2024T4}$ = 80.41 [GPa]	B_{BeCu} = 102.5 [GPa]	B_{SS304} = 169.4 [GPa]
$B_{Titanium}$ = 108.9 [GPa]	$E_{y,AL2024T4}$ = 86.84 [GPa]	$E_{y,BeCu}$ = 132.2 [GPa]
$E_{y,SS304}$ = 198.2 [GPa]	$E_{y,Titanium}$ = 117.6 [GPa]	$G_{AL2024T4}$ = 32.89 [GPa]
G_{BeCu} = 51.43 [GPa]	G_{SS304} = 75.92 [GPa]	$G_{Titanium}$ = 44.55 [GPa]
ν_{AL} = 0.32	ν_{BeCu} = 0.285	ν_{SS304} = 0.305
$\nu_{Titanium}$ = 0.32	T = 25 [K]	

Thus, at 25 K:

Young's Modulus (E_y):

For AL-2024-T4 = 86.84 GPa … Ans.
For SS 304 = 198.2 GPa … Ans.
For Titanium = 117.6 GPa … Ans.
For BeCu = 132.2 GPa … Ans.

Bulk Modulus (B):

For AL-2024-T4 = 80.41 GPa … Ans.
For SS 304 = 169.4 GPa … Ans.
For Titanium = 108.9 GPa … Ans.
For BeCu = 102.5 GPa … Ans.

Shear Modulus (G):

For AL-2024-T4 = 32.89 GPa … Ans.
For SS 304 = 75.92 GPa … Ans.
For Titanium = 44.559 GPa … Ans.
For BeCu = 51.43 GPa … Ans.

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(b) Plot the variation of Bulk Modulus and Shear Modulus for these materials as the temp varies from 5 K to 300 K:

First, compute the Parametric Table:

1..16	T [K]	$E_{y,AL2024T4}$ [GPa]	$E_{y,SS304}$ [GPa]	$E_{y,BeCu}$ [GPa]	$E_{y,Titanium}$ [GPa]
Run 1	5	88.28	200.7	133.2	118.3
Run 2	20	87.2	198.8	132.4	117.8
Run 3	40	85.76	196.2	131.4	117.2
Run 4	60	84.31	193.6	130.5	116.7
Run 5	80	82.87	191	129.6	116.3
Run 6	100	81.45	188.4	128.6	115.9
Run 7	120	80.07	185.7	127.7	115.5
Run 8	140	78.73	183.1	126.8	115.1
Run 9	160	77.44	180.4	125.9	114.8
Run 10	180	76.23	177.8	125	114.3
Run 11	200	75.1	175.1	124.1	113.9
Run 12	220	74.06	172.5	123.2	113.4
Run 13	240	73.12	169.8	122.3	113
Run 14	260	72.29	167.2	121.4	112.4
Run 15	280	71.6	164.5	120.4	111.9
Run 16	300	71.04	161.9	119.5	111.4

T [K]	$B_{AL2024T4}$ [GPa]	B_{SS304} [GPa]	B_{BeCu} [GPa]	$B_{Titanium}$ [GPa]
5	81.74	171.6	103.2	109.5
20	80.74	169.9	102.6	109
40	79.4	167.7	101.9	108.5
60	78.06	165.5	101.2	108.1
80	76.73	163.2	100.4	107.7
100	75.42	161	99.72	107.3
120	74.13	158.7	99.01	107
140	72.89	156.5	98.3	106.6
160	71.71	154.2	97.6	106.3
180	70.58	152	96.9	105.9
200	69.53	149.7	96.2	105.5
220	68.57	147.4	95.49	105
240	67.7	145.1	94.79	104.6
260	66.94	142.9	94.08	104.1
280	66.3	140.6	93.36	103.6
300	65.78	138.4	92.64	103.1

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T [K]	$G_{AL2024T4}$ [GPa]	G_{SS304} [GPa]	G_{BeCu} [GPa]	$G_{Titanium}$ [GPa]
5	33.44	76.91	51.81	44.8
20	33.03	76.17	51.52	44.61
40	32.48	75.18	51.15	44.39
60	31.93	74.18	50.78	44.21
80	31.39	73.18	50.41	44.05
100	30.85	72.17	50.05	43.9
120	30.33	71.16	49.7	43.76
140	29.82	70.15	49.34	43.61
160	29.33	69.14	48.99	43.47
180	28.88	68.12	48.64	43.31
200	28.45	67.1	48.29	43.15
220	28.05	66.08	47.93	42.97
240	27.7	65.07	47.58	42.79
260	27.38	64.05	47.22	42.59
280	27.12	63.04	46.86	42.39
300	26.91	62.02	46.5	42.19

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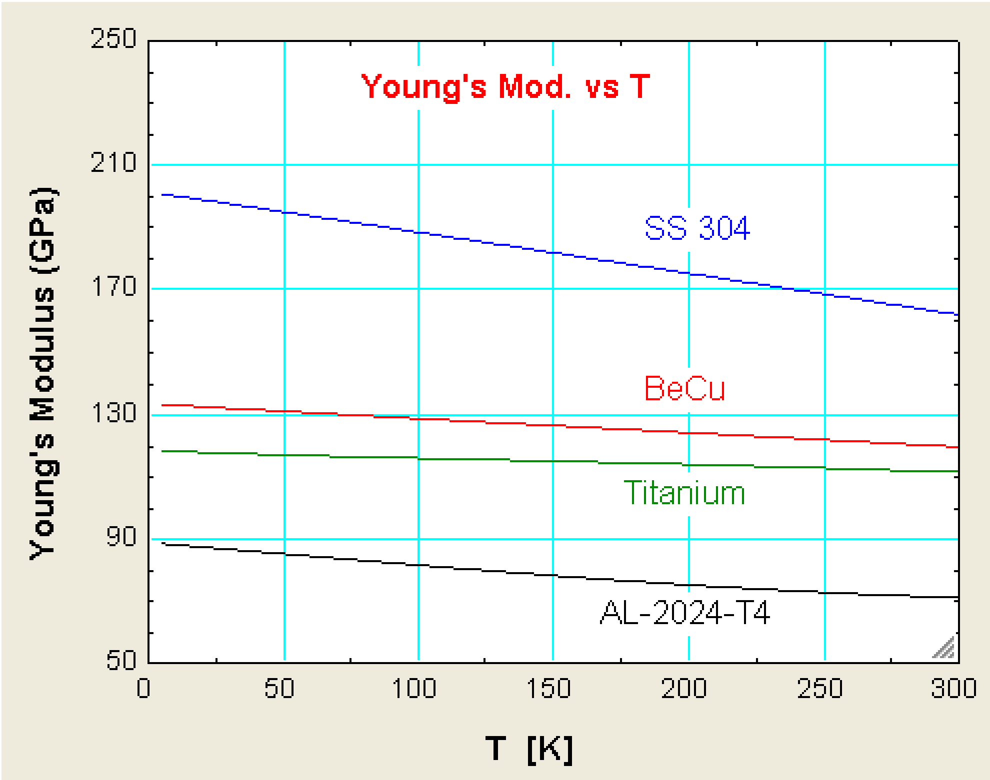

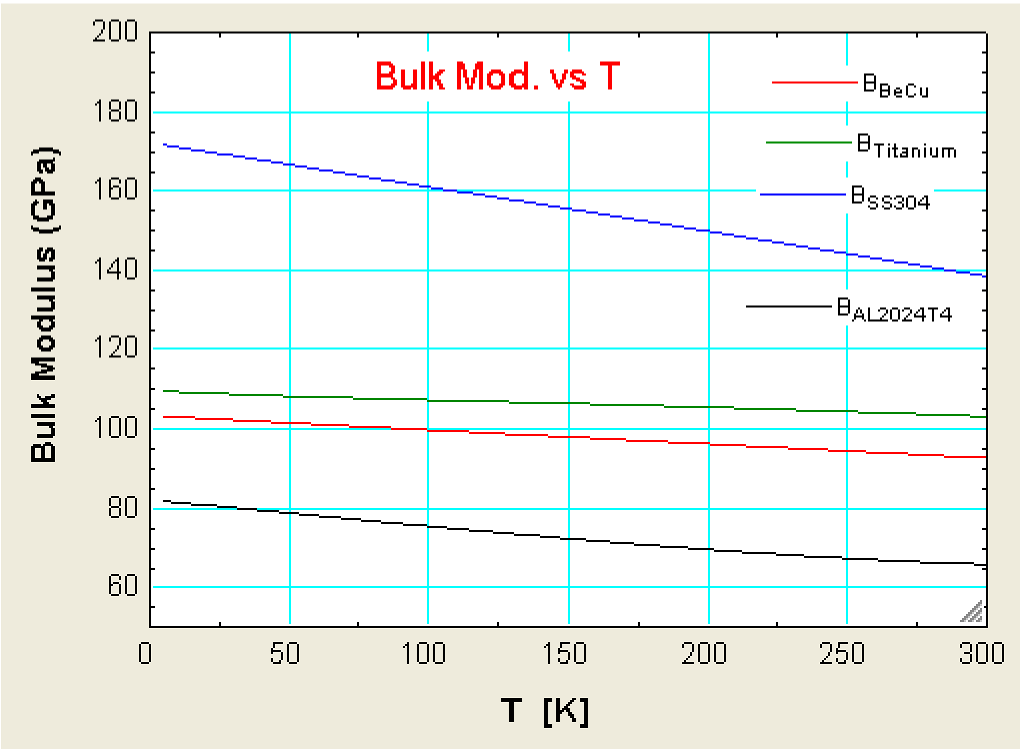

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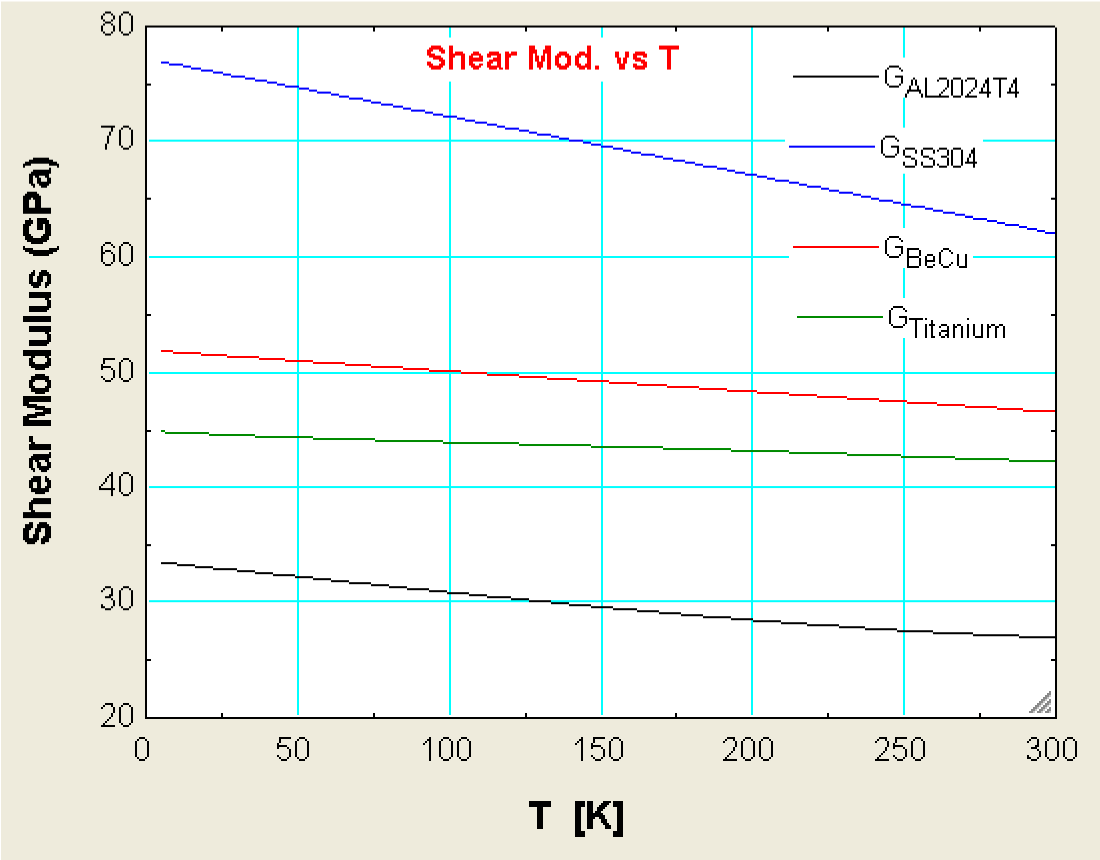

==

"**Prob.2.2.16** An air core magnet is used to produce a field of 100,000 Gauss and is constructed of 10,000 turns of Aluminium wire having a total electric resistance of 25 ohms at 0 C. The length of the solenoid is 50 cm, and the solenoid may be assumed to be an ideal coil, for which magnetic field strength is given by: H = 0.4 * pi * N * I / L, where N = total no. of turns, I is the current in Amps, and L is the length of solenoid in cm. Determine the power dissipated at 0 C and the power dissipated if the coil were immersed in liquid hydrogen at 20 K, for the same field strength. [1]"

EES Solution:

"Data:"

H = 100000"Gauss…. field strength"
N = 10000"…no. of turns"
L = 50 "cm….length of solenoid"
R_0C = 25"Ohms …. resistance of wire at 0 C"

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"Calculations:"

H = 0.4 * pi * N * I / L "…finds current I, Amps"

"At 20 K, we have the resistivity ratio, from the graph:"

R_20K / R_0C = 0.04 "..finds electrical resistance R_20K (Ohms) at 20 K"

"At 0 C, power dissipated, P_0C:"

P_0C = I^2 * R_0C "W…power dissip. at 0 C"

"At 20 K, power dissipated, P_20K, for the same current, I:"

P_20K = I^2 * R_20K "W…power dissip. at 20 K, for the same current, I"

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Results:

Unit Settings: SI K MPa J mass deg

H = 100,000 [Gauss]	I = 397.9 [A]	L = 50 [cm]	N = 10,000
P_{0C} = 3.958E+06 [W]	P_{20K} = 158,314 [W]	R_{0C} = 25 [Ω]	R_{20K} = 1 [Ω]

Thus:

Power dissipated at 0 C = P_0C = 3958 kW …. Ans.

Power dissipated at 20 K, for the same field = P_20K = 158.314 kW … Ans.

==

"**Prob.2.2.17** Determine the threshold field strength for Lead at 4 K, assuming that the parabolic rule for transition curve is valid."

EES Solution:

From the Table given under the section on Superconductivity above, we have, for Lead:

T0 = 7.2 K, Ho = 80.3 mT = 803 Gauss.

Then, we have:

"Data:"

T_0 = 7.2"K"
H_0 = 803"Gauss"

T = 4"K"

"Calculations:"

"Parabolic rule:"

H_T = H_0 * (1 – (T/T_0)^2) "….finds H_T, i.e. threshold field at T = 4 K, (Gauss)"

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Results:

Unit Settings: SI K MPa J mass deg

H_0 = 803 [Gauss] | H_T = 555.2 [Gauss] | T = 4 [K] | T_0 = 7.2 [K]

Thus:

Threshold field for Lead at 4 K = 555.2 Gauss … Ans.

==

"**Prob.2.2.18** Determine the threshold current for a Tantalum wire at 3.3 K, assuming that the parabolic rule for transition curve is valid. Wire dia is 1.25 mm [1]"

EES Solution:

From the Table given under the section on Superconductivity above, we have, for Tantalum:

T_0 = 4.5 K, H_0 = 83 mT = 830 Gauss.

Then, we have:

"Data:"

T_0 = 4.5"K"
H_0 = 830"Gauss"

T = 3.3"K"

d = 0.125 "cm"

"Calculations:"

"Parabolic rule:"

H_T = H_0 * (1 – (T/T_0)^2) "…finds H_T, i.e. threshold field at T = 3.3 K, (Gauss)"

"Threshold current at T(K):"

I_T = 2.5 * H_T * d "Amp…Note that d should be in cm when H_T is in Gauss"

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Results:

Unit Settings: SI K MPa J mass deg

$d = 0.125$ [cm] $H_0 = 830$ [Gauss] $H_T = 383.6$ [Gauss] $I_T = 119.9$ [A]

$T = 3.3$ [K] $T_0 = 4.5$ [K]

Thus:

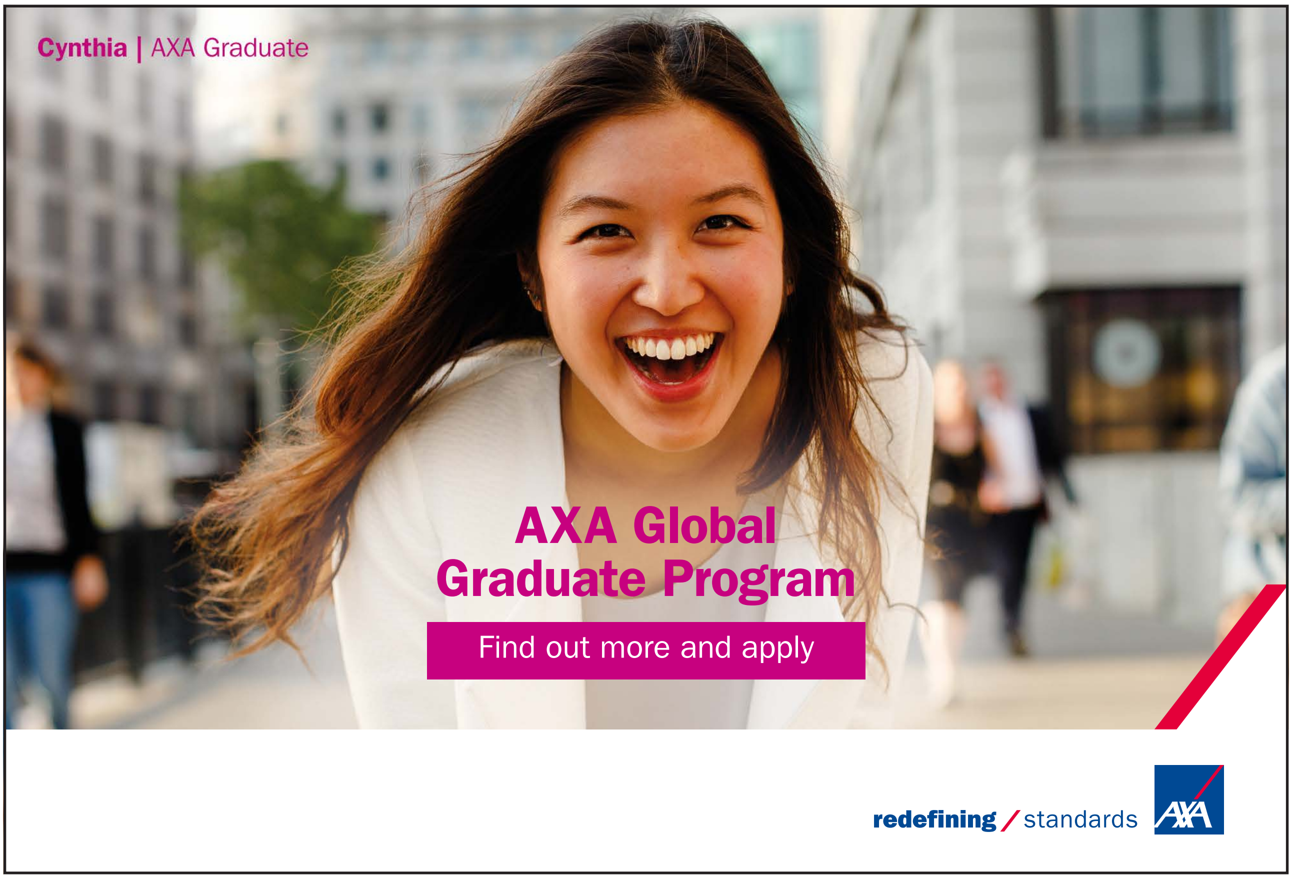
Threshold field for Tantalumat 3.3 K = 383.6 Gauss … Ans.

Threshold current for a wire of 0.125 cm dia = 119.9 Amp …Ans.

===

2.3 Problems solved with EXCEL:

Prob.2.3.1 Write EXCEL-VBA Functions to determine the thermal conductivities of SS-304L, OFHC copper, 6061- T6-Aluminium, Beryllium copper, SS-304, Brass, Invar, Lead, Nylon and Teflon and Pyrex using the data from Barron / NIST-Cryogenics website.



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EXCEL-VBA Functions:

For SS 304L:

```
Option Explicit

Function k_ss304L(T As Double) As Double
'gives th. cond. of SS304L as a function of T (K). Ref: NIST-Cryogenics.
'k in W/m.K, and,  T in K


Dim a As Double, b As Double, c As Double, d As Double
Dim e As Double, f As Double, g As Double, h As Double, i As Double


If T < 1 Or T > 300 Then

 MsgBox ("T must be between 1 K and 300 K !!")
 End
End If

a = -1.4087
b = 1.3982
c = 0.2543
d = -0.626
e = 0.2334
f = 0.4256
g = -0.4658
h = 0.165
i = -0.0199

k_ss304L = 10 ^ (a + b * (Log(T) / Log(10)) + c * (Log(T) / Log(10)) ^ 2 + _
d * (Log(T) / Log(10)) ^ 3 + _
e * (Log(T) / Log(10)) ^ 4 + f * (Log(T) / Log(10)) ^ 5 + _
g * (Log(T) / Log(10)) ^ 6 + h * (Log(T) / Log(10)) ^ 7 + i * (Log(T) / Log(10)) ^ 8)

End Function
```


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For OFHC copper:

```
Function k_OFHC_copper(T As Double) As Double
'gives th. cond. of OFHC copper as a function of T (K). Ref: NIST-Cryogenics.
'k in W/m.K, and,  T in K

Dim a As Double, b As Double, c As Double, d As Double
Dim e As Double, f As Double, g As Double, h As Double, i As Double

If T < 4 Or T > 300 Then

 MsgBox ("T must be between 4 K and 300 K !!")
 End
End If

a = 2.8075
b = -0.54074
c = -1.2777
d = 0.15362
e = 0.36444
f = -0.02105
g = -0.051727
h = 0.0012226
i = 0.0030964

k_OFHC_copper = 10 ^ ((a + c * T ^ 0.5 + e * T + g * T ^ 1.5 + i * T ^ 2) / (1 + _
b * T ^ 0.5 + d * T + f * T ^ 1.5 + h * T ^ 2))

End Function
```

For AL-6061-T6:

```
Function k_AL_6061_T6(T As Double) As Double
'gives th. cond. of AL_6061_T6 as a function of T (K). Ref: NIST-Cryogenics.
'k in W/m.K, and,  T in K

Dim a As Double, b As Double, c As Double, d As Double
Dim e As Double, f As Double, g As Double, h As Double, i As Double

If T < 1 Or T > 300 Then

 MsgBox ("T must be between 1 K and 300 K !!")
 End
End If

a = 0.07918
b = 1.0957
c = -0.07277
d = 0.08084
e = 0.02803
f = -0.09464
g = 0.04179
h = -0.00571
i = 0#

k_AL_6061_T6 = 10 ^ (a + b * (Log(T) / Log(10)) + c * (Log(T) / Log(10)) ^ 2 + d * (Log(T) / _
Log(10)) ^ 3 + e * (Log(T) / Log(10)) ^ 4 + f * (Log(T) / Log(10)) ^ 5 + g * (Log(T) / _
Log(10)) ^ 6 + h * (Log(T) / Log(10)) ^ 7 + i * (Log(T) / Log(10)) ^ 8)

End Function
```


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For Beryllium copper:

We have the graph from Barron [1]:

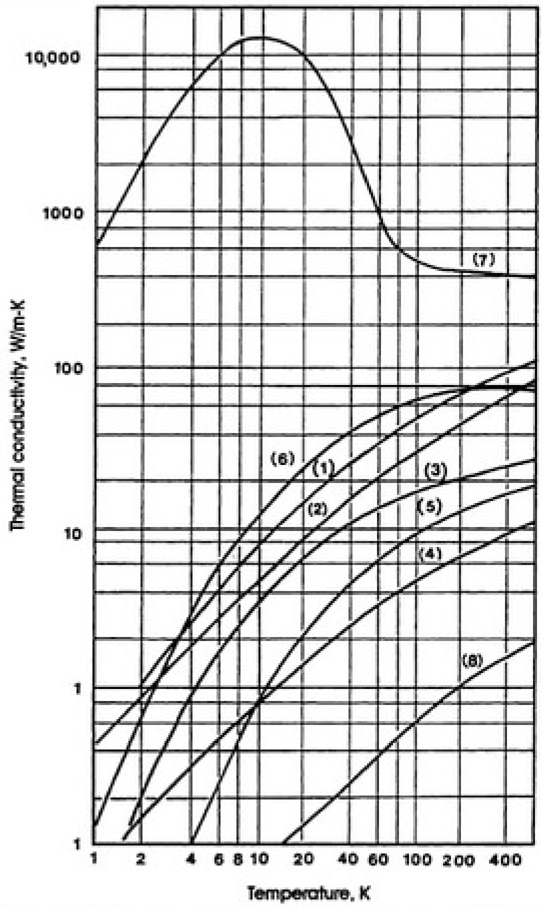

Figure 1-4 Thermal conductivity of solids at low temperatures: (1) 2024-T4 aluminum; (2) beryllium copper; (3) K Monel; (4) titanium; (5) 304 stainless steel; (6) C1020 carbon steel; (7) pure copper, single crystal; (8) Teflon (Stewart and Johnson 1961).

Curve no. 2 in the above fig. is for BeCu.

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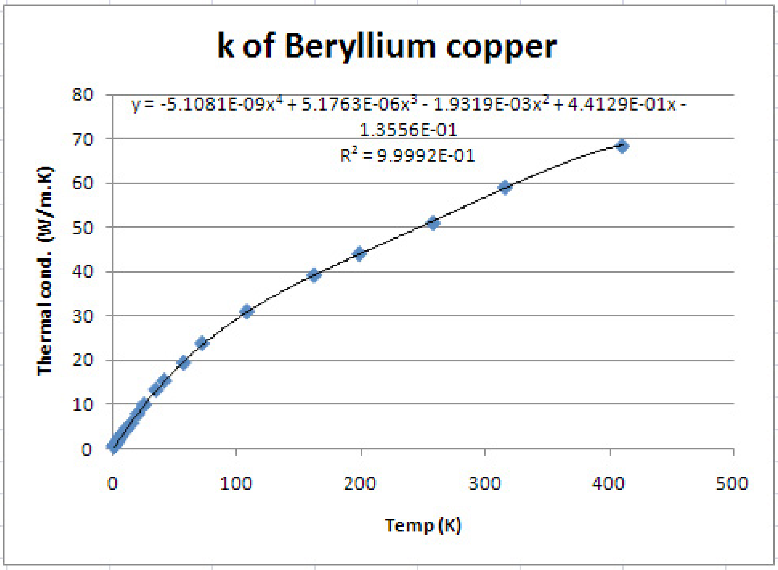
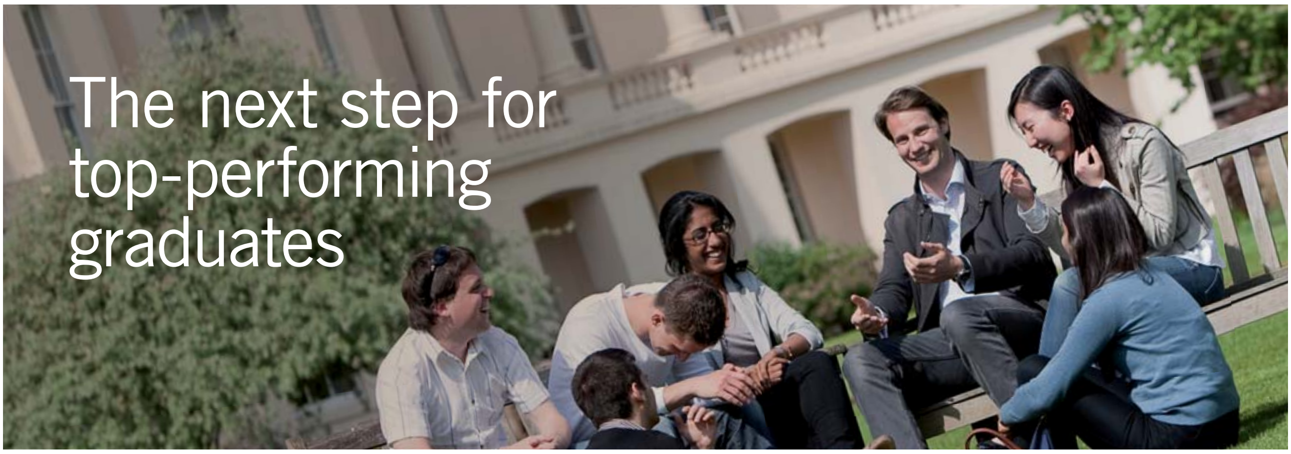
It is digitized with the Java based free Plot Digitizer. (Ref: http://plotdigitizer.sourceforge.net) and then curve fitted with EXCEL:

Th. cond of BeCu (Ref: Barron):	
T(K)	K (W/m.K)
0.993106	0.4171
1.447596	0.543202
1.823986	0.74936
2.581783	1.034345
3.653385	1.513409
4.740489	1.96984
6.150204	2.639755
8.21577	3.436369
11.29895	4.474015
15.09587	5.656863
20.16018	7.805986
25.41279	9.866953
34.94466	13.22631
41.57771	15.3143
57.1889	19.36586
72.0993	23.77575
108.1967	30.96821
162.3897	39.17781
198.9439	44.06585
258.2876	51.04404
316.3839	59.11055
410.7593	68.47118





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Now, write the VBA Function for k of BeCu:

```
Function k_BeCu(T As Double) As Double
'gives th. cond. of Beryllium copper as a function of T (K). Ref: Graphs from Barron [1].
'Digitized, curve-fitted in EXCEL.
'k in W/m.K, and,  T in K

If T < 1 Or T > 410 Then

 MsgBox ("T must be between 1 K and 410 K !!")
 End
End If

k_BeCu = -0.0000000051081 * T ^ 4 + 0.0000051763 * T ^ 3 - 0.0019319 * T ^ 2 + _
0.44129 * T - 0.13556

End Function
```

For SS 304:

We have, the equation from NIST-cryogenics, and we write the VBA Function:

```
Function k_SS304(T As Double) As Double
'gives th. cond. of SS304 as a function of T (K). Ref: NIST-Cryogenics.
'k in W/m.K, and,  T in K

Dim a As Double, b As Double, c As Double, d As Double
Dim e As Double, f As Double, g As Double, h As Double, i As Double

If T < 1 Or T > 300 Then

 MsgBox ("T must be between 1 K and 300 K !!")
 End
End If

a = -1.4087
b = 1.3982
c = 0.2543
d = -0.626
e = 0.2334
f = 0.4256
g = -0.4658
h = 0.165
i = -0.0199

k_SS304 = 10 ^ (a + b * (Log(T) / Log(10)) + c * (Log(T) / Log(10)) ^ 2 + d * (Log(T) / _
Log(10)) ^ 3 + e * (Log(T) / Log(10)) ^ 4 + f * (Log(T) / Log(10)) ^ 5 + g * (Log(T) / _
Log(10)) ^ 6 + h * (Log(T) / Log(10)) ^ 7 + i * (Log(T) / Log(10)) ^ 8)

End Function
```


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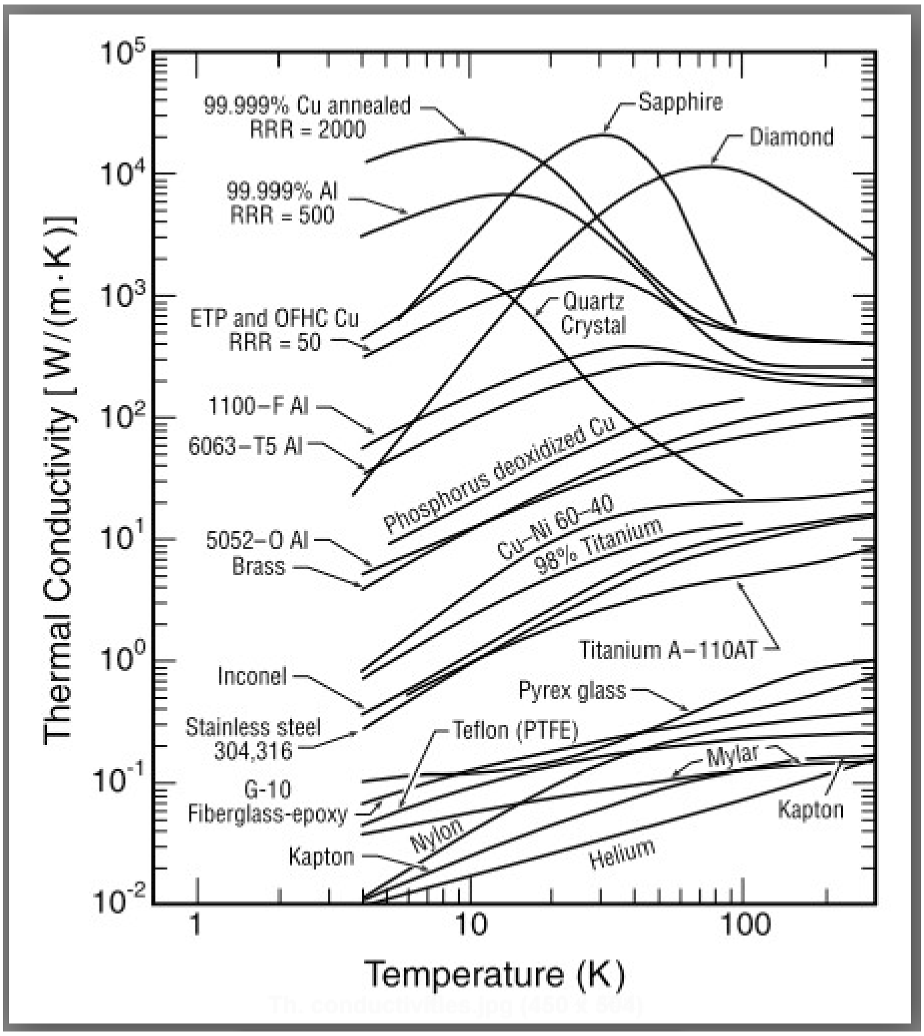
For Brass:

We have the graph from Ref.[9]:



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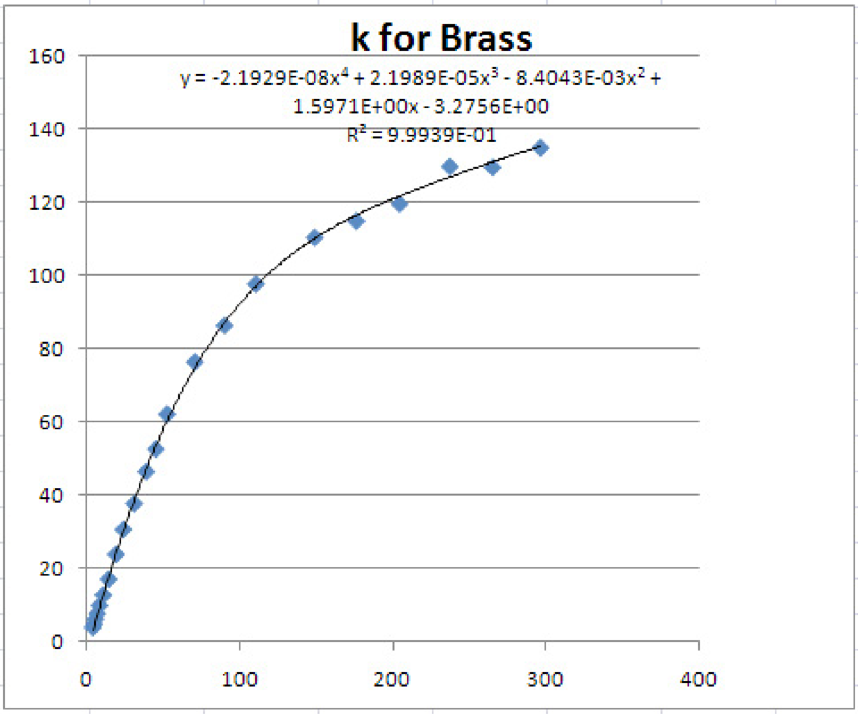
Digitize the curve for Brass and curve fit in EXCEL:



k For Brass	
T(K)	k(W/m.
4.175603	4.02279
5.031142	4.95132
5.841571	6.3595
7.03845	7.82748
8.640631	10.0455
11.00907	12.8850
14.55947	17.2280
19.25719	24.025
24.08406	30.8245
31.25726	37.8977
39.08726	46.6196
45.36705	52.7772
52.66214	62.3162
70.93435	76.5737
90.34502	86.5689
110.8702	97.9225
149.3028	110.613
176.4967	115.083
204.8032	119.767
237.6783	129.998
265.7054	129.784

Now, write the VBA Function for k of Brass:

```
Function k_Brass(T As Double) As Double
'gives th. cond. of SS-304 as a function of T (K). Ref: Graphs from Van Sciever.
'Digitized, curve-fitted in EXCEL.
'k in W/m.K, and,  T in K

If T < 4 Or T > 300 Then
|
 MsgBox ("T must be between 4 K and 300 K !!")
 End
End If

k_Brass = -0.000000021929 * T ^ 4 + 0.000021989 * T ^ 3 - 0.0084043 * T ^ 2 + _
1.5971 * T - 3.2756

End Function
```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For Invar:

```
Function k_Invar(T As Double) As Double
'gives th. cond. of Invar as a function of T (K). Ref: NIST-Cryogenics.
'k in W/m.K, and,  T in K


Dim a As Double, b As Double, c As Double, d As Double
Dim e As Double, f As Double, g As Double, h As Double, i As Double


If T < 4 Or T > 300 Then

 MsgBox ("T must be between 4 K and 300 K !!")
 End
End If

a = -2.7064
b = 8.5191
c = -15.923
d = 18.276
e = -11.9116
f = 4.40318
g = -0.86018
h = 0.068508
i = 0

k_Invar = 10 ^ (a + b * (Log(T) / Log(10)) + c * (Log(T) / Log(10)) ^ 2 + d * (Log(T) / _
Log(10)) ^ 3 + e * (Log(T) / Log(10)) ^ 4 + f * (Log(T) / Log(10)) ^ 5 + g * (Log(T) / _
Log(10)) ^ 6 + h * (Log(T) / Log(10)) ^ 7 + i * (Log(T) / Log(10)) ^ 8)

End Function
```

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For Lead:

```
Function k_Lead(T As Double) As Double
'gives th. cond. of Lead as a function of T (K). Ref: NIST-Cryogenics.
'k in W/m.K, and,  T in K


Dim a As Double, b As Double, c As Double, d As Double
Dim e As Double, f As Double, g As Double, h As Double, i As Double


If T < 5 Or T > 295 Then

 MsgBox ("T must be between 5 K and 295 K !!")
 End
End If

a = 38.963479
b = -221.40505
c = 597.56622
d = -900.93831
e = 816.40461
f = -455.08342
g = 152.94025
h = -28.451163
i = 2.2516244

k_Lead = 10 ^ (a + b * (Log(T) / Log(10)) + c * (Log(T) / Log(10)) ^ 2 + d * (Log(T) / _
Log(10)) ^ 3 + e * (Log(T) / Log(10)) ^ 4 + f * (Log(T) / Log(10)) ^ 5 + g * (Log(T) / _
Log(10)) ^ 6 + h * (Log(T) / Log(10)) ^ 7 + i * (Log(T) / Log(10)) ^ 8)

End Function
```

For Nylon:

```
Function k_Nylon(T As Double) As Double
'gives th. cond. of Nylon as a function of T (K). Ref: NIST-Cryogenics.
'k in W/m.K, and,  T in K


Dim a As Double, b As Double, c As Double, d As Double
Dim e As Double, f As Double, g As Double, h As Double, i As Double


If T < 1 Or T > 300 Then

 MsgBox ("T must be between 1 K and 300 K !!")
 End
End If

a = -2.6135
b = 2.3239
c = -4.7586
d = 7.1602
e = -4.9155
f = 1.6324
g = -0.2507
h = 0.0131
i = 0

k_Nylon = 10 ^ (a + b * (Log(T) / Log(10)) + c * (Log(T) / Log(10)) ^ 2 + d * (Log(T) / _
Log(10)) ^ 3 + e * (Log(T) / Log(10)) ^ 4 + f * (Log(T) / Log(10)) ^ 5 + g * (Log(T) / _
Log(10)) ^ 6 + h * (Log(T) / Log(10)) ^ 7 + i * (Log(T) / Log(10)) ^ 8)

End Function
```


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For Teflon:

```
Function k_Teflon(T As Double) As Double
'gives th. cond. of Teflon as a function of T (K). Ref: NIST-Cryogenics.
'k in W/m.K, and,  T in K


Dim a As Double, b As Double, c As Double, d As Double
Dim e As Double, f As Double, g As Double, h As Double, i As Double


If T < 4 Or T > 300 Then

 MsgBox ("T must be between 4 K and 300 K !!")
 End
End If

a = 2.738
b = -30.677
c = 89.43
d = -136.99
e = 124.69
f = -69.556
g = 23.32
h = -4.3135
i = 0.33829

k_Teflon = 10 ^ (a + b * (Log(T) / Log(10)) + c * (Log(T) / Log(10)) ^ 2 + d * (Log(T) / _
Log(10)) ^ 3 + e * (Log(T) / Log(10)) ^ 4 + f * (Log(T) / Log(10)) ^ 5 + g * (Log(T) / _
Log(10)) ^ 6 + h * (Log(T) / Log(10)) ^ 7 + i * (Log(T) / Log(10)) ^ 8)

End Function
```

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For Pyrex glass:

Using the graph from Ref. [9], curve for Pyrex glass is digitized, and we get the following Table of k vs T:

	A	B	C
97		T(K)	k_Pyrex(W/m.K)
98		3.974	0.105
99		4.546	0.1091
100		5.379	0.1133
101		6.154	0.1133
102		6.808	0.1176
103		7.921	0.1176
104		9.062	0.1176
105		11.09	0.1222
106		13.12	0.1269
107		15.01	0.1318
108		17.76	0.1369
109		20.67	0.1534
110		24.05	0.1655
111		27.05	0.1786
112		31.47	0.2001
113		35.41	0.2242
114		39.83	0.2512
115		46.35	0.271
116		52.14	0.3154
117		57.68	0.3534
118		60.67	0.367
119		70.58	0.4113
120		76.78	0.4437
121		84.93	0.4786
122		97.17	0.557
123		120.9	0.6483
124		136	0.7264
125		150.5	0.7545
126		169.3	0.8139
127		190.5	0.8781
128		237	0.9473
129		253.5	0.9839
130		295	1.022
131		300	1.022

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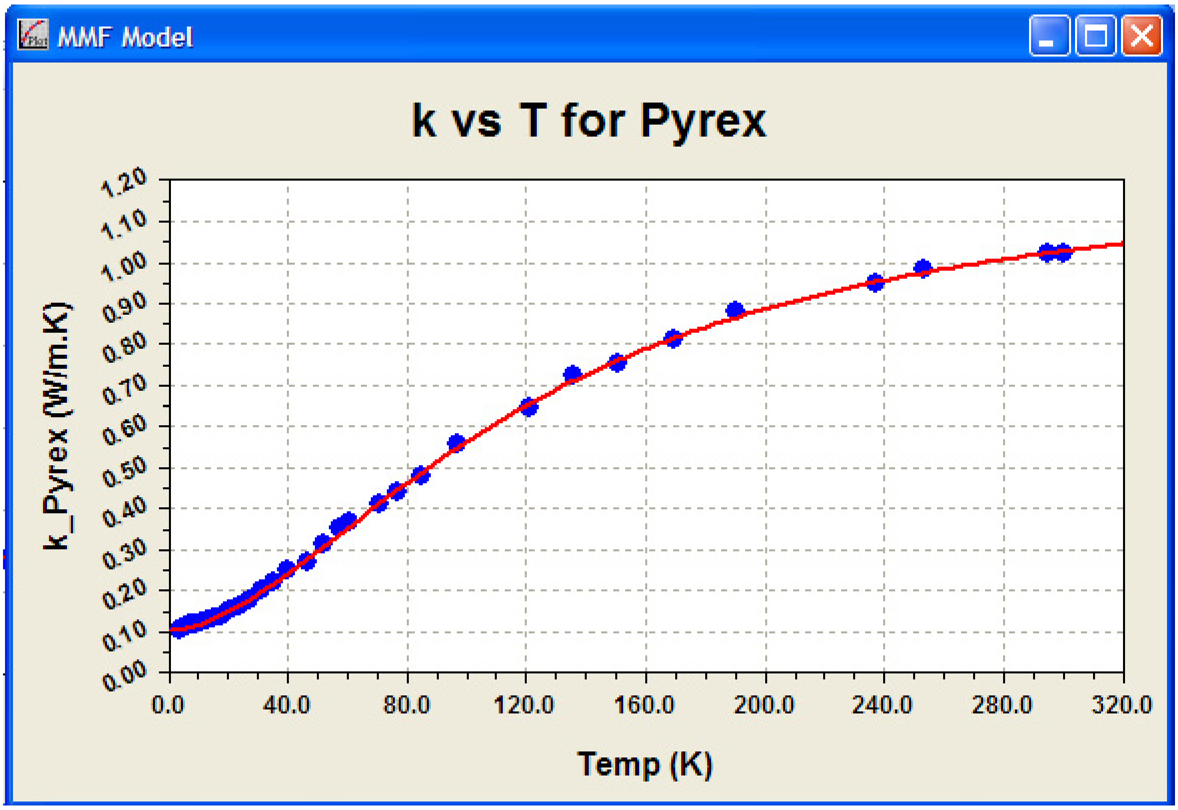
Now, the above data is curve fitted with 'Curve Expert':



And, the curve fit equation is:

k = (a*b+c*T^d)/(b+T^d), where

a =	0.10576279
b =	4300.1909
c =	1.2216365
d =	1.7397766

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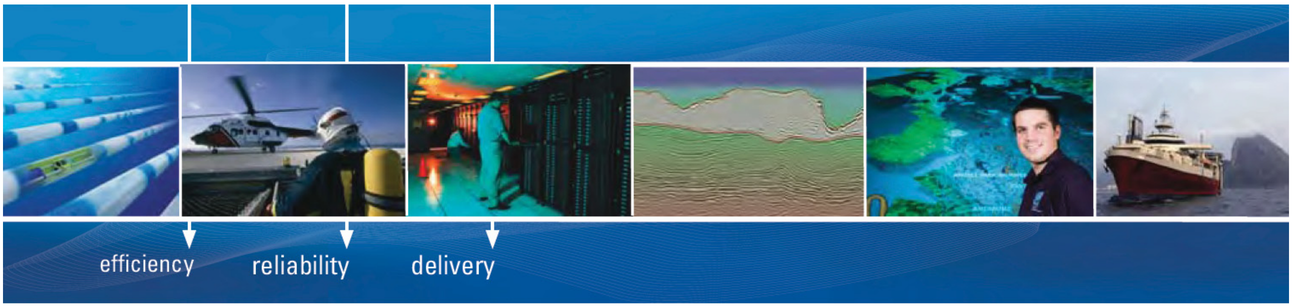
Now, write the VBA Function for k as a function of T:

```
Function k_Pyrex(T As Double) As Double
'gives th. cond. of Pyrex glass as a function of T (K). Ref: Graphs from Ref.[9].
'Digitized, curve-fitted in 'Curve Expert'.
'k in W/m.K, and,  T in K

Dim a As Double, b As Double, c As Double, d As Double

a = 0.10576279
b = 4300.1909
c = 1.2216365
d = 1.7397766

If T < 4 Or T > 300 Then

 MsgBox ("T must be between 4 K and 300 K !!")
 End
End If

k_Pyrex = (a * b + c * T ^ d) / (b + T ^ d)

End Function
```

Prob.2.3.2 Using the above written EXCEL-VBA Functions for the thermal conductivities of SS-304L, OFHC copper, 6061- T6-Aluminium, Beryllium copper, SS-304, Brass, Invar, Lead, Nylon, Teflon and Pyrex, determine the thermal conductivities of these materials at 80 K.



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Solution:

When these Functions are written in EXCEL VBA, they are available for use in the 'User defined' category of EXCEL Functions.

Following is the worksheet which gives thermal cond. values of these materials at 80 K:

D4 f_x =k_ss304L(80)

	B	C	D
1			
2			
3		Material	k at 80 K (W/m.K)
4		SS304L	8.114
5		OFHC Cu	558.037
6		6061_AL_T6	85.561
7		BeCu	25.245
8		SS304	8.114
9		Brass	81.065
10		SS304	8.114
11		Invar	6.386
12		Lead	36.981
13		Nylon	0.297
14		Teflon	0.234
15		Pyrex	0.466

Note that the Formula entered in cell D4 can be seen in the Formula bar; similarly the formulas for other materials are entered in cells D5 to D15.

Prob.2.3.3 Write EXCEL-VBA Functions for the thermal conductivity integrals for SS-304, OFHC copper, 6061- T6-Aluminium, Beryllium copper, SS-304L, Brass, Invar, Lead, Nylon and Teflon and Pyrex, between temperatures Tmin and Tmax.

Solution:

Thermal conductivity integrals are useful to calculate the heat loss through the necks of Dewars or Cryostats when the temperatures vary from a low temperature Tmin to a higher temperature Tmax ,and the thermal conductivity also varies with temperature.

If the area of cross-section is A (m^2) and length, L (m), and k (W/m.K) is given as function of T, we have the heat transfer Q given by:

$$Q = \left(\frac{A}{L}\right) * \int_{Tmin}^{Tmax} k(T) * dT \qquad \mathbf{W}$$

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Quantity within the Integral can be calculated for various materials of interest, if the relation between k and T are known.

Since we have already written VBA Functions for thermal conductivities of these materials as functions of T, now it is easy to calculate the thermal cond. integrals.

There are two cases: (i) thermal conductivities as function of T are presented in a tabular form, or (ii) thermal conductivities as functions of T are given in a formula.

Methods of calculating thermal conductivity integrals for both these cases in EXCEL-VBA are now explained:

Remember that integral $\int k(T).dT$ is the area under the curve of k vs T. Numerical method of calculating this area is to divide the area in to a large no. of sub-areas of trapezoidal shape and sum the areas of each trapezoid.

Case 1: Thermal conductivity integral when k vs T is given in a Tabular form:

We write a general VBA Function to calculate the area when the range of x-values and the range of y-values are given:

```
Function Function_Integral_T(x_values, y_values) As Double

'gives Function integral, when function is given as Table. Ref: Walkenbach.

'Uses Trapezoidal method to find the integral from Table values

Dim area As Double
Dim N1 As Integer, J As Integer

area = 0

N1 = y_values.Count
For J = 2 To N1
  area = area + (x_values(J) - x_values(J - 1)) * (y_values(J) + y_values(J - 1)) / 2
Next J

Function_Integral_T = area

End Function
```

Above simple Function has two inputs: x-values range and y-values range. It calculates the Integral by summing up the areas of trapezoids.

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As an example, let us say that the values of k vs T are given for SS 304 in a Tabular form as follows:

E18 | f_x =k_SS304(D18)

	A	B	C	D	E
16				**Th cond vs T for SS304:**	
17				T_values	k_values
18				20	2.168622
19				25	2.825386
20				30	3.468573
21				35	4.085846
22				40	4.670281
23				45	5.21865
24				50	5.730167
25				55	6.205596
26				60	6.646641
27				65	7.055534
28				70	7.434752
29				75	7.786845
30				80	8.114319

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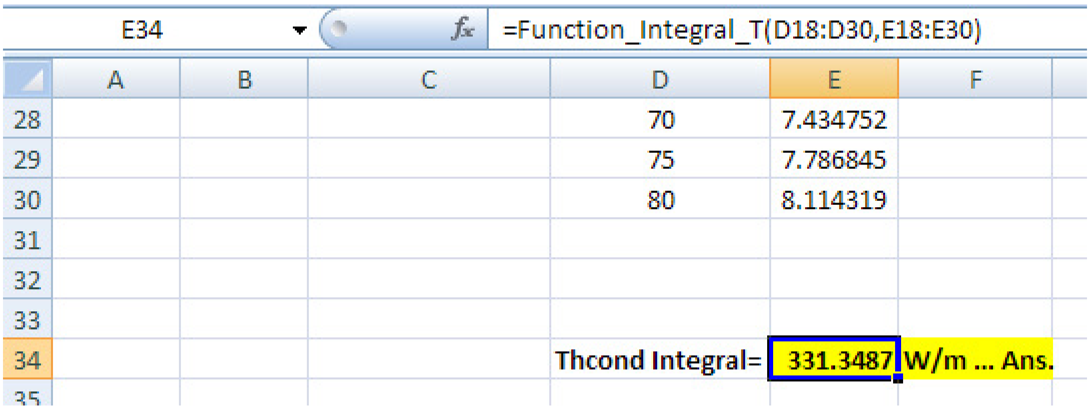
Now, use the above written Function to find out thermal cond. integral between 20 K and 80 K for SS 304:



E34 =Function_Integral_T(D18:D30,E18:E30)

	A	B	C	D	E	F
28				70	7.434752	
29				75	7.786845	
30				80	8.114319	
31						
32						
33						
34				Thcond Integral=	331.3487	W/m ... Ans.
35						

In cell E34 the Function is used; see the Formula bar and observe the range of x-values and y-values. The result is **331.3487 W/m.**

Note: Accuracy of calculated value obviously depends on the number of trapezoids. i.e. the increment in value of T. Here, we have used ΔT = 5 deg. If we use ΔT = 1 deg., the accuracy will be better.

Case 2: Thermal conductivity integral when k vs T is given in a Functional form:

Here, we write a VBA Function which has a flexibility to change the number of sub-divisions (or trapezoids).

For SS 304:

```
Function ThCondIntegral_SS304(Tmin As Double, Tmax As Double, N As Integer) As Double

'Finds Th. cond. integral by Trapezoidal rule
'Tmin, Tmax are temps in K, N is the no. of trapezoidal divisions
'Ref: Excel Scientific and Engineering Cookbook by David M. Bourg

    Dim dx As Double, i As Integer
    Dim sum As Double
    Dim y As Double

    dx = (Tmax - Tmin) / N

    sum = (k_SS304(Tmin) + k_SS304(Tmax)) / 2#

    For i = 1 To (N - 1)
        y = k_SS304(Tmin + (dx * i))
        sum = sum + y
    Next i

    sum = sum * dx

    ThCondIntegral_SS304 = sum

End Function
```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In the above Function, Inputs are temp limits, Tmin and Tmax and no. of sub-divisions, N.

As an example of use of this Function, solve the problem solved earlier when k vs T was given in Tabular form, i.e. find the thermal conductivity integral for SS 304 between the temp limits of 5 K and 80 K:

E36 | fx | =ThCondIntegral_SS304(20,80,100)

	A	B	C	D	E	F
28				70	7.434752	
29				75	7.786845	
30				80	8.114319	
31						
32						
33						
34				**Thcond Integral=**	**331.3487**	**W/m ... Ans.**
35						
36				**By ThCondIntegral Function**	331.4892	W/m... Ans.

The Function is entered in cell E36, see the Formula bar. Note that we have used N = 100, i.e. 100 sub-divisions. And the values of thermal conductivity integrals obtained by both the methods are quite close.

If we use N = 500, we get:

E36 | fx | =ThCondIntegral_SS304(20,80,500)

	A	B	C	D	E	F
28				70	7.434752	
29				75	7.786845	
30				80	8.114319	
31						
32						
33						
34				**Thcond Integral=**	**331.3487**	**W/m ... Ans.**
35						
36				**By ThCondIntegral Function**	331.4912	W/m... Ans.

Answer in cell E36 is almost the same as obtained earlier with N = 100.

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Now, let us write VBA Functions for thermal conductivity integrals of other materials, viz. OFHC copper, 6061- T6-Aluminium, Beryllium copper, SS-304L, Brass, Invar, Lead, Nylon, Teflon and Pyrex, between temperatures Tmin and Tmax:

```
Function ThCondIntegral_OFHC_copper(Tmin As Double, Tmax As Double, N As Integer) As Double

'Finds Th. cond. integral by Trapezoidal rule
'Tmin, Tmax are temps in K, N is the no. of trapezoidal divisions
'Ref: Excel Scientific and Engineering Cookbook by David M. Bourg

    Dim dx As Double, i As Integer
    Dim sum As Double
    Dim y As Double

    dx = (Tmax - Tmin) / N

    sum = (k_OFHC_copper(Tmin) + k_OFHC_copper(Tmax)) / 2#

    For i = 1 To (N - 1)
        y = k_OFHC_copper(Tmin + (dx * i))
        sum = sum + y
    Next i

    sum = sum * dx

    ThCondIntegral_OFHC_copper = sum

End Function
```

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```
Function ThCondIntegral_AL_6061_T6(Tmin As Double, Tmax As Double, N As Integer) As Double

'Finds Th. cond. integral by Trapezoidal rule
'Tmin, Tmax are temps in K, N is the no. of trapezoidal divisions
'Ref: Excel Scientific and Engineering Cookbook by David M. Bourg

    Dim dx As Double, i As Integer
    Dim sum As Double
    Dim y As Double

    dx = (Tmax - Tmin) / N

    sum = (k_AL_6061_T6(Tmin) + k_AL_6061_T6(Tmax)) / 2#

    For i = 1 To (N - 1)
        y = k_AL_6061_T6(Tmin + (dx * i))
        sum = sum + y
    Next i

    sum = sum * dx

    ThCondIntegral_AL_6061_T6 = sum

End Function
```

```
Function ThCondIntegral_BeCu(Tmin As Double, Tmax As Double, N As Integer) As Double

'Finds Th. cond. integral by Trapezoidal rule
'Tmin, Tmax are temps in K, N is the no. of trapezoidal divisions
'Ref: Excel Scientific and Engineering Cookbook by David M. Bourg

    Dim dx As Double, i As Integer
    Dim sum As Double
    Dim y As Double

    dx = (Tmax - Tmin) / N

    sum = (k_BeCu(Tmin) + k_BeCu(Tmax)) / 2#

    For i = 1 To (N - 1)
        y = k_BeCu(Tmin + (dx * i))
        sum = sum + y
    Next i

    sum = sum * dx

    ThCondIntegral_BeCu = sum

End Function
```


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```
Function ThCondIntegral_SS304L(Tmin As Double, Tmax As Double, N As Integer) As Double

'Finds Th. cond. integral by Trapezoidal rule
'Tmin, Tmax are temps in K, N is the no. of trapezoidal divisions
'Ref: Excel Scientific and Engineering Cookbook by David M. Bourg

    Dim dx As Double, i As Integer
    Dim sum As Double
    Dim y As Double

    dx = (Tmax - Tmin) / N

    sum = (k_ss304L(Tmin) + k_ss304L(Tmax)) / 2#

    For i = 1 To (N - 1)
        y = k_ss304L(Tmin + (dx * i))
        sum = sum + y
    Next i

    sum = sum * dx

    ThCondIntegral_SS304L = sum

End Function
```

```
Function ThCondIntegral_Brass(Tmin As Double, Tmax As Double, N As Integer) As Double

'Finds Th. cond. integral by Trapezoidal rule
'Tmin, Tmax are temps in K, N is the no. of trapezoidal divisions
'Ref: Excel Scientific and Engineering Cookbook by David M. Bourg

    Dim dx As Double, i As Integer
    Dim sum As Double
    Dim y As Double

    dx = (Tmax - Tmin) / N

    sum = (k_Brass(Tmin) + k_Brass(Tmax)) / 2#

    For i = 1 To (N - 1)
        y = k_Brass(Tmin + (dx * i))
        sum = sum + y
    Next i

    sum = sum * dx

    ThCondIntegral_Brass = sum

End Function
```


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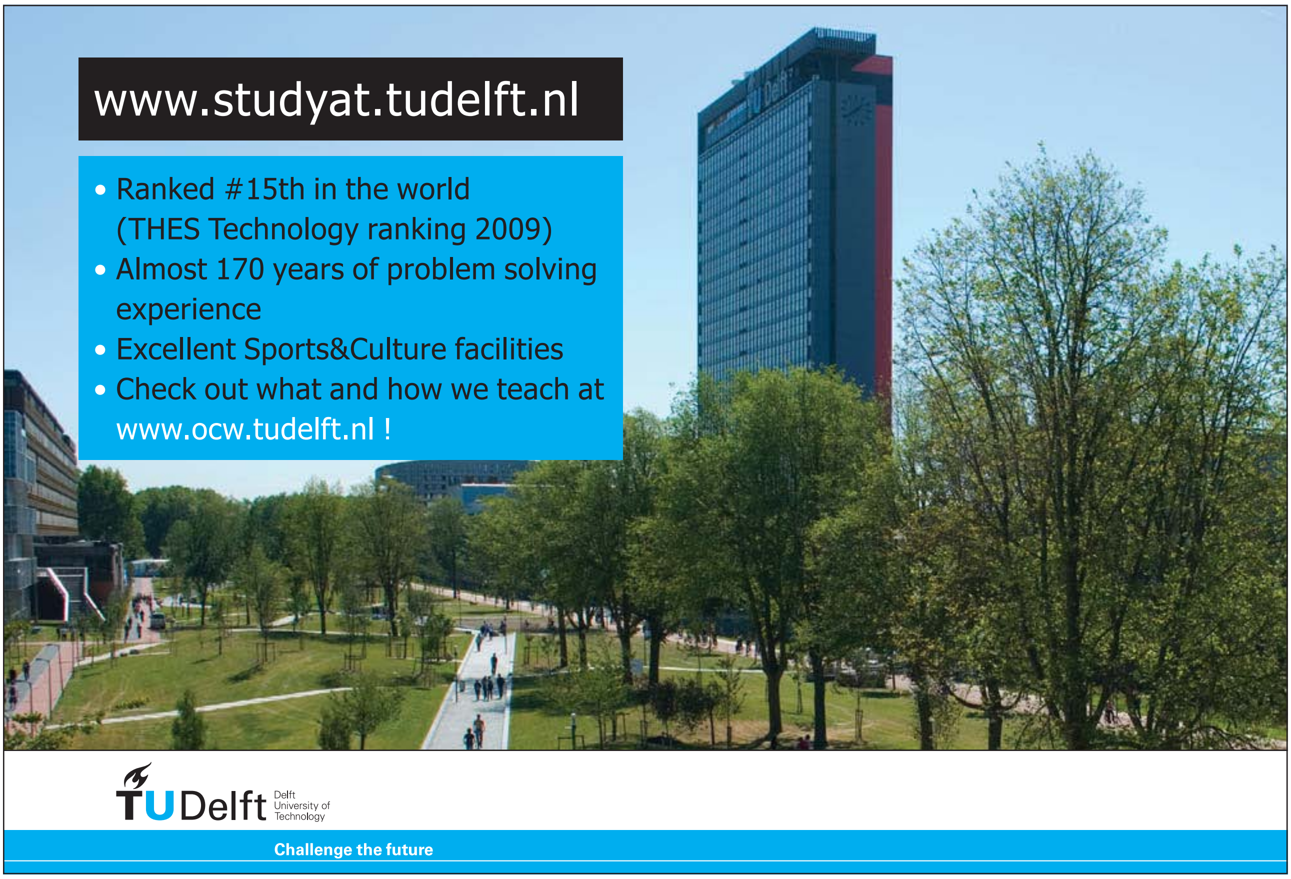
```
Function ThCondIntegral_Invar(Tmin As Double, Tmax As Double, N As Integer) As Double

'Finds Th. cond. integral by Trapezoidal rule
'Tmin, Tmax are temps in K, N is the no. of trapezoidal divisions
'Ref: Excel Scientific and Engineering Cookbook by David M. Bourg

    Dim dx As Double, i As Integer
    Dim sum As Double
    Dim y As Double

    dx = (Tmax - Tmin) / N

    sum = (k_Invar(Tmin) + k_Invar(Tmax)) / 2#

    For i = 1 To (N - 1)
        y = k_Invar(Tmin + (dx * i))
        sum = sum + y
    Next i

    sum = sum * dx

    ThCondIntegral_Invar = sum

End Function
```



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```
Function ThCondIntegral_Lead(Tmin As Double, Tmax As Double, N As Integer) As Double

'Finds Th. cond. integral by Trapezoidal rule
'Tmin, Tmax are temps in K, N is the no. of trapezoidal divisions
'Ref: Excel Scientific and Engineering Cookbook by David M. Bourg

    Dim dx As Double, i As Integer
    Dim sum As Double
    Dim y As Double

    dx = (Tmax - Tmin) / N

    sum = (k_Lead(Tmin) + k_Lead(Tmax)) / 2#

    For i = 1 To (N - 1)
        y = k_Lead(Tmin + (dx * i))
        sum = sum + y
    Next i

    sum = sum * dx

    ThCondIntegral_Lead = sum

End Function
```

```
Function ThCondIntegral_Nylon(Tmin As Double, Tmax As Double, N As Integer) As Double

'Finds Th. cond. integral by Trapezoidal rule
'Tmin, Tmax are temps in K, N is the no. of trapezoidal divisions
'Ref: Excel Scientific and Engineering Cookbook by David M. Bourg

    Dim dx As Double, i As Integer
    Dim sum As Double
    Dim y As Double

    dx = (Tmax - Tmin) / N

    sum = (k_Nylon(Tmin) + k_Nylon(Tmax)) / 2#

    For i = 1 To (N - 1)
        y = k_Nylon(Tmin + (dx * i))
        sum = sum + y
    Next i

    sum = sum * dx

    ThCondIntegral_Nylon = sum

End Function
```


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```
Function ThCondIntegral_Teflon(Tmin As Double, Tmax As Double, N As Integer) As Double

'Finds Th. cond. integral by Trapezoidal rule
'Tmin, Tmax are temps in K, N is the no. of trapezoidal divisions
'Ref: Excel Scientific and Engineering Cookbook by David M. Bourg

    Dim dx As Double, i As Integer
    Dim sum As Double
    Dim y As Double

    dx = (Tmax - Tmin) / N

    sum = (k_Teflon(Tmin) + k_Teflon(Tmax)) / 2#

    For i = 1 To (N - 1)
        y = k_Teflon(Tmin + (dx * i))
        sum = sum + y
    Next i

    sum = sum * dx

    ThCondIntegral_Teflon = sum

End Function


Function ThCondIntegral_Pyrex(Tmin As Double, Tmax As Double, N As Integer) As Double

'Finds Th. cond. integral by Trapezoidal rule
'Tmin, Tmax are temps in K, N is the no. of trapezoidal divisions
'Ref: Excel Scientific and Engineering Cookbook by David M. Bourg

    Dim dx As Double, i As Integer
    Dim sum As Double
    Dim y As Double

    dx = (Tmax - Tmin) / N

    sum = (k_Pyrex(Tmin) + k_Pyrex(Tmax)) / 2#

    For i = 1 To (N - 1)
        y = k_Pyrex(Tmin + (dx * i))
        sum = sum + y
    Next i

    sum = sum * dx

    ThCondIntegral_Pyrex = sum

End Function
```

Prob.2.3.4 Using the above written EXCEL-VBA Functions for the thermal conductivity integrals for OFHC copper, 6061- T6-Aluminium, Beryllium copper, SS-304L, Brass, Invar, Lead, Nylon, Teflon and Pyrex, calculate the thermal conductivity integrals for these materials between temperatures Tmin = 20 K and Tmax = 80 K.

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Solution:

Following worksheet gives the results:

E38 =ThCondIntegral_OFHC_copper(20,80,500)

	A	B	C	D	E	F
37						
38			Th. Cond. Integral	For OFHC copper (20 - 80 K)	116629.5	W/m... Ans.
39						
40			Th. Cond. Integral	For Beryllium copper (20 - 80	1040.631	W/m... Ans.
41						
42			Th. Cond. Integral	For SS304L (20 - 80 K)	331.4912	W/m... Ans.
43						
44			Th. Cond. Integral	For Brass (20 - 80 K)	3392.771	W/m... Ans.
45						
46			Th. Cond. Integral	For Invar (20 - 80 K)	250.1898	W/m... Ans.
47						
48			Th. Cond. Integral	For Lead (20 - 80 K)	2488.788	W/m... Ans.
49						
50			Th. Cond. Integral	For Nylon (20 - 80 K)	13.35179	W/m... Ans.
51						
52			Th. Cond. Integral	For Teflon (20 - 80 K)	12.1816	W/m... Ans.
53						
54			Th. Cond. Integral	For Pyrex (20 - 80 K)	18.13093	W/m... Ans.

Note that in cell E38, Function for Thermal conductivity integral for OFHC copper is entered. Observe in the Formula bar that we have used Tmin = 20 K, Tmax = 80 K, and the no. of trapezoidal divisions N = 500. With these conditions, thermal conductivity integral **for OFHC copper is 116629.5 W/m.** Similarly, thermal cond. integrals for other materials are calculated.

Prob.2.3.5 Write a VBA Function to determine (Cv/R) when (T/θ_D) is known. Here, θ_D is the Debye temp of the material.

Solution:

From Barron, we have (Cv/R) against (T/θ_D) in Tabular form:

Note that (T/θ_D) values are from cell M57 to M92, and corresponding (Cv/R) values are from cell N57 to N92.

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	M	N
56	TbyThetaD	CvbyR
57	0.05	0.1191
58	0.09	0.1682
59	0.1	0.2275
60	0.12	0.3733
61	0.14	0.5464
62	0.16	0.7334
63	0.18	0.9228
64	0.2	1.106
65	0.25	1.509
66	0.3	1.823
67	0.35	2.06
68	0.4	2.238
69	0.45	2.373
70	0.5	2.476
71	0.6	2.621
72	0.7	2.715
73	0.8	2.748
74	0.9	2.823
75	1	2.855

	TbyThetaD	CvbyR		
	M	N	K	L
76	1.1	2.88		
77	1.2	2.898		
78	1.3	2.913		
79	1.4	2.925		
80	1.5	2.934		
81	1.6	2.942		
82	1.7	2.949		
83	1.8	2.954		
84	1.9	2.959		
85	2	2.963		
86	2.2	2.969		
87	2.4	2.974		
88	2.6	2.978		
89	2.8	2.981		
90	3	2.983		
91	4	2.984		
92	5	2.99		

We shall first get the curve fit equation from 'Curve Expert' and then write a VBA Function which will get the value of CvbyR for any given value of TbyThetaD.

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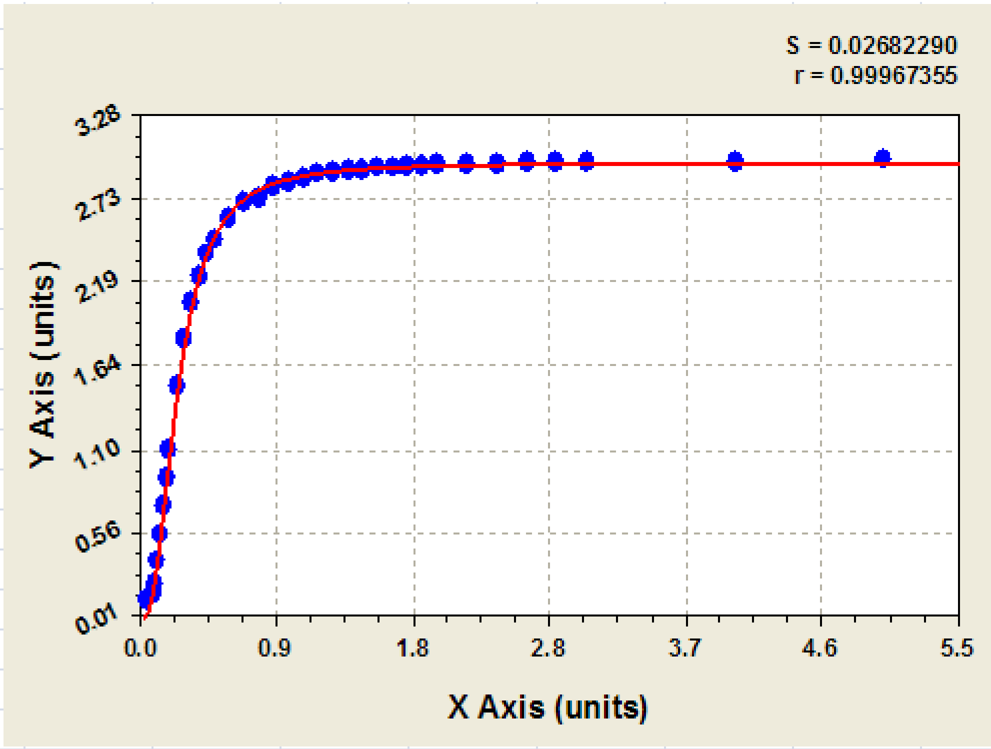
With Curve Expert: X-axis is TbyThetaD and Y-axis is CvbyR:



Curve fit equation is:

MMF Model: y = (a*b+c*x^d)/(b+x^d), where

a =	-0.037636752
b =	0.036770896
c =	2.9757569
d =	2.3784036

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Now, we will write the VBA Function which uses this curve fit equation to get the value of CvbyR for a given value of TbyThetaD:

```
Function CvbyR_curvefit(TbyThetaD As Double) As Double

'gives CvbyR as a function of TbyThetaD. Ref: Barron

'ThetaD = Debye Temp (K), T in K

'Note: R = Ru/M where Ru = 8314.47 J/kg.K, M = Mol. wt. of material

Dim a As Double, b As Double, c As Double, d As Double

a = -0.037636752
b = 0.036770896
c = 2.9757569
d = 2.3784036

If TbyThetaD < 0.05 Then

MsgBox (" use: CvbyR = 233.8 * (TbyThetaD) ^ 3")

End

End If

If TbyThetaD > 5 Then

MsgBox (" use: CvbyR = 3")

End

End If

CvbyR_curvefit = (a * b + c * TbyThetaD ^ d) / (b + TbyThetaD ^ d)

End Function
```

Note that in the above Function, CvbyR values are obtained by curve fit equation for values of TbyThetaD between 0.05 and 5.

Prob.2.3.6 Use the above written VBA Function to get sp. heat of Aluminium, copper, Niobium, Chromium and Silver at a temp of 25 K.

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Solution:

Following is the EXCEL worksheet:

C61 · fx 8314.47

	A	B	C	
59				
60		Data:		
61		R_u	8314.47	J/kg.K
62		Theta_D_Al =	385	K
63		Theta_D_Cu =	310	K
64		Theta_D_Nb=	265	K
65		Theta_D_Ag =	220	K
66		Theta_D_Cr =	430	K
67				
68		M_Al =	26.98	
69		M_Cu =	63.55	
70		M_Nb =	92.91	
71		M_Ag =	107.87	
72		M_Cr =	52	
73				
74		T=	25	K
75				

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C84 =CvbyR_curvefit(C78)

	A	B	C
78		TbyThetaD_AL	0.064935065
79		TbyThetaD_Cu	0.080645161
80		TbyThetaD_Nb	0.094339623
81		TbyThetaD_Ag	0.113636364
82		TbyThetaD_Cr	0.058139535
83			
84		CvbyR_AL	0.080341801
85		CvbyR_Cu	0.15480255
86		CvbyR_Nb	0.233968726
87		CvbyR_Ag	0.364990217
88		CvbyR_Cr	0.053894671

See that in cell C84 CvbyR is calculated for Aluminium. Formula bar shows the VBA Function used.

And, results:

C90 =C84*(C61/C68)

	A	B	C	D
89				
90		Cv_AL	24.75906	J/kg.K ... Ans.
91		Cv_Cu	20.25336	J/kg.K ... Ans.
92		Cv_Nb	20.93775	J/kg.K ... Ans.
93		Cv_Ag	28.13294	J/kg.K ... Ans.
94		Cv_Cr	8.61742	J/kg.K ... Ans.
95				

Results can be read in cells C90 to C94. Cv is given as: Cv = CvbyR * R, where R = Ru/M.

See the formula entered in cell C90, in the Formula bar.

Prob.2.3.7 Write EXCEL VBA Functions for sp. heat of various materials used in Cryogenics, viz. SS304, SS304L, AL-6061-T6, OFHC copper, Nylon, Teflon, Brass, Pyrex and Lead.

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VBA Functions:

For SS304:

```
Function cp_ss304(T As Double) As Double
'gives th. cond. of SS 304 as a function of T (K). Ref: NIST-Cryogenics.
'cp in J/kg.K, and,  T in K

Dim a As Double, b As Double, c As Double, d As Double
Dim e As Double, f As Double, g As Double, h As Double, i As Double

If T < 4 Or T > 300 Then

 MsgBox ("T must be between 4 K and 300 K !!")
 End
End If

a = 22.0061
b = -127.5528
c = 303.647
d = -381.0098
e = 274.0328
f = -112.9212
g = 24.7593
h = -2.239153
i = 0

cp_ss304 = 10 ^ (a + b * (Log(T) / Log(10)) + c * (Log(T) / Log(10)) ^ 2 + d * (Log(T) / _
Log(10)) ^ 3 + e * (Log(T) / Log(10)) ^ 4 + f * (Log(T) / Log(10)) ^ 5 + g * (Log(T) / _
Log(10)) ^ 6 + h * (Log(T) / Log(10)) ^ 7 + i * (Log(T) / Log(10)) ^ 8)

End Function
```

For SS304L:

```
Function cp_ss304L(T As Double) As Double
'gives th. cond. of SS 304L as a function of T (K). Ref: NIST-Cryogenics.
'cp in J/kg.K, and,  T in K

Dim a As Double, b As Double, c As Double, d As Double
Dim e As Double, f As Double, g As Double, h As Double, i As Double

If T < 4 Or T > 23 Then
 MsgBox ("T must be between 4 K and 23 K !!")
 End
End If

a = -351.51
b = 3123.695
c = -12017.28
d = 26143.99
e = -35176.33
f = 29981.75
g = -15812.78
h = 4719.64
i = -610.515

cp_ss304L = 10 ^ (a + b * (Log(T) / Log(10)) + c * (Log(T) / Log(10)) ^ 2 + d * (Log(T) / _
Log(10)) ^ 3 + e * (Log(T) / Log(10)) ^ 4 + f * (Log(T) / Log(10)) ^ 5 + g * (Log(T) / _
Log(10)) ^ 6 + h * (Log(T) / Log(10)) ^ 7 + i * (Log(T) / Log(10)) ^ 8)

End Function
```


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For AL-6061-T6:

```
Function cp_AL_6061_T6(T As Double) As Double
'gives th. cond. of AL_6061_T6 as a function of T (K). Ref: NIST-Cryogenics.
'cp in J/kg.K, and,  T in K

Dim a As Double, b As Double, c As Double, d As Double
Dim e As Double, f As Double, g As Double, h As Double, i As Double

If T < 4 Or T > 300 Then
 MsgBox ("T must be between 4 K and 300 K !!")
 End
End If

a = 46.6467
b = -314.292
c = 866.662
d = -1298.3
e = 1162.27
f = -637.795
g = 210.351
h = -38.3094
i = 2.96344

cp_AL_6061_T6 = 10 ^ (a + b * (Log(T) / Log(10)) + c * (Log(T) / Log(10)) ^ 2 + d * (Log(T) / _
Log(10)) ^ 3 + e * (Log(T) / Log(10)) ^ 4 + f * (Log(T) / Log(10)) ^ 5 + g * (Log(T) / _
Log(10)) ^ 6 + h * (Log(T) / Log(10)) ^ 7 + i * (Log(T) / Log(10)) ^ 8)

End Function
```

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For OFHC copper:

```
Function cp_OFHC_copper(T As Double) As Double
'gives th. cond. of OFHC_copper as a function of T (K). Ref: NIST-Cryogenics.
'cp in J/kg.K, and,  T in K

Dim a As Double, b As Double, c As Double, d As Double
Dim e As Double, f As Double, g As Double, h As Double, i As Double

If T < 4 Or T > 300 Then
 MsgBox ("T must be between 4 K and 300 K !!")
 End
End If

a = -1.91844
b = -0.15973
c = 8.61013
d = -18.9964
e = 21.9661
f = -12.7328
g = 3.54322
h = -0.3797
i = 0

cp_OFHC_copper = 10 ^ (a + b * (Log(T) / Log(10)) + c * (Log(T) / Log(10)) ^ 2 + d * (Log(T) / _
Log(10)) ^ 3 + e * (Log(T) / Log(10)) ^ 4 + f * (Log(T) / Log(10)) ^ 5 + g * (Log(T) / _
Log(10)) ^ 6 + h * (Log(T) / Log(10)) ^ 7 + i * (Log(T) / Log(10)) ^ 8)

End Function
```

For Nylon:

```
Function cp_Nylon(T As Double) As Double
'gives th. cond. of Nylon as a function of T (K). Ref: NIST-Cryogenics.
'cp in J/kg.K, and,  T in K

Dim a As Double, b As Double, c As Double, d As Double
Dim e As Double, f As Double, g As Double, h As Double, i As Double

If T < 4 Or T > 300 Then
 MsgBox ("T must be between 4 K and 300 K !!")
 End
End If

a = -5.2929
b = 25.301
c = -54.874
d = 71.061
e = -52.236
f = 21.648
g = -4.7317
h = 0.42518
i = 0

cp_Nylon = 10 ^ (a + b * (Log(T) / Log(10)) + c * (Log(T) / Log(10)) ^ 2 + d * (Log(T) / _
Log(10)) ^ 3 + e * (Log(T) / Log(10)) ^ 4 + f * (Log(T) / Log(10)) ^ 5 + g * (Log(T) / _
Log(10)) ^ 6 + h * (Log(T) / Log(10)) ^ 7 + i * (Log(T) / Log(10)) ^ 8)

End Function
```


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For Teflon:

```
Function cp_Teflon(T As Double) As Double
'gives th. cond. of Teflon as a function of T (K). Ref: NIST-Cryogenics.
'cp in J/kg.K, and,  T in K

Dim a As Double, b As Double, c As Double, d As Double
Dim e As Double, f As Double, g As Double, h As Double, i As Double

If T < 4 Or T > 300 Then
 MsgBox ("T must be between 4 K and 300 K !!")
 End
End If

a = 31.88256
b = -166.51949
c = 352.01879
d = -393.44232
e = 259.98072
f = -104.61429
g = 24.99276
h = -3.20792
i = 0.16503

cp_Teflon = 10 ^ (a + b * (Log(T) / Log(10)) + c * (Log(T) / Log(10)) ^ 2 + d * (Log(T) / _
Log(10)) ^ 3 + e * (Log(T) / Log(10)) ^ 4 + f * (Log(T) / Log(10)) ^ 5 + g * (Log(T) / _
Log(10)) ^ 6 + h * (Log(T) / Log(10)) ^ 7 + i * (Log(T) / Log(10)) ^ 8)

End Function
```

For Brass:

```
Function cp_Brass_curvefit(T As Double) As Double

'gives Cp as a function of T. Ref:[9]..digitized, curve fit with 'Curve Expert'.

Dim a As Double, b As Double, c As Double, d As Double

If T < 2 Or T > 300 Then
MsgBox (" T must be between 2 K and 300 K !!")
End
End If

a = -2.7779824
b = 14383.254
c = 494.3505
d = 2.0861122

cp_Brass_curvefit = (a * b + c * T ^ d) / (b + T ^ d)

End Function
```


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For Pyrex:

```
Function cp_Pyrex_curvefit(T As Double) As Double

'gives Cp as a function of T. Ref:[14]..digitized, curve fit with 'Curve Expert'.

Dim a As Double, b As Double, c As Double, d As Double

If T < 1 Or T > 300 Then
MsgBox (" T must be between 1 K and 300 K !!")
End
End If

a = 2.8634691
b = -29.672679
c = 0.67340045

cp_Pyrex_curvefit = Exp(a + b / T + c * Log(T))

End Function
```

For Lead:

We have the cp vs T values in Tabular form in the Excel Worksheet in the range M209:N257. We will use linear interpolation to get the value of cp for a given value of T.

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As a first step, we have VBA Function for linear interpolation:

```
Function InterpLinear(lookup_value As Double, known_xs, known_ys)

'Ref: Walkenbach.

Dim pointer As Integer
Dim X0 As Double, Y0 As Double, X1 As Double, Y1 As Double

pointer = Application.Match(lookup_value, known_xs, 1)

X0 = known_xs(pointer)

Y0 = known_ys(pointer)

X1 = known_xs(pointer + 1)

Y1 = known_ys(pointer + 1)

InterpLinear = Y0 + (lookup_value - X0) * (Y1 - Y0) / (X1 - X0)

End Function
```

Above Interpolation Function has 3 inputs: the look up value for which the corresponding y value is required, the range of known x values and the range of known y values. It does the simple linear interpolation.

Now, this Interpolation function is used to get the corresponding value of cp for a given value of T from the Table of T vs cp for Lead:

```
Function cp_Lead(T As Double) As Double

'Sp. heat of (Normal) Lead: Ref: BNL Selected Cryogenic Data Notebook - Vol. 1 (Aug. 1980)

'T= Temp (K), cp in J/kg.K

If T < 1 Or T > 310 Then

MsgBox (" T must be between 1 K and 310 K !!")

End

End If

cp_Lead = InterpLinear(T, Range("M209:M257"), Range("N209:N257"))

End Function
```

Prob.2.3.8 Using the above written EXCEL VBA Functions for sp. heat of SS304, SS304L, AL-6061-T6, OFHC copper, Nylon, Teflon, Brass, Pyrex and Lead, determine the sp. heats of these materials at 25 K.

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Solution:

Following is the EXCEL Worksheet:

C135 | f_x =cp_ss304(20)

	A	B	C
132			
133		**Sp. heats at 20 K:**	
134		**Material**	**cp (J/kg.K)**
135		SS 304	13.45248
136		SS304L	11.87770
137		AL_6061_T6	8.85427
138		OFHC copper	7.49086
139		Nylon	99.90099
140		Teflon	76.79180
141		Brass 65/35	14.49425
142		Pyrex	29.87920
143		Lead	52
144			

Note that in cell C135, we have the cp of SS304 at 20 K. Function used can be seen in the Formula bar.

Similarly, cp of other materials is calculated.

Prob.2.3.9 Write EXCEL VBA Functions for sp. heat integrals of of SS304, SS304L, AL-6061-T6, OFHC copper, Nylon, Teflon, Brass, Pyrex and Lead, between the temperatures Tmin and Tmax.

Solution:

Remember that when a mass m (kg) is cooled from a temp of Tmax to Tmin, the amount of heat rejected, Q (J) is given by:

$$Q = m.\int_{Tmin}^{Tmax} cp.dT \qquad \text{J}$$

Since we have already written VBA Functions for cp as a function of T for many materials, it is now easy to write the Functions for Sp. heat integrals (just as we wrote for Thermal conductivity integrals):

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For SS304:

```
Function Spheat_Integral_SS304(Tmin As Double, Tmax As Double, N As Integer) As Double

'Finds Sp. heat integral by Trapezoidal rule
'Tmin, Tmax are temps in K, N is the no. of trapezoidal divisions
'Ref: Excel Scientific and Engineering Cookbook by David M. Bourg

    Dim dx As Double, i As Integer
    Dim sum As Double
    Dim y As Double

    dx = (Tmax - Tmin) / N
    sum = (cp_ss304(Tmin) + cp_ss304(Tmax)) / 2#

    For i = 1 To (N - 1)
        y = cp_ss304(Tmin + (dx * i))
        sum = sum + y
    Next i

    sum = sum * dx
    Spheat_Integral_SS304 = sum

End Function
```

In the above Function, inputs are: temp limits Tmin and Tmax and no. of trapezoidal subdivisions, Note that we can choose the no. of trapezoidal divisions, N. (say 100, 200…or 1000 etc.). Obviously, larger the no. of divisions, higher is the accuracy.

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Similarly, for other materials:

For SS304L:

```
Function Spheat_Integral_SS304L(Tmin As Double, Tmax As Double, N As Integer) As Double

'Finds Sp. heat integral by Trapezoidal rule
'Tmin, Tmax are temps in K, N is the no. of trapezoidal divisions
'Ref: Excel Scientific and Engineering Cookbook by David M. Bourg

    Dim dx As Double, i As Integer
    Dim sum As Double
    Dim y As Double

    dx = (Tmax - Tmin) / N
    sum = (cp_ss304L(Tmin) + cp_ss304L(Tmax)) / 2#

    For i = 1 To (N - 1)
        y = cp_ss304L(Tmin + (dx * i))
        sum = sum + y
    Next i

    sum = sum * dx
    Spheat_Integral_SS304L = sum

End Function
```

For AL-6061-T6:

```
Function Spheat_Integral_AL_6061_T6(Tmin As Double, Tmax As Double, N As Integer) As Double

'Finds Sp. heat integral by Trapezoidal rule
'Tmin, Tmax are temps in K, N is the no. of trapezoidal divisions
'Ref: Excel Scientific and Engineering Cookbook by David M. Bourg

    Dim dx As Double, i As Integer
    Dim sum As Double
    Dim y As Double

    dx = (Tmax - Tmin) / N
    sum = (cp_AL_6061_T6(Tmin) + cp_AL_6061_T6(Tmax)) / 2#

    For i = 1 To (N - 1)
        y = cp_AL_6061_T6(Tmin + (dx * i))
        sum = sum + y
    Next i

    sum = sum * dx
    Spheat_Integral_AL_6061_T6 = sum

End Function
```


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For OFHC copper:

```
Function Spheat_Integral_OFHC_copper(Tmin As Double, Tmax As Double, N As Integer) As Double

'Finds Sp. heat integral by Trapezoidal rule
'Tmin, Tmax are temps in K, N is the no. of trapezoidal divisions
'Ref: Excel Scientific and Engineering Cookbook by David M. Bourg

    Dim dx As Double, i As Integer
    Dim sum As Double
    Dim y As Double

    dx = (Tmax - Tmin) / N
    sum = (cp_OFHC_copper(Tmin) + cp_OFHC_copper(Tmax)) / 2#

    For i = 1 To (N - 1)
        y = cp_OFHC_copper(Tmin + (dx * i))
        sum = sum + y
    Next i

    sum = sum * dx
    Spheat_Integral_OFHC_copper = sum

End Function
```

For Nylon:

```
Function Spheat_Integral_Nylon(Tmin As Double, Tmax As Double, N As Integer) As Double

'Finds Sp. heat integral by Trapezoidal rule
'Tmin, Tmax are temps in K, N is the no. of trapezoidal divisions
'Ref: Excel Scientific and Engineering Cookbook by David M. Bourg

    Dim dx As Double, i As Integer
    Dim sum As Double
    Dim y As Double

    dx = (Tmax - Tmin) / N
    sum = (cp_Nylon(Tmin) + cp_Nylon(Tmax)) / 2#

    For i = 1 To (N - 1)
        y = cp_Nylon(Tmin + (dx * i))
        sum = sum + y
    Next i

    sum = sum * dx
    Spheat_Integral_Nylon = sum

End Function
```


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For Teflon:

```
Function Spheat_Integral_Teflon(Tmin As Double, Tmax As Double, N As Integer) As Double

'Finds Sp. heat integral by Trapezoidal rule
'Tmin, Tmax are temps in K, N is the no. of trapezoidal divisions
'Ref: Excel Scientific and Engineering Cookbook by David M. Bourg

    Dim dx As Double, i As Integer
    Dim sum As Double
    Dim y As Double

    dx = (Tmax - Tmin) / N
    sum = (cp_Teflon(Tmin) + cp_Teflon(Tmax)) / 2#

    For i = 1 To (N - 1)
        y = cp_Teflon(Tmin + (dx * i))
        sum = sum + y
    Next i

    sum = sum * dx
    Spheat_Integral_Teflon = sum

End Function
```

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For Brass:

```
Function Spheat_Integral_Brass(Tmin As Double, Tmax As Double, N As Integer) As Double

'Finds Sp. heat integral by Trapezoidal rule
'Tmin, Tmax are temps in K, N is the no. of trapezoidal divisions
'Ref: Excel Scientific and Engineering Cookbook by David M. Bourg

    Dim dx As Double, i As Integer
    Dim sum As Double
    Dim y As Double

    dx = (Tmax - Tmin) / N
    sum = (cp_Brass_curvefit(Tmin) + cp_Brass_curvefit(Tmax)) / 2#

    For i = 1 To (N - 1)
        y = cp_Brass_curvefit(Tmin + (dx * i))
        sum = sum + y
    Next i

    sum = sum * dx
    Spheat_Integral_Brass = sum

End Function
```

For Pyrex:

```
Function Spheat_Integral_Pyrex(Tmin As Double, Tmax As Double, N As Integer) As Double

'Finds Sp. heat integral by Trapezoidal rule
'Tmin, Tmax are temps in K, N is the no. of trapezoidal divisions
'Ref: Excel Scientific and Engineering Cookbook by David M. Bourg

    Dim dx As Double, i As Integer
    Dim sum As Double
    Dim y As Double

    dx = (Tmax - Tmin) / N
    sum = (cp_Pyrex_curvefit(Tmin) + cp_Pyrex_curvefit(Tmax)) / 2#

    For i = 1 To (N - 1)
        y = cp_Pyrex_curvefit(Tmin + (dx * i))
        sum = sum + y
    Next i

    sum = sum * dx
    Spheat_Integral_Pyrex = sum

End Function
```


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For Lead:

```
Function Spheat_Integral_Lead(Tmin As Double, Tmax As Double, N As Integer) As Double

'Finds Sp. heat integral by Trapezoidal rule
'Tmin, Tmax are temps in K, N is the no. of trapezoidal divisions
'Ref: Excel Scientific and Engineering Cookbook by David M. Bourg

    Dim dx As Double, i As Integer
    Dim sum As Double
    Dim y As Double

    dx = (Tmax - Tmin) / N
    sum = (cp_Lead(Tmin) + cp_Lead(Tmax)) / 2#

    For i = 1 To (N - 1)
        y = cp_Lead(Tmin + (dx * i))
        sum = sum + y
    Next i

    sum = sum * dx
    Spheat_Integral_Lead = sum

End Function
```

Prob.2.3.10 Using the above written EXCEL VBA Functions for sp. heat integrals of SS304, AL-6061-T6, OFHC copper, Nylon, Teflon, Brass, Pyrex and Lead, determine the amount of heat to be removed from 1 kg of each material as it is cooled from Tmax = 300 K to Tmin = 77 K.

Solution:

We have: $Q = m.\int_{Tmin}^{Tmax} cp.dT$ J

Following is the EXCEL worksheet for calculations:

C148 | fx | =1 * Spheat_Integral_SS304(77,300,100)

	A	B	C	D
144				
145				
146	Using Sp. heat Integrals:			
147		Material	Q (J/kg)	
148		SS 304	86578.96755	
149		AL_6061_T6	168860.0616	
150		OFHC copper	74145.84184	
151		Nylon	254016.5039	
152		Teflon	153728.2	
153		Brass 65/35	82124.88615	
154		Pyrex	111601.918	
155		Lead	27626.00322	

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Note that in cell C148, we have Q for SS 304. The Function used is shown in the Formula bar.

Note that we have used N = 100 subdivisions in the trapezoidal rule.

Similarly, Q for other materials is calculated.

Prob.2.3.11 Write EXCEL VBA Functions for Yield stress of various materials used in Cryogenics, viz. SS304, AL-2024-T4, Teflon, BeCu, Ti, 9% Ni steel, k Monel and C1020CSteel.

Solution:

See Prob. 2.2.10. Here, original graphs from Ref.[1] were digitized using the PlotDigitizer [Ref: 13]. The resulting data tables were transferred to EXCEL and plotted. The **'Trendline'** menu was used to fit the plot to a 4^{th} order polynomial. Then, the EES Functions were written using these curve-fit equations.

Here, we shall use the curve fit equations obtained in Prob.2.2.10 to write the VBA Functions for Yield stress vs Temp.

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Following are the VBA Functions:

For SS304:

```
Function Yield_stress_SS304(T As Double) As Double

'Yield stress of SS304. Ref: Cryogenics Systems by Barron.
'Yield stress in MPa, T in K
'Finds Yield stress in the range: T = 0 - 350 K:

If (T < 0) Or (T > 350) Then

      MsgBox ("Temp. must be between 0 and 350 K !")

End
End If

Yield_stress_SS304 = 0.000000022855 * T ^ 4 - 0.000016446 * T ^ 3 + _
0.0026638 * T ^ 2 - 0.52548 * T + 1348.2

End Function
```

For AL-2024-T4:

```
Function Yield_stress_AL_2024_T4(T As Double) As Double

'Yield stress of AL_2024_T4. Ref: Cryogenics Systems by Barron.
'Yield stress in MPa, T in K
'Finds Yield stress in the range: T = 0 - 350 K:

If (T < 0) Or (T > 350) Then

      MsgBox ("Temp. must be between 0 and 350 K !")

End
End If

Yield_stress_AL_2024_T4 = 0.000000026112 * T ^ 4 - 0.000024015 * T ^ 3 + _
0.010138 * T ^ 2 - 2.3091 * T + 526.43

End Function
```


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For Teflon:

```
Function Yield_stress_Teflon(T As Double) As Double

'Yield stress of Teflon. Ref: Cryogenics Systems by Barron.
'Yield stress in MPa, T in K
'Finds Yield stress in the range: T = 0 - 350 K:

If (T < 0) Or (T > 350) Then

      MsgBox ("Temp. must be between 0 and 350 K !")

End
End If

Yield_stress_Teflon = 0.000000015834 * T ^ 4 - 0.000016104 * T ^ 3 + _
0.0067618 * T ^ 2 - 1.398 * T + 141.76

End Function
```

For Beryllium copper:

```
Function Yield_stress_BeCu(T As Double) As Double

'Yield stress of BeCu. Ref: Cryogenics Systems by Barron.
'Yield stress in MPa, T in K
'Finds Yield stress in the range: T = 0 - 350 K:

If (T < 0) Or (T > 350) Then

      MsgBox ("Temp. must be between 0 and 350 K !")

End
End If

Yield_stress_BeCu = 0.000000023953 * T ^ 4 - 0.000024822 * T ^ 3 + 0.01188 * T ^ 2 - _
2.8776 * T + 947.41

End Function
```


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For Titanium:

```
Function Yield_stress_Ti(T As Double) As Double

'Yield stress of Titanium. Ref: Cryogenics Systems by Barron.
'Yield stress in MPa, T in K
'Finds Yield stress in the range: T = 0 - 350 K:

If (T < 0) Or (T > 350) Then

      MsgBox ("Temp. must be between 0 and 350 K !")

End
End If

Yield_stress_Ti = 0.000000068681 * T ^ 4 - 0.000064487 * T ^ 3 + 0.024406 * T ^ 2 - _
6.7607 * T + 1823.5

End Function
```

For 9 % Ni Steel:

```
Function Yield_stress_9percentNiSteel(T As Double) As Double

'Yield stress of 9% NiSteel. Ref: Cryogenics Systems by Barron.
'Yield stress in MPa, T in K
'Finds Yield stress in the range: T = 0 - 350 K:

If (T < 0) Or (T > 350) Then

      MsgBox ("Temp. must be between 0 and 350 K !")

End
End If

Yield_stress_9percentNiSteel = -0.0000097458 * T ^ 3 + 0.0091459 * T ^ 2 - _
3.5097 * T + 1133.5

End Function
```

For k Monel:

```
Function Yield_stress_kMonel(T As Double) As Double

'Yield stress of kMonel. Ref: Cryogenics Systems by Barron.
'Yield stress in MPa, T in K
'Finds Yield stress in the range: T = 0 - 350 K:

If (T < 0) Or (T > 350) Then

      MsgBox ("Temp. must be between 0 and 350 K !")

End
End If

Yield_stress_kMonel = 0.000000015041 * T ^ 4 - 0.000011053 * T ^ 3 + 0.0048733 * T ^ 2 - _
1.6876 * T + 1091.2

End Function
```


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For C1020C Steel:

```
Function Yield_stress_C1020CSteel(T As Double) As Double

'Yield stress of C1020CSteel. Ref: Cryogenics Systems by Barron.
'Yield stress in MPa, T in K
'Finds Yield stress in the range: T = 0 - 350 K:

If (T < 0) Or (T > 350) Then

      MsgBox ("Temp. must be between 0 and 350 K !")

End
End If

Yield_stress_C1020CSteel = 0.00000002715 * T ^ 4 - 0.00002784 * T ^ 3 + _
0.011711 * T ^ 2 - 3.0361 * T + 711.24

End Function
```

Prob.2.3.12 Using the above written EXCEL VBA Functions for Yield stress of SS304, AL-2024-T4, Teflon, BeCu, Ti, 9% Ni steel, k Monel and C1020CSteel, determine the Yield stress of each material at a temp of 20 K.

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Solution:

Following is the EXCEL worksheet calculations:

C259 | fx | =Yield_stress_SS304(20)

	A	B	C
256			
257			
258		**Material**	**Yield stress (MPa) at 20 K**
259		SS 304	1338.628
260		AL_2024_T4	484.115
261		Teflon	116.378
262		BeCu	894.415
263		Titanium	1697.543
264		9 % Ni steel	1066.886
265		k Monel	1059.311
266		C1020C Steel	654.984

In cell C259, Yield stress of SS304 at 20 K is calculated as 1338.628 MPa. See the Formula bar to see the Function entered.
Similarly, Yield stress for other materials is calculated.

Prob.2.3.13 Write VBA Functions to determine Young's Modulus for SS 304, AL-2024-T4, BeCu, kMonel, Titanium, C1020 Steel and 9% Ni Steel.

See Prob. 2.2.13. Therein, original graphs from Ref.[1] were digitized using the PlotDigitizer [Ref: 13]. The resulting data tables were transferred to EXCEL and plotted. The '**Trendline**' menu was used to fit the plot to a $3^{rd}/4^{th}$ order polynomials.

Here, we shall use the curve fit equations obtained in Prob.2.2.13 to write the VBA Functions for Young's Modulus vs Temp.

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Following are the VBA Functions:

For SS 304:

```
Function Youngs_Modulus_SS304(T As Double) As Double

'E_y for SS304. Ref: Cryogenics Systems by Barron. Curve fitted with EXCEL.
'Ey in GPa, T in K
'Finds E_y in the range: T = 0 - 350 K

If (T < 0) Or (T > 350) Then

    MsgBox ("Temp. must be between 0 and 350 K !")

End If

Youngs_Modulus_SS304 = 0.000000038231 * T ^ 3 - 0.000023528 * T ^ 2 - _
0.12801 * T + 201.37

End Function
```

For AL-2024-T4:

```
Function Youngs_Modulus_AL_2024_T4(T As Double) As Double

'E_y for AL_2024_T4. Ref: Cryogenics Systems by Barron. Curve fitted with EXCEL.
'Ey in GPa, T in K
'Finds E_y in the range: T = 0 - 350 K

If (T < 0) Or (T > 350) Then

    MsgBox ("Temp. must be between 0 and 350 K !")

End If

Youngs_Modulus_AL_2024_T4 = 0.00000024395 * T ^ 3 - 0.000031441 * T ^ 2 - _
0.071171 * T + 88.637

End Function
```

For BeCu:

```
Function Youngs_Modulus_BeCu(T As Double) As Double

'E_y for BeCu. Ref: Cryogenics Systems by Barron. Curve fitted with EXCEL.
'Ey in GPa, T in K
'Finds E_y in the range: T = 0 - 350 K

If (T < 0) Or (T > 350) Then

    MsgBox ("Temp. must be between 0 and 350 K !")

End If

Youngs_Modulus_BeCu = -0.000000045324 * T ^ 3 + 0.000024745 * T ^ 2 - 0.049673 * T + 133.4

End Function
```


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For kMonel:

```
Function Youngs_Modulus_KMonel(T As Double) As Double

'E_y for KMonel. Ref: Cryogenics Systems by Barron. Curve fitted with EXCEL.
'Ey in GPa, T in K
'Finds E_y in the range: T = 0 - 350 K

If (T < 0) Or (T > 350) Then

    MsgBox ("Temp. must be between 0 and 350 K !")

End If

Youngs_Modulus_KMonel = -0.000000025449 * T ^ 3 + 0.000012554 * T ^ 2 - 0.042499 * T + 192.68

End Function
```

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For Titanium:

```
Function Youngs_Modulus_Titanium(T As Double) As Double

'E_y for Titanium. Ref: Cryogenics Systems by Barron. Curve fitted with EXCEL.
'Ey in GPa, T in K
'Finds E_y in the range: T = 0 - 350 K

If (T < 0) Or (T > 350) Then

    MsgBox ("Temp. must be between 0 and 350 K !")

End If

Youngs_Modulus_Titanium = 0.00000000089385 * T ^ 4 - 0.0000007261 * T ^ 3 + _
0.00018471 * T ^ 2 - 0.037787 * T + 118.46

End Function
```

For C1020 Steel:

```
Function Youngs_Modulus_C1020_Steel(T As Double) As Double

'E_y for C1020_Steel. Ref: Cryogenics Systems by Barron. Curve fitted with EXCEL.
'Ey in GPa, T in K
'Finds E_y in the range: T = 0 - 350 K

If (T < 0) Or (T > 350) Then

    MsgBox ("Temp. must be between 0 and 350 K !")

End If

Youngs_Modulus_C1020_Steel = -0.000000029236 * T ^ 3 + 0.0000095092 * T ^ 2 - _
0.047625 * T + 219.75

End Function
```

For 9% Ni Steel:

```
Function Youngs_Modulus_9percentNiSteel(T As Double) As Double

'E_y for 9% Ni Steel. Ref: Cryogenics Systems by Barron. Curve fitted with EXCEL.
'Ey in GPa, T in K
'Finds E_y in the range: T = 0 - 350 K

If (T < 0) Or (T > 350) Then

    MsgBox ("Temp. must be between 0 and 350 K !")

End If

Youngs_Modulus_9percentNiSteel = 0.000000075177 * T ^ 3 - 0.000023851 * T ^ 2 - _
0.081419 * T + 214.53

End Function
```


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Prob.2.3.14 Use the VBA Functions written above for Young's Modulii of SS 304, AL-2024-T4, BeCu, kMonel, Titanium, C1020 Steel and 9 % Ni Steel, to determine Young's Modulus of those materials at 20 K.

Solution:

The EXCEL worksheet is given below:

C271 | =Youngs_Modulus_SS304(20)

	A	B	C	D
269				
270		Material	Youngs Mod. (GPa) at 20 K	
271		SS 304	198.8007	
272		AL_2024_T4	87.2030	
273		BeCu	132.4161	
274		Kmonel	191.8348	
275		Titanium	117.7725	
276		C1020 Steel	218.8011	
277		9% Ni Steel	212.8927	

In cell C271 Young's Mod of SS304 is calculated as 198.8007 GPa. The Function used can be seen in the Formula bar.

Similarly, the Young's Mod for other materials is calculated.

Prob.2.3.15 Using the above written VBA Functions, plot the variation of Young's Modulus, Bulk Modulus and Shear Modulus for: (i) SS 304,(ii) AL-2024-T4 and (iii) Beryllium copper, for the temp range 5K to 300 K.

Solution:

Bulk Mod and Shear Mod are related to Young's Mod and Poisson's ratio as follows:

$$B = \frac{E}{3(1-2\nu)}$$

$$G = \frac{E}{2(1+\nu)}$$

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where

E = Young's Mod.

B = Bulk Mod. And

G = Shear Mod.

ν = Poisson's ratio

First, let us write VBA Functions to determine Bulk Mod and Shear Mod when Young's Mod and Poissons ratio are inputs:

```
Function Bulk_Modulus(Youngs_Modulus As Double, Poissons_Ratio As Double) As Double

'Youngs Mod.(Ey., Bulk Mod.(B) in GPa or MPa, T in K
'Temp. range: T = 0 - 350 K

Bulk_Modulus = Youngs_Modulus / (3 * (1 - 2 * Poissons_Ratio))

End Function
```

```
Function Shear_Modulus(Youngs_Modulus As Double, Poissons_Ratio As Double) As Double

'Youngs Mod.(Ey), Shear Mod.(G) in GPa or MPa, T in K
'Temp. range: T = 0 - 350 K

Shear_Modulus = Youngs_Modulus / (2 * (1 + Poissons_Ratio))

End Function
```

Using the VBA Functions written above, we calculate the values of Young's Mod, Bulk Mod and Shear Mod for the three materials desired, as the temp varies from 5 K to 300 K.

Following is the EXCEL worksheet for these calculations:

K290

	A	B	C	D
281				
282				
283		**Data:**		
284		**Material**		**Poisson's ratio**
285		SS 304	nu_SS304 =	0.305
286		AL	nu_AL =	0.32
287		BeCu	nu_BeCu =	0.285
288				
289		**Calculations:**		

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Observe in the Formula bar the Function entered for Bulk Mod of SS304 in cell F294:

F294 =Bulk_Modulus(C294,D285)

	A	B	C	D	E	F	G	H	I	J	K
284		Material		Poisson's ratio							
285		SS 304	nu_SS304 =	0.305							
286		AL	nu_AL =	0.32							
287		BeCu	nu_BeCu =	0.285							
288											
289		Calculations:									
290											
291											
292			SS 304	AL-2024-T4	BeCu	SS 304	AL-2024-T4	BeCu	SS 304	AL-2024-T4	BeCu
293		Temp (K)	Youngs Mod (Gpa)	Youngs Mod (GPa)	Youngs Mod (GPa)	Bulk Mod (GPa)	Bulk Mod (GpP)	Bulk Mod (GPa)	Shear Mod (GPa)	Shear Mod (GPa	Shear Mod (GPa)
294		5	200.729	88.280	133.152	171.564	81.741	103.219	76.908	33.440	51.810

And, observe in the Formula bar the Function entered for Shear Mod of SS304 in cell I294:

I294 =Shear_Modulus(C294,D285)

	A	B	C	D	E	F	G	H	I	J	K
284		Material		Poisson's ratio							
285		SS 304	nu_SS304 =	0.305							
286		AL	nu_AL =	0.32							
287		BeCu	nu_BeCu =	0.285							
288											
289		Calculations:									
290											
291											
292			SS 304	AL-2024-T4	BeCu	SS 304	AL-2024-T4	BeCu	SS 304	AL-2024-T4	BeCu
293		Temp (K)	Youngs Mod (Gpa)	Youngs Mod (GPa)	Youngs Mod (GPa)	Bulk Mod (GPa)	Bulk Mod (GpP)	Bulk Mod (GPa)	Shear Mod (GPa)	Shear Mod (GPa	Shear Mod (GPa)
294		5	200.729	88.280	133.152	171.564	81.741	103.219	76.908	33.440	51.810

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Now, the final results for variation of Young's Mod with temp are:

C294 =Youngs_Modulus_SS304(B294)

	A	B	C	D	E
290					
291					
292			SS 304	AL-2024-T4	BeCu
293		Temp (K)	Youngs Mod (Gpa)	Youngs Mod (GPa)	Youngs Mod (GPa)
294		5	200.729	88.280	133.152
295		20	198.801	87.203	132.416
296		40	196.214	85.755	131.450
297		60	193.613	84.306	130.499
298		80	190.998	82.867	129.561
299		100	188.372	81.449	128.635
300		120	185.736	80.065	127.717
301		140	183.092	78.726	126.806
302		160	180.443	77.444	125.900
303		180	177.789	76.230	124.996
304		200	175.133	75.097	124.093
305		220	172.476	74.055	123.187
306		240	169.821	73.117	122.277
307		260	167.169	72.295	121.361
308		280	164.522	71.599	120.437
309		300	161.882	71.043	119.501

And, the final results for variation of Bulk Mod and Shear Mod with temp are:

	F	G	H	I	J	K	L
290							
291							
292	SS 304	AL-2024-T4	BeCu	SS 304	AL-2024-T4	BeCu	
293	Bulk Mod (GPa)	Bulk Mod (GpP)	Bulk Mod (GPa)	Shear Mod (GPa)	Shear Mod (GPa)	Shear Mod (GPa)	Temp (K)
294	171.564	81.741	103.219	76.908	33.440	51.810	5
295	169.915	80.743	102.648	76.169	33.031	51.524	20
296	167.705	79.403	101.899	75.178	32.483	51.148	40
297	165.481	78.061	101.162	74.181	31.934	50.778	60
298	163.246	76.729	100.435	73.179	31.389	50.413	80
299	161.002	75.416	99.717	72.173	30.852	50.052	100
300	158.749	74.135	99.006	71.163	30.328	49.695	120
301	156.489	72.895	98.300	70.150	29.821	49.341	140
302	154.225	71.707	97.597	69.135	29.335	48.988	160
303	151.956	70.584	96.896	68.118	28.875	48.637	180
304	149.686	69.534	96.196	67.101	28.446	48.285	200
305	147.415	68.570	95.494	66.083	28.051	47.933	220
306	145.146	67.701	94.789	65.065	27.696	47.579	240
307	142.879	66.940	94.078	64.049	27.384	47.222	260
308	140.617	66.296	93.362	63.035	27.121	46.862	280
309	138.360	65.780	92.637	62.024	26.910	46.499	300

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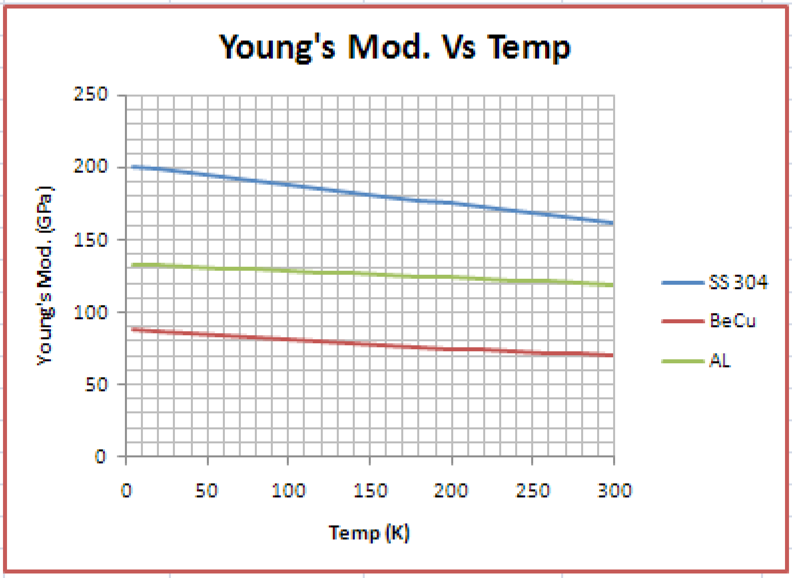
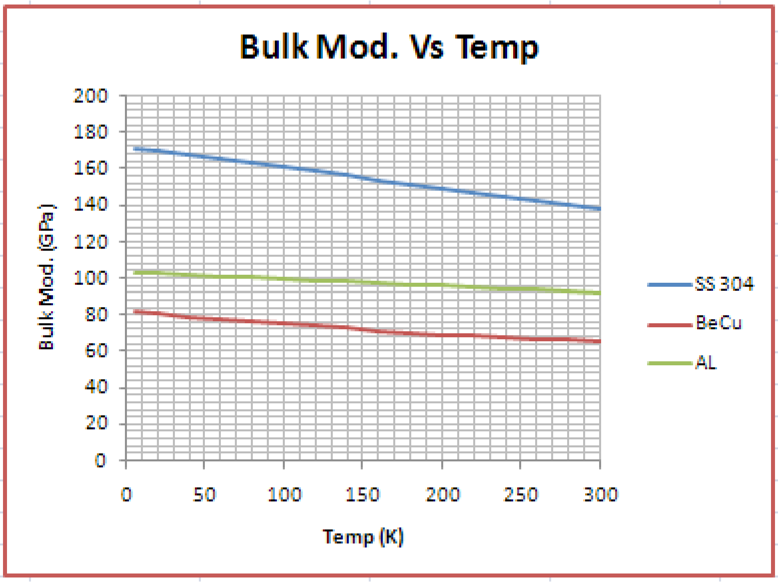
Now, draw the graphs for Young's Mod, Bulk Mod and Shear Mod against Temp in EXCEL:





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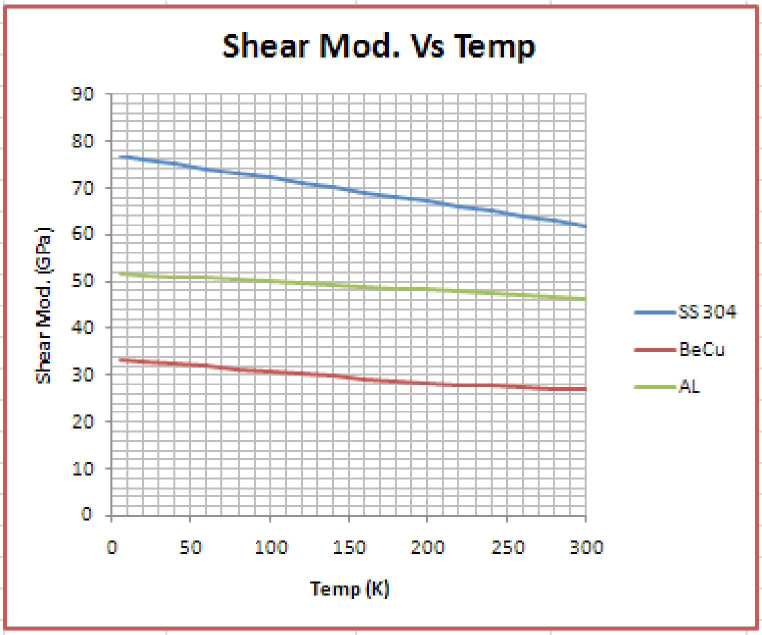
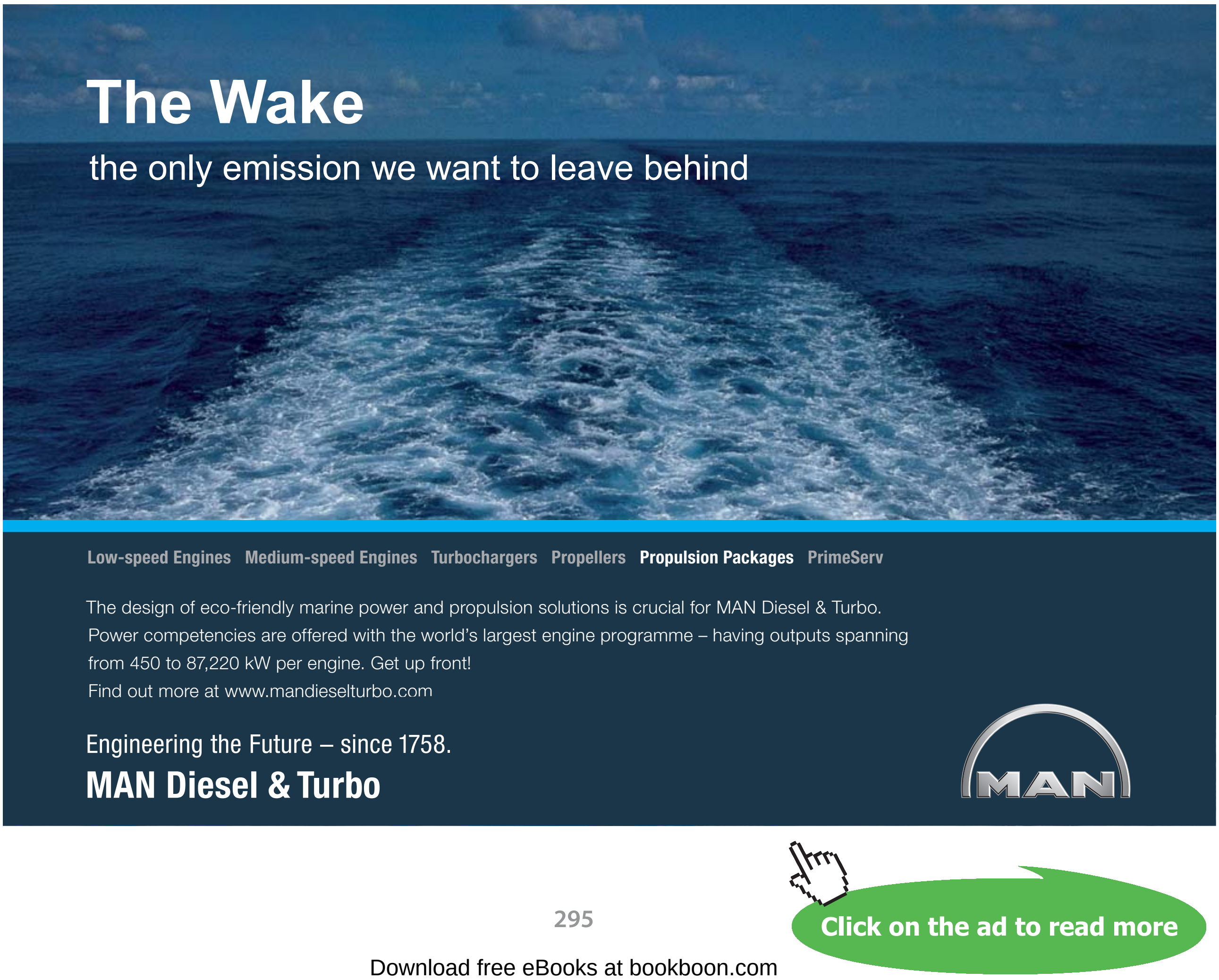


2.4 Problems solved with MathCad:

Pob. 2.4.1 Write Mathcad Functions for Thermal conductivities of SS 304, OFHCcopper, AL-6061-T6, AL-1100, Beryllium copper, Brass, Invar, Lead, Nylon, Teflon, Pyrex, G10-norm(direction) and G10-warp(direction).



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Solution:

Curve fit equations for thermal conductivity (k) and specific heat (cp), given in NIST-Cryogenics website are of following form:

Curve fit equation of the form:

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

Solves as:

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

Where: Coefficients a - *i* are summarized in the appropriate table and T is the temperature in K (x-axis), and y is the property to solve for.

First, put the coefficients given in NIST-cryogenics equations for thermal conductivity in respective data vectors:

$$coeff\_SS304 := \begin{bmatrix} -1.4087 \\ 1.3982 \\ 0.2543 \\ -0.626 \\ 0.2334 \\ 0.4256 \\ -0.4658 \\ 0.165 \\ -0.0199 \end{bmatrix} \quad coeff\_OFHC\_Cu := \begin{bmatrix} 2.8075 \\ -0.54074 \\ -1.2777 \\ 0.15362 \\ 0.36444 \\ -0.02105 \\ -0.051727 \\ 0.0012226 \\ 0.0030964 \end{bmatrix} \quad coeff\_6061AL\_T6 := \begin{bmatrix} 0.07981 \\ 1.0957 \\ -0.07277 \\ 0.08084 \\ 0.02803 \\ -0.09464 \\ 0.04179 \\ -0.00571 \\ 0.0 \end{bmatrix}$$

$$coeff\_AL\_1100 := \begin{bmatrix} 23.39172 \\ -148.5733 \\ 422.1917 \\ -653.6664 \\ 607.0402 \\ -346.152 \\ 118.4276 \\ -22.2781 \\ 1.77019 \end{bmatrix} \quad coeff\_Invar := \begin{bmatrix} -2.7064 \\ 8.5191 \\ -15.923 \\ 18.276 \\ -11.9116 \\ 4.40318 \\ -0.86018 \\ 0.068508 \\ 0 \end{bmatrix} \quad coeff\_Lead := \begin{bmatrix} 38.963479 \\ -221.40505 \\ 597.56622 \\ -900.93831 \\ 816.40461 \\ -455.08342 \\ 152.94025 \\ -28.451163 \\ 2.2516244 \end{bmatrix}$$

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$$coeff\_Nylon := \begin{bmatrix} -2.6135 \\ 2.3239 \\ -4.7586 \\ 7.1602 \\ -4.9155 \\ 1.6324 \\ -0.2507 \\ 0.0131 \\ 0 \end{bmatrix} \quad coeff\_Teflon := \begin{bmatrix} 2.738 \\ -30.677 \\ 89.43 \\ -136.99 \\ 124.69 \\ -69.556 \\ 23.32 \\ -4.3135 \\ 0.33829 \end{bmatrix} \quad coeff\_G10norm := \begin{bmatrix} -4.1236 \\ 13.788 \\ -26.068 \\ 26.272 \\ -14.663 \\ 4.4954 \\ -0.6905 \\ 0.0397 \\ 0.0 \end{bmatrix}$$

$$coeff\_G10warp := \begin{bmatrix} -2.64827 \\ 8.80228 \\ -24.8998 \\ 41.1625 \\ -39.8754 \\ 23.1778 \\ -7.95635 \\ 1.48806 \\ -0.11701 \end{bmatrix}$$

Now, write the Mathcad Functions using the equations given in NIST-cryogenics:

For SS 304: (Ref: NIST-Cryogenics)

k in W/m.K, and, T in K

$$k\_SS304(T) := \left| \begin{array}{l} \text{return "T should be between 1 K and 300 K !!" if } T<1 \\ \text{return "T should be between 1 K and 300 K !!" if } T>300 \\ 10^{\sum_{i=0}^{8} coeff\_SS304_i \cdot \log(T)^i} \end{array} \right.$$

Ex: $k\_SS304(80) = 8.114$ W/m.K

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For OFHCcopper: (Ref: NIST-Cryogenics)

k in W/m.K, and, T in K

$$k\_OFHC\_Cu(T) := \left| \begin{array}{l} \text{return "T should be between 4 K and 300 K !!" if } T<4 \\ \text{return "T should be between 4 K and 300 K !!" if } T>300 \\ 10^{\frac{\left(coeff\_OFHC\_Cu_0 + coeff\_OFHC\_Cu_2 \cdot T^{0.5} + coeff\_OFHC\_Cu_4 \cdot T + coeff\_OFHC\_Cu_6 \cdot T^{1.5} + coeff\_OFHC\_Cu_8 \cdot T^2\right)}{\left(1 + coeff\_OFHC\_Cu_1 \cdot T^{0.5} + coeff\_OFHC\_Cu_3 \cdot T + coeff\_OFHC\_Cu_5 \cdot T^{1.5} + coeff\_OFHC\_Cu_7 \cdot T^2\right)}} \end{array} \right.$$

Ex: $k\_OFHC\_Cu(80) = 558.037$ W/m.K

For AL- 6061-T6: (Ref: NIST-Cryogenics)
k in W/m.K, and, T in K

$$k\_AL\_6061\_T6(T) := \left| \begin{array}{l} \text{return "T should be between 1 K and 300 K !!" if } T<1 \\ \text{return "T should be between 1 K and 300 K !!" if } T>300 \\ 10^{\sum_{i=0}^{8} coeff\_6061AL\_T6_i \cdot \log(T)^i} \end{array} \right.$$

Ex: $k\_AL\_6061\_T6(80) = 85.685$ W/m.K

For AL- 1100: (Ref: NIST-Cryogenics)
k in W/m.K, and, T in K

$$k\_AL\_1100(T) := \left| \begin{array}{l} \text{return "T should be between 4 K and 300 K !!" if } T<4 \\ \text{return "T should be between 1 K and 300 K !!" if } T>300 \\ 10^{\sum_{i=0}^{8} coeff\_AL\_1100_i \cdot \log(T)^i} \end{array} \right.$$

Ex: $k\_AL\_1100(80) = 283.683$ W/m.K

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For Beryllium copper: (Ref: Barron, digitized and curve fitted)

k in W/m.K, and, T in K

$$k\_BeCu(T) := \begin{vmatrix} \text{return "T should be between 1 K and 410 K !!" if } T<1 \\ \text{return "T should be between 1 K and 410 K !!" if } T>410 \\ -0.0000000051081\cdot T^4 + 0.0000051763\cdot T^3 - 0.0019319\cdot T^2 + 0.44129\cdot T - 0.13556 \end{vmatrix}$$

Ex: $k\_BeCu(80) = 25.245$ W/m.K

For Brass: (Ref:Van Sciever, digitized and curve fitted)

k in W/m.K, and, T in K

$$k\_Brass(T) := \begin{vmatrix} \text{return "T should be between 4 K and 300 K !!" if } T<4 \\ \text{return "T should be between 4 K and 300 K !!" if } T>300 \\ -0.000000021929\cdot T^4 + 0.000021989\cdot T^3 - 0.0084043\cdot T^2 + 1.5971\cdot T - 3.2756 \end{vmatrix}$$

Ex: $k\_Brass(80) = 81.065$ W/m.K

For Invar: (Ref: NIST-Cryogenics)

k in W/m.K, and, T in K

$$k\_Invar(T) := \begin{vmatrix} \text{return "T should be between 4 K and 300 K !!" if } T<4 \\ \text{return "T should be between 4 K and 300 K !!" if } T>300 \\ 10^{\sum_{i=0}^{8} coeff\_Invar_i \cdot \log(T)^i} \end{vmatrix}$$

Ex: $k\_Invar(80) = 6.386$ W/m.K

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For Lead: (Ref: NIST-Cryogenics)

k in W/m.K, and, T in K

$$k\_Lead(T) := \begin{cases} \text{return "T should be between 5 K and 295 K !!"} & \text{if } T < 5 \\ \text{return "T should be between 5 K and 295 K !!"} & \text{if } T > 295 \\ 10^{\sum_{i=0}^{8} coeff\_Lead_i \cdot \log(T)^i} & \end{cases}$$

Ex: $k\_Lead(80) = 36.981$ W/m.K

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For Nylon: (Ref: NIST-Cryogenics)

$$k\_Nylon(T) := \begin{array}{|l} \text{return "T should be between 1 K and 300 K !!" if } T<1 \\ \text{return "T should be between 1 K and 300 K !!" if } T>300 \\ 10^{\sum_{i=0}^{8} coeff\_Nylon_i \cdot \log(T)^i} \end{array}$$

Ex: $k\_Nylon(80) = 0.297$ W/m.K

For Teflon: (Ref: NIST-Cryogenics)

k in W/m.K, and, T in K

$$k\_Teflon(T) := \begin{array}{|l} \text{return "T should be between 4 K and 300 K !!" if } T<4 \\ \text{return "T should be between 4 K and 300 K !!" if } T>300 \\ 10^{\sum_{i=0}^{8} coeff\_Teflon_i \cdot \log(T)^i} \end{array}$$

Ex: $k\_Teflon(80) = 0.234$ W/m.K

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For Pyrex:

Ref: Graphs from (Ref:Van Sciever, digitized and curve fitted with 'Curve Expert'.

k in W/m.K, and, T in K

$$k\_Pyrex(T) := \left| \begin{array}{l} \text{return "T should be between 4 K and 300 K !!" if } T < 4 \\ \text{return "T should be between 4 K and 300 K !!" if } T > 300 \\ a \leftarrow 0.10576279 \\ b \leftarrow 4300.1909 \\ c \leftarrow 1.2216365 \\ d \leftarrow 1.7397766 \\ \dfrac{\left(a \cdot b + c \cdot T^{d}\right)}{\left(b + T^{d}\right)} \end{array} \right.$$

Ex: $k\_Pyrex(80) = 0.466$ W/m.K

For G10, Th. cond. in normal direction: (Ref: NIST-Cryogenics)

k in W/m.K, and, T in K

$$k\_G10norm(T) := \left| \begin{array}{l} \text{return "T should be between 10 K and 300 K !!" if } T < 10 \\ \text{return "T should be between 10 K and 300 K !!" if } T > 300 \\ 10^{\sum_{i=0}^{8} coeff\_G10norm_i \cdot \log(T)^i} \end{array} \right.$$

Ex: $k\_G10norm(80) = 0.284$ W/m.K

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For G10, Th. cond. in warp direction: (Ref: NIST-Cryogenics)

k in W/m.K, and, T in K

$$k\_G10warp(T) := \begin{array}{|l} \text{return "T should be between 12 K and 300 K !!" if } T<12 \\ \text{return "T should be between 12 K and 300 K !!" if } T>300 \\ 10^{\sum_{i=0}^{8} coeff\_G10warp_i \cdot \log(T)^i} \end{array}$$

Ex: $k\_G10warp(80) = 0.394$ W/m.K

Prob. 2.4.2 Plot the k values against T, for a few materials, using the Mathcad Functions written above.

The procedure is quite simple:

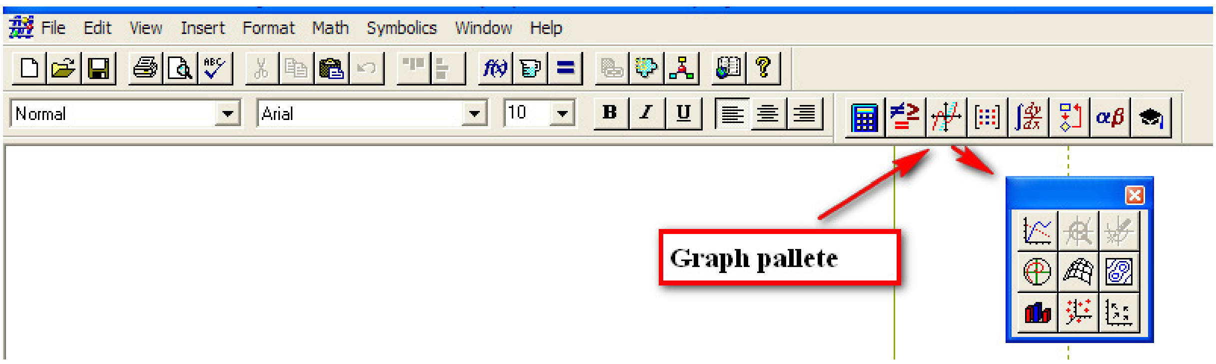
First, define the range variables, which will go on the x-axis in our case:

$t := 4, 6 .. 300$ ....define the range variable t

$tnorm := 10, 12 .. 300$ ....define the range variable tnorm

$twarp := 12, 14 .. 300$ ....define the range variable twarp

Press graph pallete and in the resulting choices press the top, left symbol for x-y graph.



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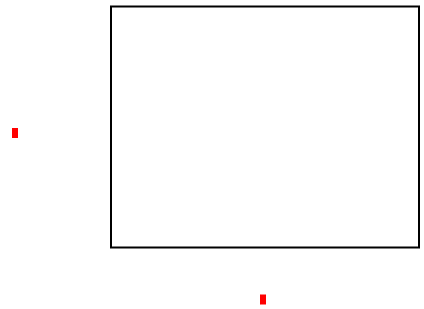
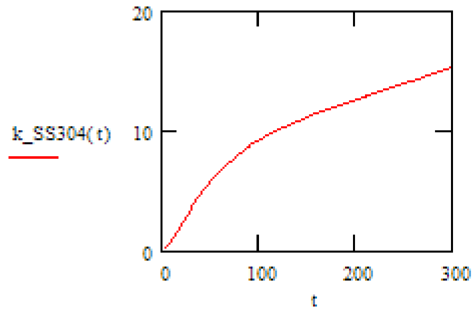
Alternatively, press Shift+2, and in either case, we get:



Fill in for the place holders in the x-axis and y-axis, t and k_SS304(T) respectively. Click elsewhere in the worksheet and we get:



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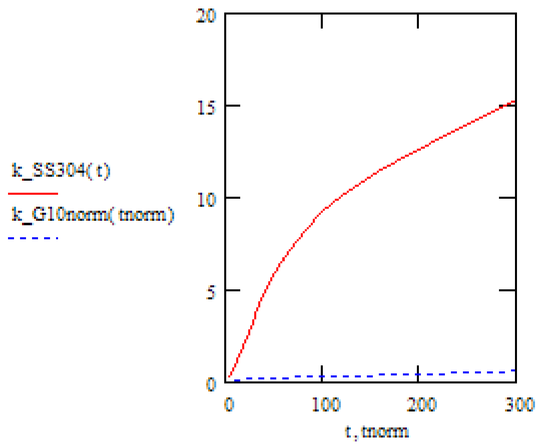
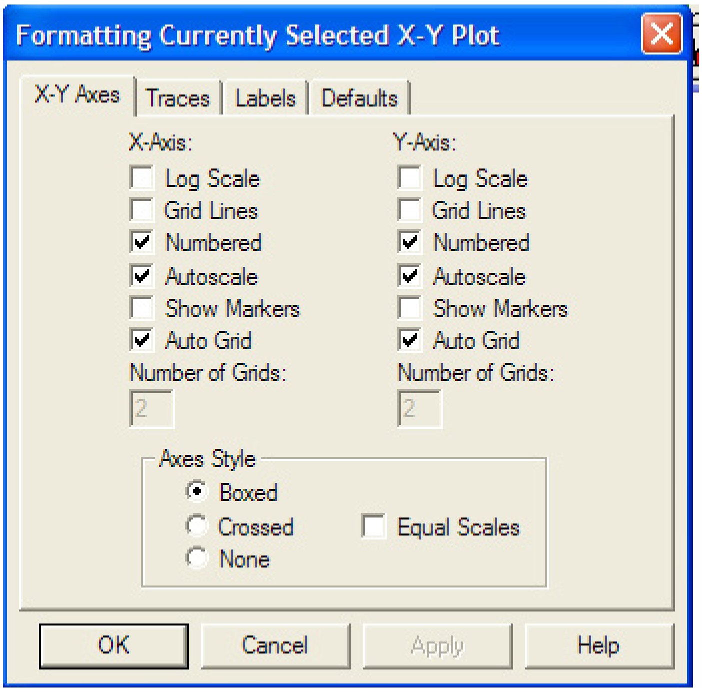
To draw the next set of graphs, fill in the next (x, y) pair, and we get:



Double click on the graph, and the formatting options appear:



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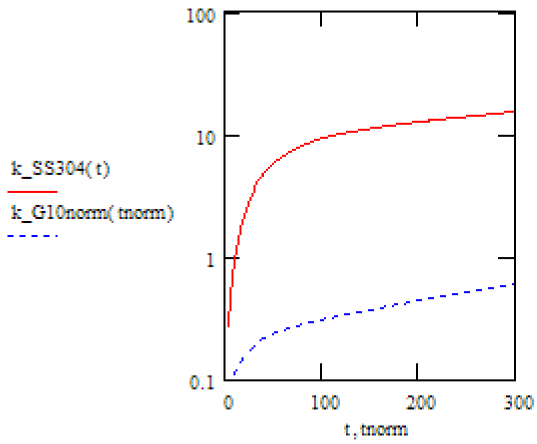
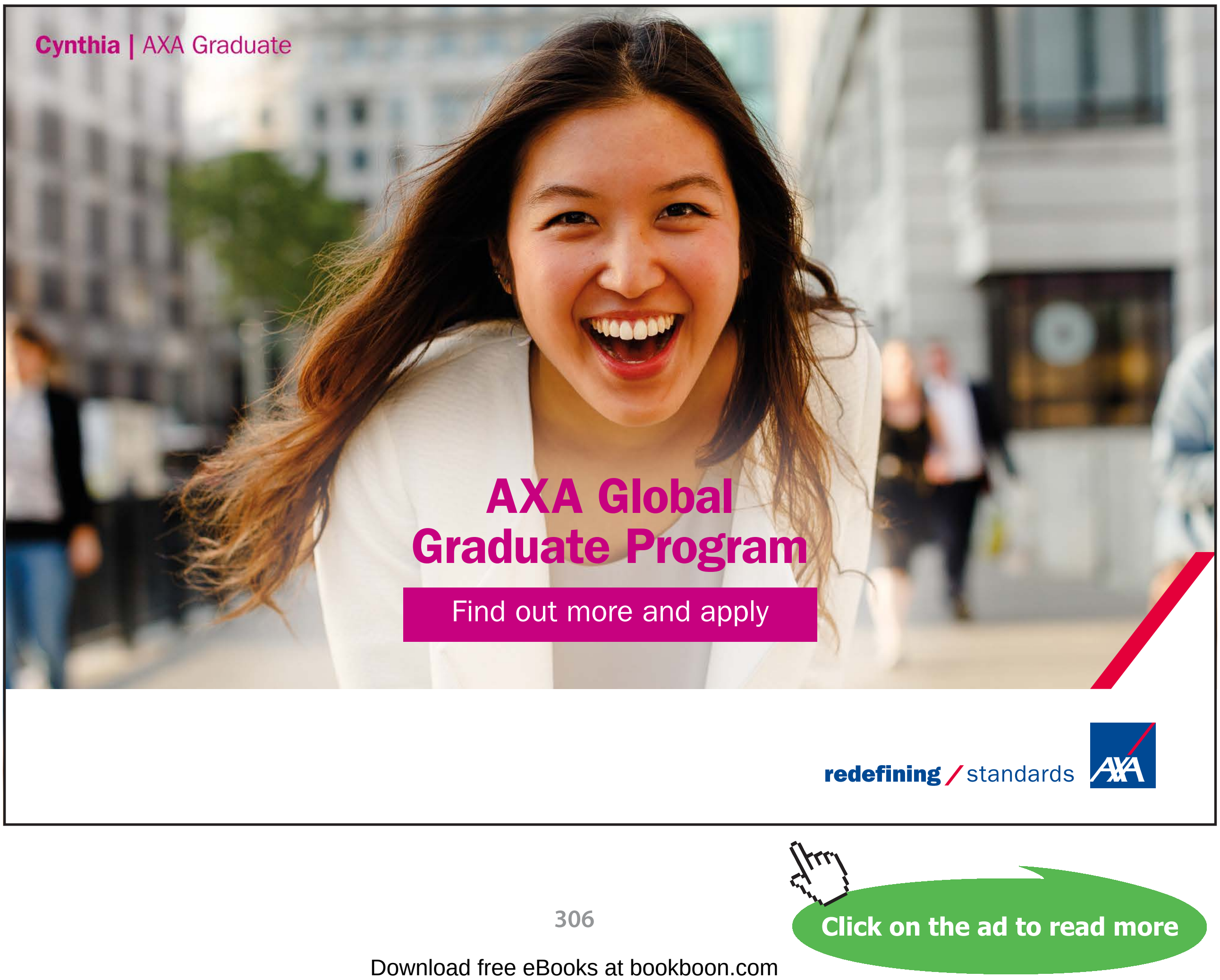
Choose log scale for y-axis. We get:





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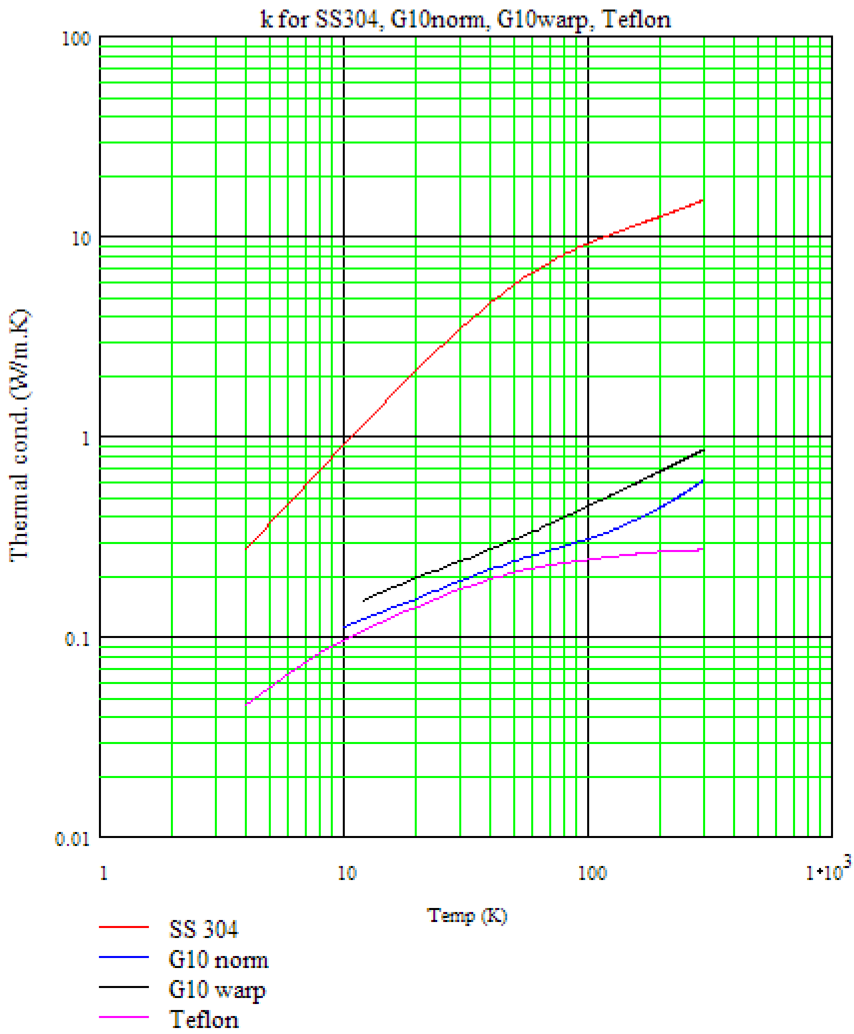
Final, formatted plot is:



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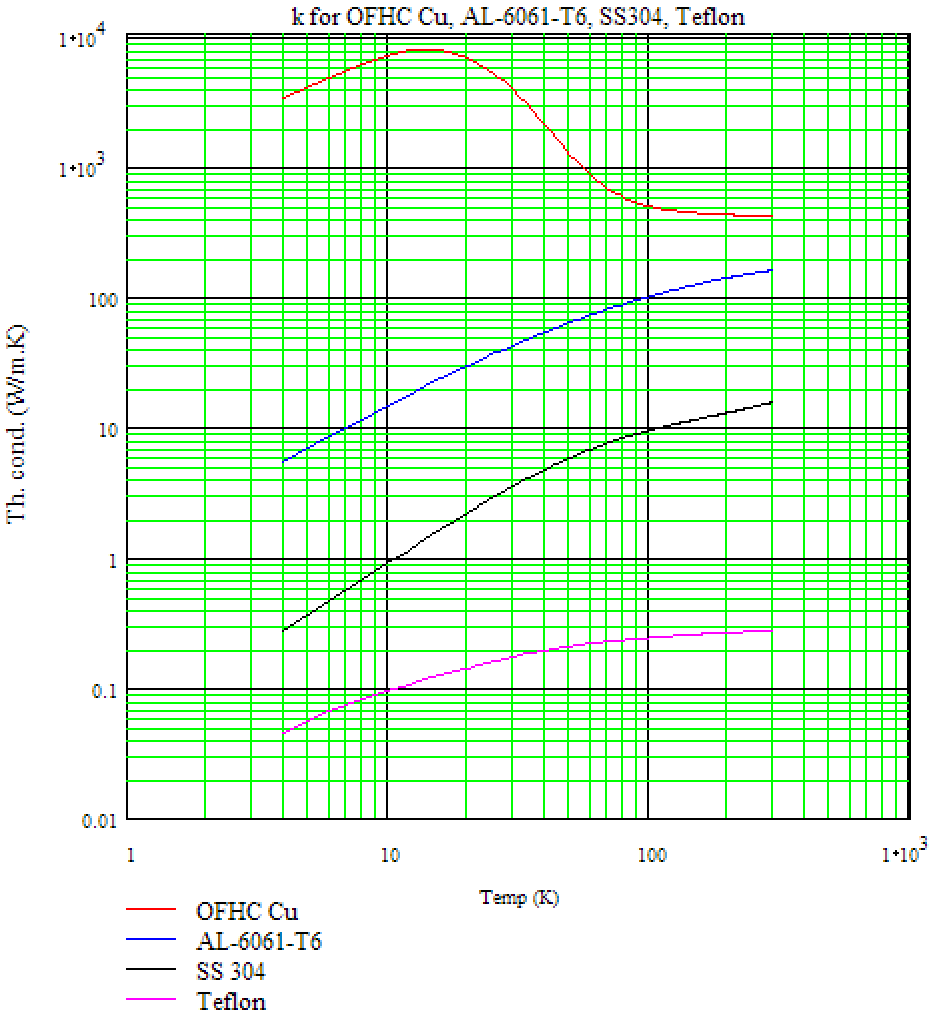
Similarly, draw other graphs:



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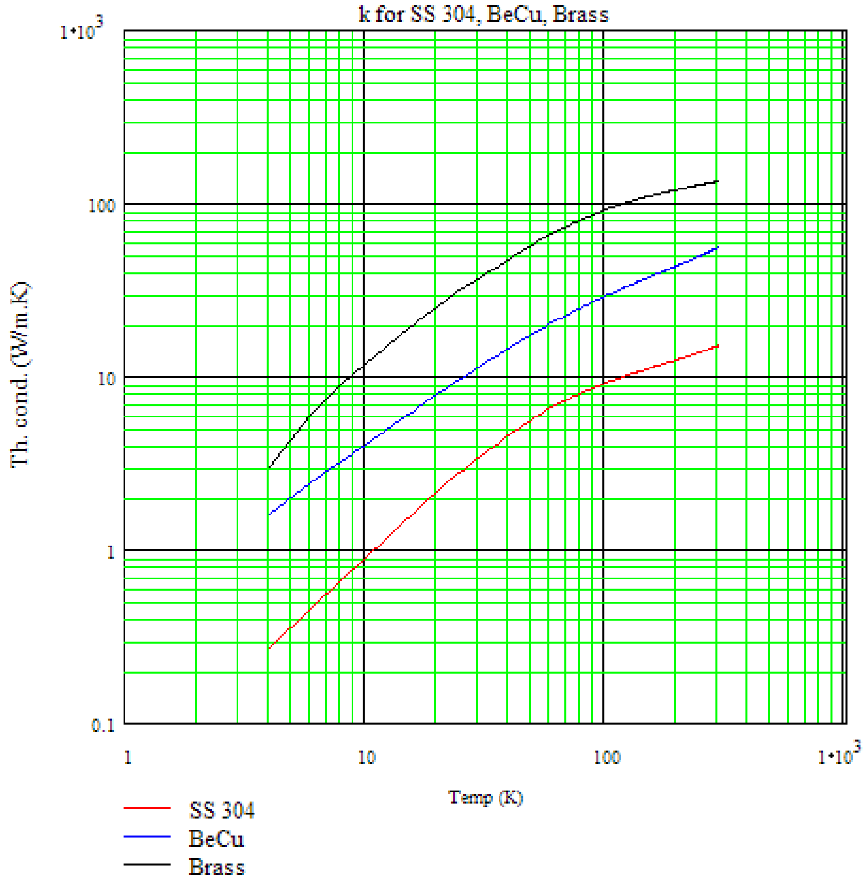

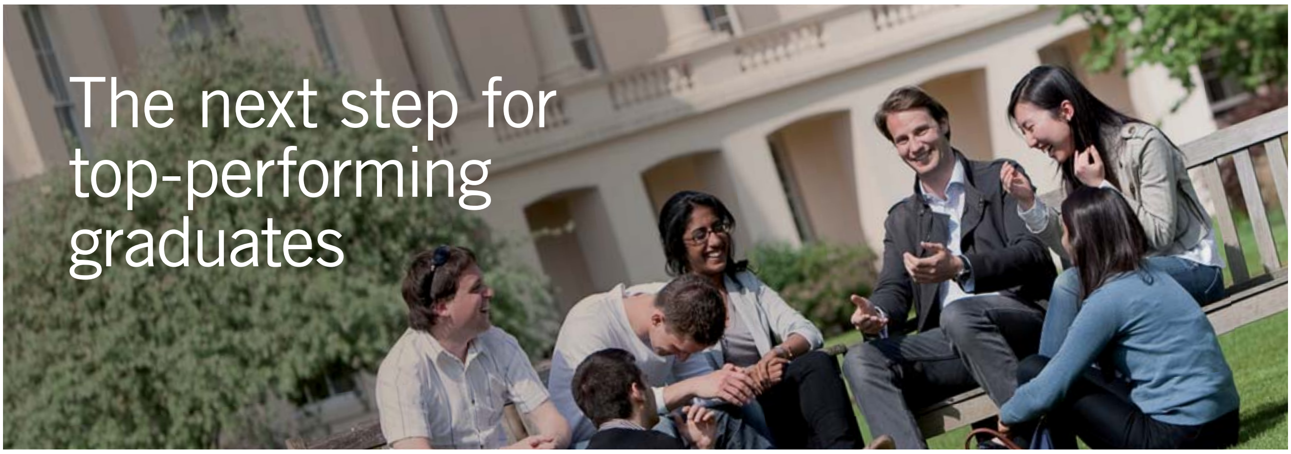

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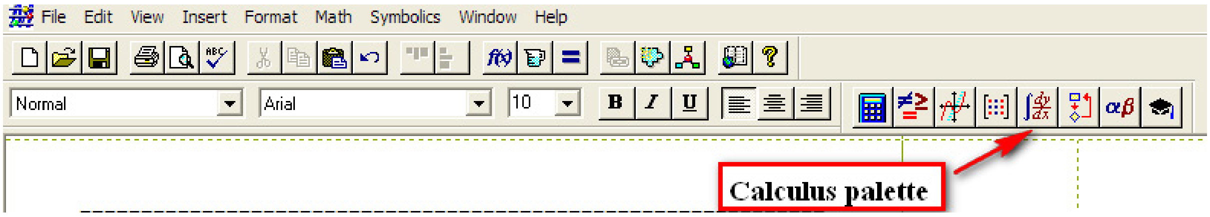
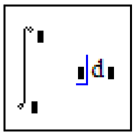
Prob.2.4.3 Write Mathcad Functions for Thermal conductivity Integrals of various materials between temperatures Tmin and Tmax.

Click on Calculus palette:



We get:

Now, click on the definite integral sign, and we get:



And, fill in the place holders, as will be shown below in the Functions:

For SS 304:

$$\mathrm{Thcond\_Integral\_SS304}(\mathrm{Tmin}, \mathrm{Tmax}) := \int_{\mathrm{Tmin}}^{\mathrm{Tmax}} \mathrm{k\_SS304}(T)\, dT$$

Ex: $\mathrm{Thcond\_Integral\_SS304}(20, 80) = 331.491$ W/m....between 20 K and 80 K

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For OFHC copper:

$$\text{Thcond\_Integral\_OFHC\_Cu}(\text{Tmin}, \text{Tmax}) := \int_{\text{Tmin}}^{\text{Tmax}} \text{k\_OFHC\_Cu}(T)\, dT$$

Ex: $\text{Thcond\_Integral\_OFHC\_Cu}(20, 80) = 1.16629 \cdot 10^{5}$ W/m....between 20 K and 80 K

For BeCu:

$$\text{Thcond\_Integral\_BeCu}(\text{Tmin}, \text{Tmax}) := \int_{\text{Tmin}}^{\text{Tmax}} \text{k\_BeCu}(T)\, dT$$

Ex: $\text{Thcond\_Integral\_BeCu}(20, 80) = 1.0406 \cdot 10^{3}$ W/m

---

For Brass:

$$\text{Thcond\_Integral\_Brass}(\text{Tmin}, \text{Tmax}) := \int_{\text{Tmin}}^{\text{Tmax}} \text{k\_Brass}(T)\, dT$$

Ex: $\text{Thcond\_Integral\_Brass}(20, 80) = 3.3928 \cdot 10^{3}$ W/m....between 20 K and 80 K

For Invar:

$$\text{Thcond\_Integral\_Invar}(\text{Tmin}, \text{Tmax}) := \int_{\text{Tmin}}^{\text{Tmax}} \text{k\_Invar}(T)\, dT$$

Ex: $\text{Thcond\_Integral\_Invar}(20, 80) = 250.19$ W/m....between 20 K and 80 K

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For Lead:

$$\text{Thcond\_Integral\_Lead}(\text{Tmin}, \text{Tmax}) := \int_{\text{Tmin}}^{\text{Tmax}} \text{k\_Lead}(T)\, dT$$

Ex: $\text{Thcond\_Integral\_Lead}(20, 80) = 2.4888 \cdot 10^{3}$ W/m....between 20 K and 80 K

For Nylon:

$$\text{Thcond\_Integral\_Nylon}(\text{Tmin}, \text{Tmax}) := \int_{\text{Tmin}}^{\text{Tmax}} \text{k\_Nylon}(T)\, dT$$

Ex: $\text{Thcond\_Integral\_Nylon}(20, 80) = 13.352$ W/m....between 20 K and 80 K

For Teflon:

$$\text{Thcond\_Integral\_Teflon}(\text{Tmin}, \text{Tmax}) := \int_{\text{Tmin}}^{\text{Tmax}} \text{k\_Teflon}(T)\, dT$$

Ex: $\text{Thcond\_Integral\_Teflon}(20, 80) = 12.182$ W/m....between 20 K and 80 K

For Pyrex:

$$\text{Thcond\_Integral\_Pyrex}(\text{Tmin}, \text{Tmax}) := \int_{\text{Tmin}}^{\text{Tmax}} \text{k\_Pyrex}(T)\, dT$$

Ex: $\text{Thcond\_Integral\_Pyrex}(20, 80) = 18.1309$ W/m....between 20 K and 80 K

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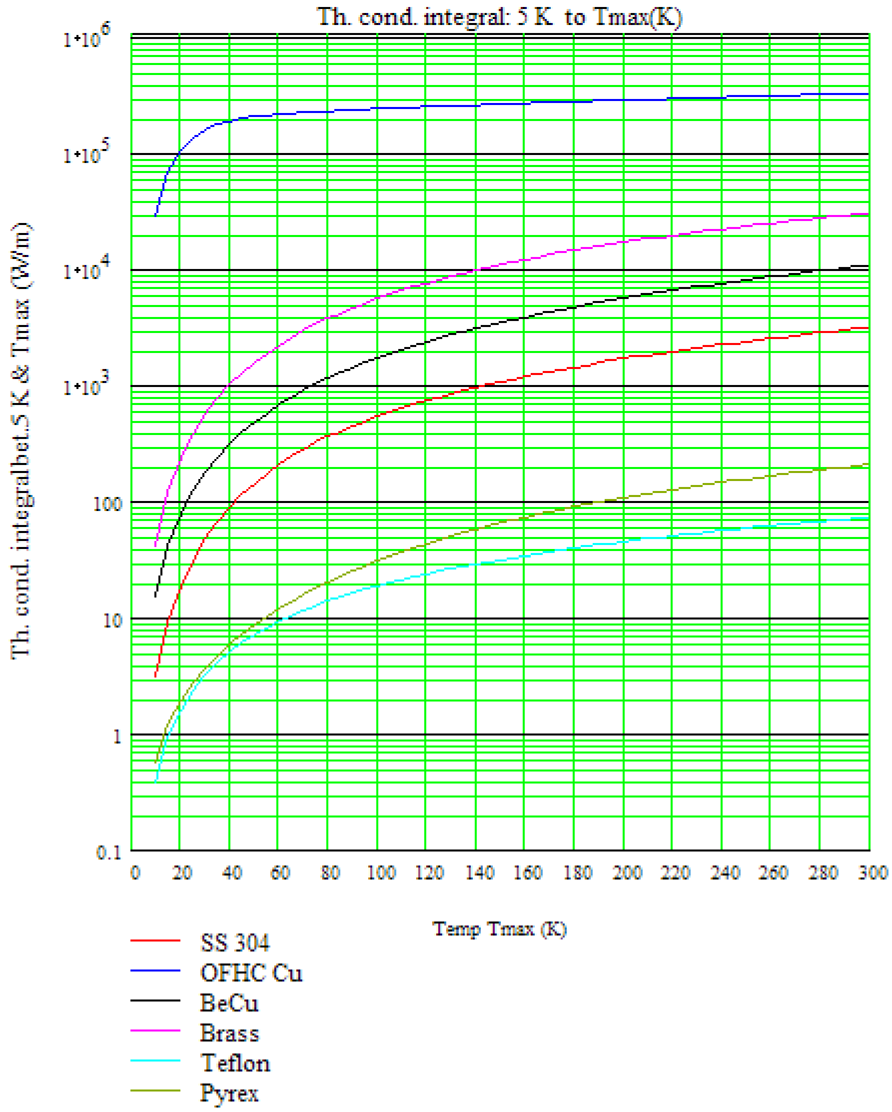
Prob. 2.4.4 Plot Thermal cond. Integrals for a few materials.

Tmin := 5

Tmax := 5, 10.. 300 ...define a range variable



Prob. 2.4.5 Write a Mathcad Function to find specific heat by Debye Theory when T and TbyThetaD are given.

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Solution:

Following Mathcad Function gives CvbyR as a function of TbyThetaD…Ref: Barron

Curve fitted with 'Curve Expert'.

ThetaD = Debye Temp (K), T in K

Note: R = Ru/M where Ru = 8314.47 J/kg.K, M = Mol. wt. of material

$$\mathrm{CvbyR(TbyThetaD)} := \left| \begin{array}{l} \text{return } 233.8 \cdot \mathrm{TbyThetaD}^3 \text{ if } \mathrm{TbyThetaD} < 0.05 \\ \text{return } 3 \text{ if } \mathrm{TbyThetaD} > 5 \\ a \leftarrow -0.037636752 \\ b \leftarrow 0.036770896 \\ c \leftarrow 2.9757569 \\ d \leftarrow 2.3784036 \\ \dfrac{\left(a \cdot b + c \cdot \mathrm{TbyThetaD}^d\right)}{\left(b + \mathrm{TbyThetaD}^d\right)} \end{array} \right.$$

Ex: $\mathrm{CvbyR}\left(\frac{25}{385}\right) = 0.08034$ ...for AL at 25 K

Prob. 2.4.6 Using the above Function for CvbyR, plot CvbyR against TbyThetaD:

$\mathrm{TbyThetaD} := 0.01, 0.02 .. 5$ ....define a range variable

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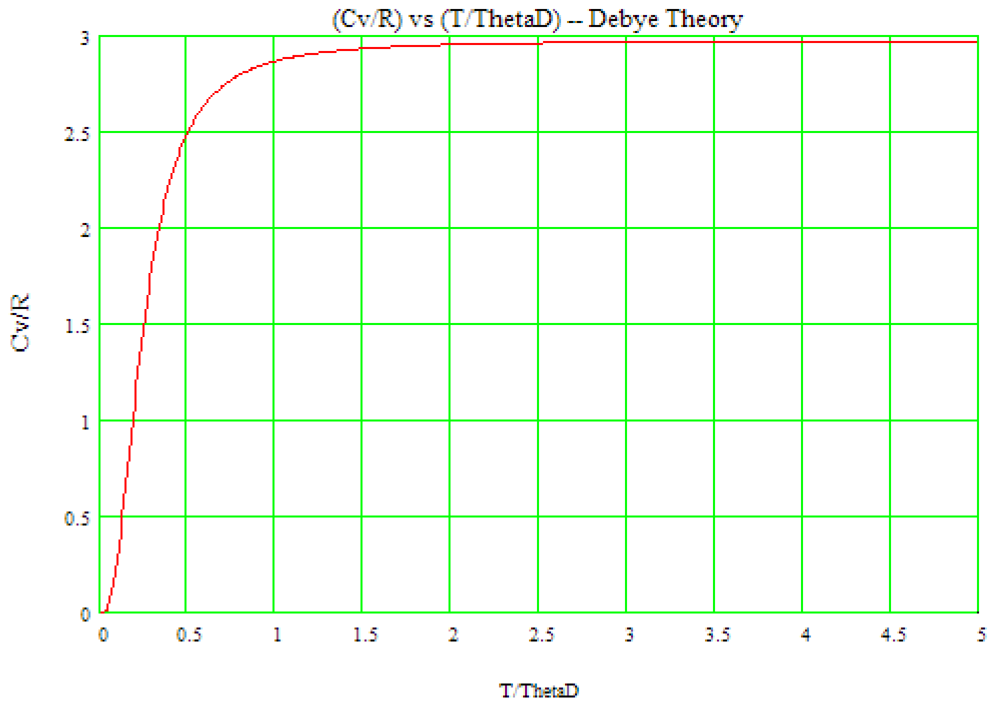

Prob. 2.4.7 Write Mathcad Functions to find specific heats of materials as a function of T.

Solution:

Recollect that equations for cp from NIST are of the following form:

Curve fit equation of the form:

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

Solves as:

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

Where: Coefficients a - i are summarized in the appropriate table and T is the temperature in K (x-axis), and y is the property to solve for.

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First put the coefficients in the NIST-Cryogenics equations for specific heat, in respective data vectors:

$$coeff\_cp\_SS304 := \begin{bmatrix} 22.0061 \\ -127.5528 \\ 303.647 \\ -381.0098 \\ 274.0328 \\ -112.9212 \\ 24.7593 \\ -2.239153 \\ 0 \end{bmatrix} \quad coeff\_cp\_SS304L := \begin{bmatrix} -351.51 \\ 3123.695 \\ -12017.28 \\ 26143.99 \\ -35176.33 \\ 29981.75 \\ -15812.78 \\ 4719.64 \\ -610.515 \end{bmatrix} \quad coeff\_cp\_AL\_6061\_T6 := \begin{bmatrix} 46.6467 \\ -314.292 \\ 866.662 \\ -1298.3 \\ 1162.27 \\ -637.795 \\ 210.351 \\ -38.3094 \\ 2.96344 \end{bmatrix}$$

$$coeff\_cp\_OFHC\_copper := \begin{bmatrix} -1.91844 \\ -0.15973 \\ 8.61013 \\ -18.9964 \\ 21.9661 \\ -12.7328 \\ 3.54322 \\ -0.3797 \\ 0 \end{bmatrix} \quad coeff\_cp\_Nylon := \begin{bmatrix} -5.2929 \\ 25.301 \\ -54.874 \\ 71.061 \\ -52.236 \\ 21.648 \\ -4.7317 \\ 0.42518 \\ 0 \end{bmatrix} \quad coeff\_cp\_Teflon := \begin{bmatrix} 31.88256 \\ -166.51949 \\ 352.01879 \\ -393.44232 \\ 259.98072 \\ -104.61429 \\ 24.99276 \\ -3.20792 \\ 0.16503 \end{bmatrix}$$

Eqn. range: 55 - 300 K   Eqn. range: 4 - 27 K

$$coeff\_cp\_9percentNiSteel := \begin{bmatrix} 15503.108 \\ -37280.377 \\ 26788.417 \\ 7010.0877 \\ -22731.651 \\ 15386.526 \\ -5175.7968 \\ 896.97274 \\ -64.055866 \end{bmatrix} \quad coeff\_cp\_Invar := \begin{bmatrix} 28.08 \\ -228.23 \\ 777.587 \\ -1448.423 \\ 1596.567 \\ -1040.294 \\ 371.2125 \\ -56.004 \\ 0 \end{bmatrix}$$

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Eqn. range: 1- 295 K

$$coeff\_cp\_Pt := \begin{bmatrix} -1.6135538 \\ 0.95823584 \\ 1.431777 \\ -3.5963989 \\ 5.1299735 \\ -2.4186452 \\ -0.12560841 \\ 0.34342394 \\ -0.06198179 \end{bmatrix}$$

Eqn. range: 4- 300 K

$$coeff\_cp\_Kapton := \begin{bmatrix} -1.3684 \\ 0.65892 \\ 2.8719 \\ 0.42651 \\ -3.0088 \\ 1.9558 \\ -0.51998 \\ 0.051574 \\ 0 \end{bmatrix}$$

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cp of SS 304: Ref: NIST- Cryogenics

cp in J/kg.K, T in K

$$cp\_SS304(T) := \begin{cases} \text{return "T should be between 4 K and 300 K !!"} & \text{if } T<4 \\ \text{return "T should be between 4 K and 300 K !!"} & \text{if } T>300 \\ 10^{\sum_{i=0}^{8} coeff\_cp\_SS304_i \cdot \log(T)^i} & \end{cases}$$

Ex: $cp\_SS304(20) = 13.452$ J/kg.K ... at 20 K

----

cp of SS 304L: Ref: NIST- Cryogenics

cp in J/kg.K, T in K

$$cp\_SS304L(T) := \begin{cases} \text{return "T should be between 4 K and 23 K !!"} & \text{if } T<4 \\ \text{return "T should be between 4 K and 23 K !!"} & \text{if } T>23 \\ 10^{\sum_{i=0}^{8} coeff\_cp\_SS304L_i \cdot \log(T)^i} & \end{cases}$$

Ex: $cp\_SS304L(20) = 11.878$ J/kg.K ... at 20 K

----

cp of AL-6061-T6L: Ref: NIST- Cryogenics

cp in J/kg.K, T in K

$$cp\_AL\_6061\_T6(T) := \begin{cases} \text{return "T should be between 4 K and 300 K !!"} & \text{if } T<4 \\ \text{return "T should be between 4 K and 300 K !!"} & \text{if } T>300 \\ 10^{\sum_{i=0}^{8} coeff\_cp\_AL\_6061\_T6_i \cdot \log(T)^i} & \end{cases}$$

Ex: $cp\_AL\_6061\_T6(20) = 8.854$ J/kg.K ... at 20 K

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cp of OFHC copper: Ref: NIST- Cryogenics

cp in J/kg.K, T in K

$$cp\_OFHC\_copper(T) := \left| \begin{array}{l} \text{return "T should be between 4 K and 300 K !!" if } T<4 \\ \text{return "T should be between 4 K and 300 K !!" if } T>300 \\ 10^{\sum_{i=0}^{8} coeff\_cp\_OFHC\_copper_i \cdot \log(T)^i} \end{array} \right.$$

Ex: $cp\_OFHC\_copper(20) = 7.491$ J/kg.K ... at 20 K

---

cp of Nylon: Ref: NIST- Cryogenics

cp in J/kg.K, T in K

$$cp\_Nylon(T) := \left| \begin{array}{l} \text{return "T should be between 4 K and 300 K !!" if } T<4 \\ \text{return "T should be between 4 K and 300 K !!" if } T>300 \\ 10^{\sum_{i=0}^{8} coeff\_cp\_Nylon_i \cdot \log(T)^i} \end{array} \right.$$

Ex: $cp\_Nylon(20) = 99.901$ J/kg.K ... at 20 K

---

cp of Teflon: Ref: NIST- Cryogenics

cp in J/kg.K, T in K

$$cp\_Teflon(T) := \left| \begin{array}{l} \text{return "T should be between 4 K and 300 K !!" if } T<4 \\ \text{return "T should be between 4 K and 300 K !!" if } T>300 \\ 10^{\sum_{i=0}^{8} coeff\_cp\_Teflon_i \cdot \log(T)^i} \end{array} \right.$$

Ex: $cp\_Teflon(20) = 76.792$ J/kg.K ... at 20 K

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cp of 9 % Ni Steel: Ref: NIST- Cryogenics

cp in J/kg.K, T in K

$$cp\_9percentNiSteel(T) := \begin{array}{|l} \text{return "T should be between 55 K and 300 K !!" if } T<55 \\ \text{return "T should be between 55 K and 300 K !!" if } T>300 \\ 10^{\sum_{i=0}^{8} coeff\_cp\_9percentNiSteel_i \cdot \log(T)^i} \end{array}$$

Ex: $cp\_9percentNiSteel(77) = 151.498$ J/kg.K ... at 77 K

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cp of Invar: Ref: NIST- Cryogenics

cp in J/kg.K, T in K

$$cp\_Invar(T) := \begin{cases} \text{return "T should be between 4 K and 27 K !!"} & \text{if } T<4 \\ \text{return "T should be between 4 K and 27 K !!"} & \text{if } T>27 \\ 10^{\sum_{i=0}^{8} coeff\_cp\_Invar_i \cdot \log(T)^i} & \end{cases}$$

Ex: $cp\_Invar(20) = 12.336$ J/kg.K ... at 20 K

---

cp of Platinum: Ref: NIST- Cryogenics

cp in J/kg.K, T in K

$$cp\_Pt(T) := \begin{cases} \text{return "T should be between 1 K and 295 K !!"} & \text{if } T<1 \\ \text{return "T should be between 1 K and 295 K !!"} & \text{if } T>295 \\ 10^{\sum_{i=0}^{8} coeff\_cp\_Pt_i \cdot \log(T)^i} & \end{cases}$$

Ex: $cp\_Pt(20) = 7.376$ J/kg.K ... at 20 K

---

cp of Kapton: Ref: NIST- Cryogenics

cp in J/kg.K, T in K

$$cp\_Kapton(T) := \begin{cases} \text{return "T should be between 4 K and 300 K !!"} & \text{if } T<4 \\ \text{return "T should be between 4 K and 300 K !!"} & \text{if } T>300 \\ 10^{\sum_{i=0}^{8} coeff\_cp\_Kapton_i \cdot \log(T)^i} & \end{cases}$$

Ex: $cp\_Kapton(80) = 348.942$ J/kg.K ... at 80 K

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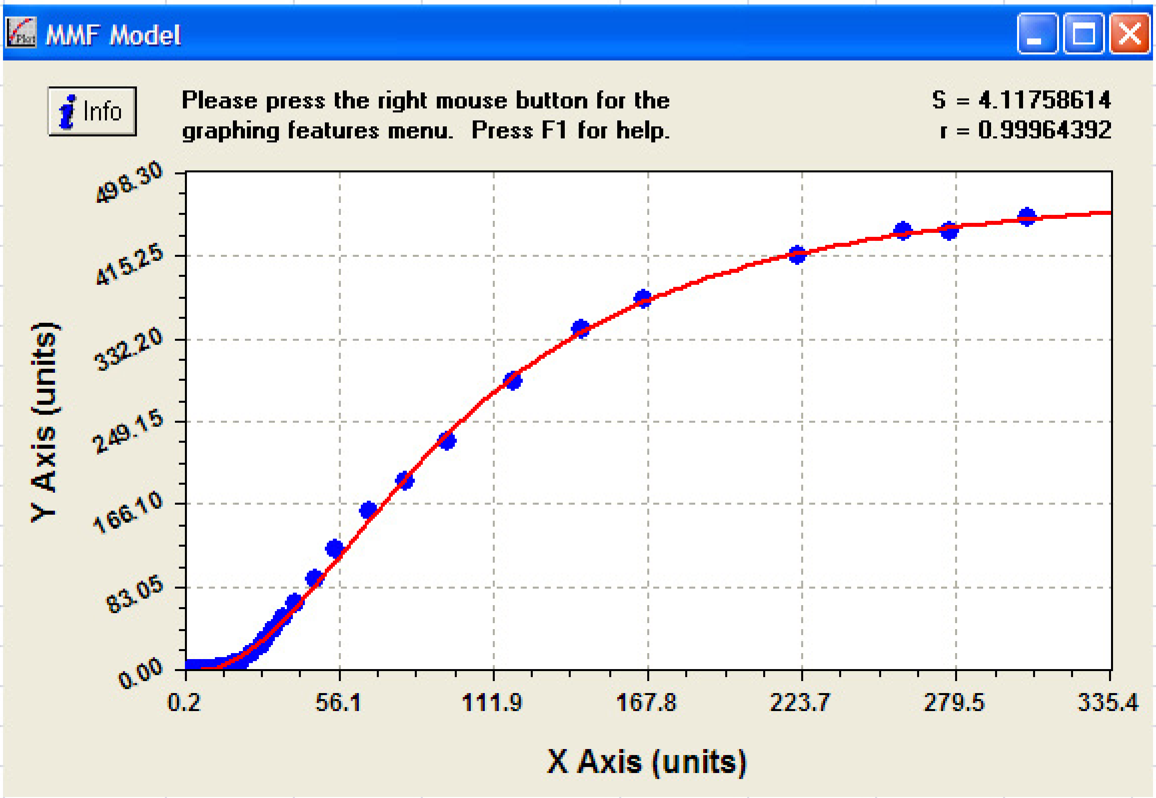
cp of Brass 65/35: Ref: Van Sciever.

In the following Curve Expert graph: x-axis is Temp, y-axis is cp:



MMF Model: y=(a*b+c*x^d)/(b+x^d)		
Coefficient Data:		
a =	-2.7779824	
b =	14383.254	
c =	494.3505	
d =	2.0861122	

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Now, write the Mathcad Function for Brass:

cp of Brass 65/35: Ref: Van Sciever

cp in J/kg.K, T in K

Digitized with Plot Digitizer, and then Curve fitted with 'Curve Expert'.

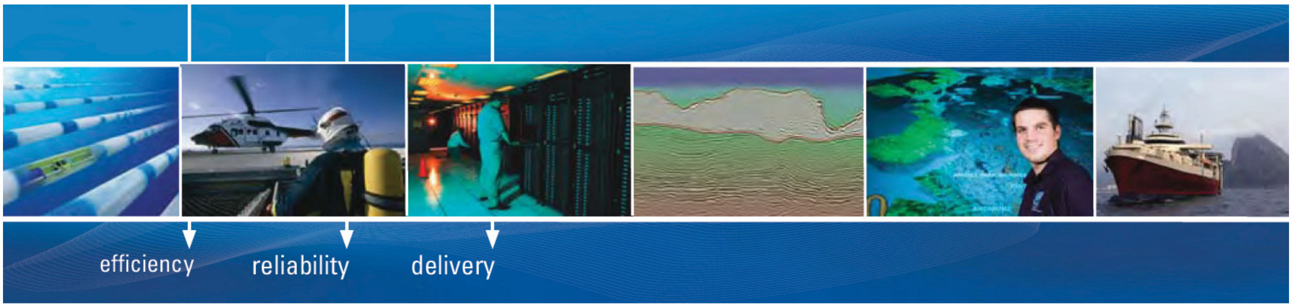
```
cp_Brass(T) := | return "T must be between 2 K and 300 K !!"  if  T<2
               | return "T must be between 2 K and 300 K !!"  if  T>300
               | a ← -2.7779824
               | b ← 14383.254
               | c ← 494.3505
               | d ← 2.0861122
               | (a·b + c·T^d) / (b + T^d)
```

$$cp\_Brass(T) = \frac{\left(a \cdot b + c \cdot T^{d}\right)}{\left(b + T^{d}\right)}$$

Ex: cp_Brass(20) = 14.494 J/kg.K ... at 20 K

---

cp of Pyrex: Ref: [14]



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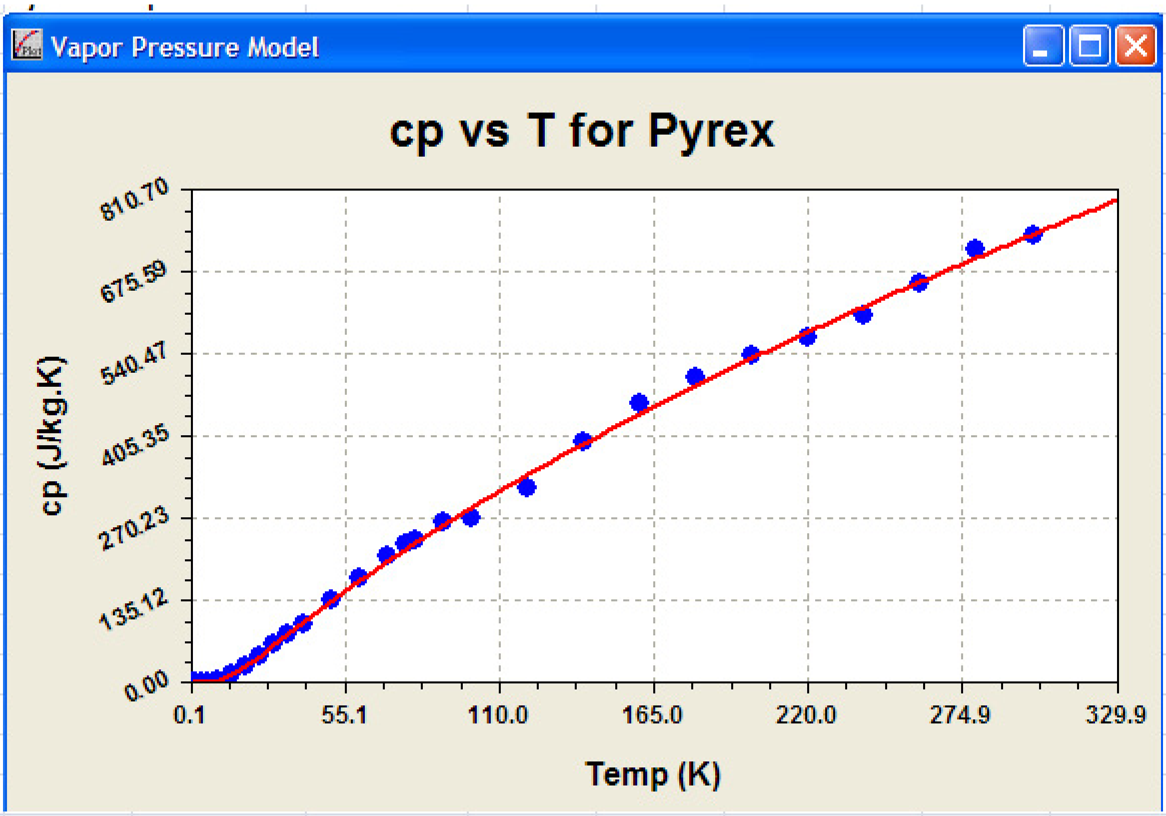
Temp (K)	cp (J/kg.K)
1	0.003
2	0.025
4	0.197
6	0.883
8	2.19
10	4.19
15	13.7
20	27.4
25	44.3
30	62.8
35	80.5
40	98.4
50	136
60	174
70	209

Temp (K)	cp (J/kg.K)
77	229
80	237
90	264
100	272
120	321
140	396
160	459
180	502
200	539
220	570
240	606
260	659
280	714
300	737

Curve fit with Curve Expert:



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Vapor Pressure Model: y=exp(a+b/x+cln(x))		
Coefficient Data:		
a =	2.8634691	
b =	-29.672679	
c =	0.67340045	

Now, write the Mathcad Function for cp of Pyrex using the above curve fit equation:

cp of Pyrex: Ref:[14], Patxi Duthil

cp in J/kg.K, T in K

Digitized with Plot Digitizer, and then Curve fitted with 'Curve Expert'.

```
cp_Pyrex(T) := | return "T must be between 1K and 300 K !!" if T<1
               | return "T must be between 1 K and 300 K !!" if T>300
               | a ← 2.8634691
               | b ← -29.672679
               | c ← 0.67340045
               | exp(a + b/T + c·ln(T))
```

$$cp\_Pyrex(T) = \exp\left(a + \frac{b}{T} + c \cdot \ln(T)\right)$$

Ex: cp_Pyrex(20) = 29.879 J/kg.K ... at 20 K

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cp of Normal Lead…. Ref: BNL Selected Cryogenic Data Notebook – Vol. 1 (Aug. 1980)

Temp (K)	cp(J/kg.K)	Temp (K)	cp(J/kg.K)
1	0.027	10	12.8
1.2	0.037	14	30
1.4	0.05	20	52
1.6	0.07	24	66
1.8	0.09	26	70
2	0.13	30	80
2.2	0.17	36	90
2.4	0.185	40	96
2.6	0.23	45	100
2.8	0.28	50	103
3	0.32	60	110
3.2	0.4	65	111
3.4	0.48	70	112
3.6	0.54	75	113
3.8	0.65	80	114
4	0.75	90	116
4.5	1.05	100	119
5	1.65	120	120
5.5	2.1	160	123
6	3	200	125
6.5	3.95	240	127
7	4.95	300	130
7.5	6.3	310	130
8	7.6		

Put Temp and cp_Lead in two separate vectors and use *linear interpolation* to get cp at the desired temp.

```
cp_Lead(T) := | return "T must be between 1K and 310 K !!"  if  T<1
              | return "T must be between 1 K and 310 K !!"  if  T>310
              | linterp(Temp, cp_Lead, T)
```

Ex: cp_Lead(25) = 68   J/kg.K … at 25 K

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Prob. 2.4.8 Write Mathcad Functions to find out Sp. heat Integrals of materials from temp Tmin to Tmax.:

Solution:

We shall proceed exactly as we did in the case of Thermal conductivity integrals:

For SS 304:

$$\text{SpHeat\_Integral\_SS304}(\text{Tmin}, \text{Tmax}) := \int_{\text{Tmin}}^{\text{Tmax}} \text{cp\_SS304}(T)\, dT$$

Ex: $\text{SpHeat\_Integral\_SS304}(77, 300) = 8.658 \cdot 10^{4}$ J/kg

---

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For AL-6061-T6:

$$\text{SpHeat\_Integral\_AL\_6061\_T6}(\text{Tmin}, \text{Tmax}) := \int_{\text{Tmin}}^{\text{Tmax}} \text{cp\_AL\_6061\_T6}(T)\, dT$$

Ex: $\text{SpHeat\_Integral\_AL\_6061\_T6}(77, 300) = 1.68862 \cdot 10^{5}$ J/kg

---

For OFHC copper:

$$\text{SpHeat\_Integral\_OFHC\_copper}(\text{Tmin}, \text{Tmax}) := \int_{\text{Tmin}}^{\text{Tmax}} \text{cp\_OFHC\_copper}(T)\, dT$$

Ex: $\text{SpHeat\_Integral\_OFHC\_copper}(77, 300) = 7.415 \cdot 10^{4}$ J/kg

---

For Nylon:

$$\text{SpHeat\_Integral\_Nylon}(\text{Tmin}, \text{Tmax}) := \int_{\text{Tmin}}^{\text{Tmax}} \text{cp\_Nylon}(T)\, dT$$

Ex: $\text{SpHeat\_Integral\_Nylon}(77, 300) = 2.5402 \cdot 10^{5}$ J/kg

---

For Teflon:

$$\text{SpHeat\_Integral\_Teflon}(\text{Tmin}, \text{Tmax}) := \int_{\text{Tmin}}^{\text{Tmax}} \text{cp\_Teflon}(T)\, dT$$

Ex: $\text{SpHeat\_Integral\_Teflon}(77, 300) = 1.5373 \cdot 10^{5}$ J/kg

---

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For 9 % Ni Steel:

$$SpHeat\_Integral\_9percentNiSteel(Tmin, Tmax) := \int_{Tmin}^{Tmax} cp\_9percentNiSteel(T)\, dT$$

Ex: $SpHeat\_Integral\_9percentNiSteel(77, 300) = 8.0302 \cdot 10^{4}$ J/kg... between 77 K and 300 K

For Invar:

$$SpHeat\_Integral\_Invar(Tmin, Tmax) := \int_{Tmin}^{Tmax} cp\_Invar(T)\, dT$$

Ex: $SpHeat\_Integral\_Invar(4, 20) = 81.6379$ J/kg... between 4 K and 20 K

For Platinum:

$$SpHeat\_Integral\_Pt(Tmin, Tmax) := \int_{Tmin}^{Tmax} cp\_Pt(T)\, dT$$

Ex: $SpHeat\_Integral\_Pt(4, 20) = 39.6546$ J/kg... between 4 K and 20 K

For Kapton:

$$SpHeat\_Integral\_Kapton(Tmin, Tmax) := \int_{Tmin}^{Tmax} cp\_Kapton(T)\, dT$$

Ex: $SpHeat\_Integral\_Kapton(4, 20) = 357.1727$ J/kg... between 4 K and 20 K

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For Brass:

$$SpHeat\_Integral\_Brass(Tmin, Tmax) := \int_{Tmin}^{Tmax} cp\_Brass(T)\,dT$$

Ex: $SpHeat\_Integral\_Brass(4, 20) = 68.2811$ J/kg... between 4 K and 20 K

For Pyrex:

$$SpHeat\_Integral\_Pyrex(Tmin, Tmax) := \int_{Tmin}^{Tmax} cp\_Pyrex(T)\,dT$$

Ex: $SpHeat\_Integral\_Pyrex(20, 77) = 7.3084 \cdot 10^{3}$ J/kg... between 20 K and 77 K

For Lead:

$$SpHeat\_Integral\_Lead(Tmin, Tmax) := \int_{Tmin}^{Tmax} cp\_Lead(T)\,dT$$

Ex: $SpHeat\_Integral\_Lead(20, 77) = 5.51541 \cdot 10^{3}$ J/kg... between 20 K and 77 K

Prob. 2.4.9 Plot the Sp. heat Integrals against Tmax, Tmin being 4 K for different materials:

$Tmin := 4$ K.

$Tmax := 4, 8 .. 300$ ...define a range variable

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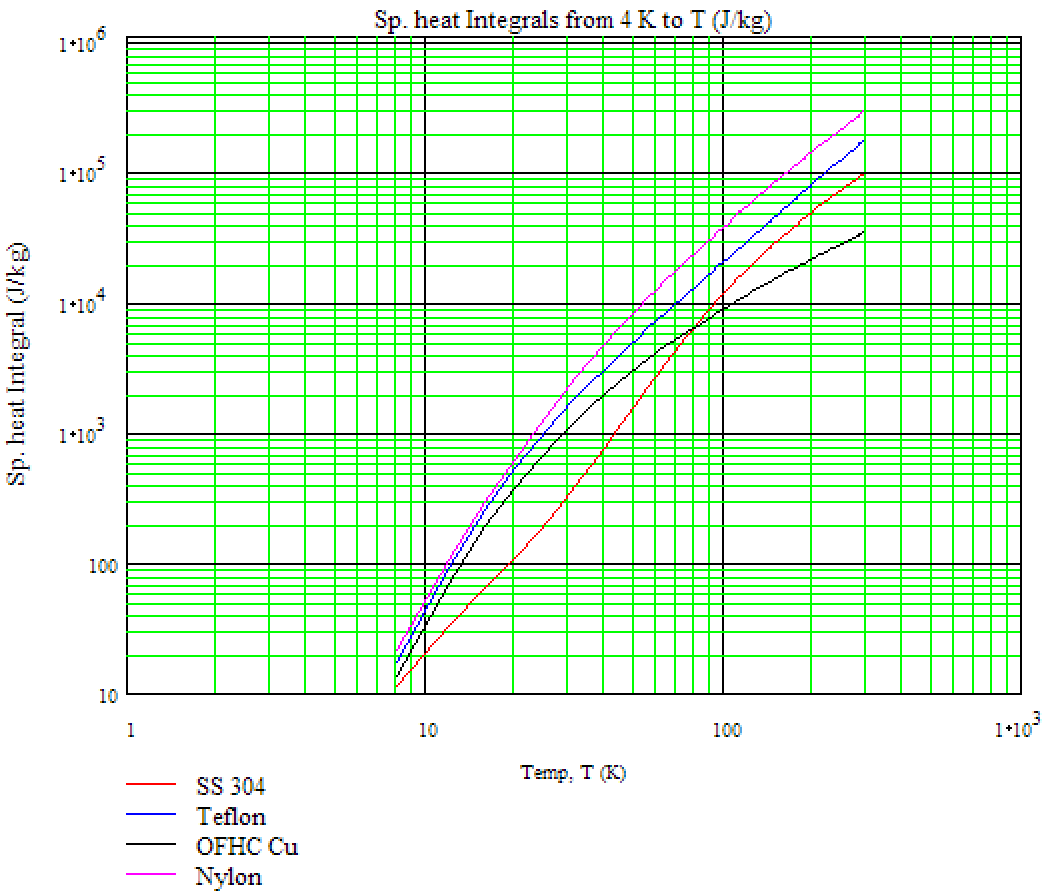

Prob. 2.4.10 Write Mathcad Functions for Yield stress of various materials.

Yield stress of SS 304: Ref: Barron.

Yield stress in MPa, T in K

Digitized with Plot Digitizer, and then Curve fitted with EXCEL.

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Yield_stress_SS304(T) :=
return "T must be between 0 K and 350 K !!" if $T<0$
return "T must be between 0 K and 350 K !!" if $T>350$
$a \leftarrow 0.000000022855$
$b \leftarrow -0.000016446$
$c \leftarrow 0.0026638$
$d \leftarrow -0.52548$
$e \leftarrow 1348.2$
$a \cdot T^4 + b \cdot T^3 + c \cdot T^2 + d \cdot T + e$

Ex: Yield_stress_SS304(20) $= 1.3386 \cdot 10^3$ MPa... Yield stress at 20 K

Yield stress of AL-2024-T4: Ref: Barron.

Yield stress in MPa, T in K

Digitized with Plot Digitizer, and then Curve fitted with EXCEL.

Yield_stress_AL_2024_T4(T) :=
return "T must be between 0 K and 350 K !!" if $T<0$
return "T must be between 0 K and 350 K !!" if $T>350$
$a \leftarrow 0.000000026112$
$b \leftarrow -0.000024015$
$c \leftarrow 0.010138$
$d \leftarrow -2.3091$
$e \leftarrow 526.43$
$a \cdot T^4 + b \cdot T^3 + c \cdot T^2 + d \cdot T + e$

Ex: Yield_stress_AL_2024_T4(20) = 484.1153 MPa... Yield stress at 20 K

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Yield stress of Teflon: Ref: Barron.

Yield stress in MPa, T in K

Digitized with Plot Digitizer, and then Curve fitted with EXCEL.

```
Yield_stress_Teflon(T) := | return "T must be between 0 K and 350 K !!" if T<0
                          | return "T must be between 0 K and 350 K !!" if T>350
                          | a ← 0.000000015834
                          | b ← - 0.000016104
                          | c ← 0.0067618
                          | d ← - 1.398
                          | e ← 141.76
                          | a·T^4 + b·T^3 + c·T^2 + d·T + e
```

Ex: Yield_stress_Teflon(20) = 116.3784 MPa... Yield stress at 20 K

Yield stress of BeCu: Ref: Barron.

Yield stress in MPa, T in K

Digitized with Plot Digitizer, and then Curve fitted with EXCEL.

```
Yield_stress_BeCu(T) := | return "T must be between 0 K and 350 K !!" if T<0
                        | return "T must be between 0 K and 350 K !!" if T>350
                        | a ← 0.000000023953
                        | b ← - 0.000024822
                        | c ← 0.01188
                        | d ← - 2.8776
                        | e ← 947.41
                        | a·T^4 + b·T^3 + c·T^2 + d·T + e
```

Ex: Yield_stress_BeCu(20) = 894.4153 MPa... Yield stress at 20 K

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Yield stress of Titanium: Ref: Barron.

Yield stress in MPa, T in K

Digitized with Plot Digitizer, and then Curve fitted with EXCEL.

```
Yield_stress_Ti(T) := | return "T must be between 0 K and 350 K !!" if T<0
                      | return "T must be between 0 K and 350 K !!" if T>350
                      | a ← 0.000000068681
                      | b ← -0.000064487
                      | c ← 0.024406
                      | d ← -6.7607
                      | e ← 1823.5
                      | a·T^4 + b·T^3 + c·T^2 + d·T + e
```

Ex: Yield_stress_Ti(20) = $1.6975 \cdot 10^{3}$ MPa... Yield stress at 20 K

Yield stress of 9 % Ni Steel: Ref: Barron.

Yield stress in MPa, T in K

Digitized with Plot Digitizer, and then Curve fitted with EXCEL.

```
Yield_stress_9percentNiSteel(T) := | return "T must be between 0 K and 350 K !!" if T<0
                                   | return "T must be between 0 K and 350 K !!" if T>350
                                   | a ← -0.0000097458
                                   | b ← 0.0091459
                                   | c ← -3.5097
                                   | d ← 1133.5
                                   | a·T^3 + b·T^2 + c·T + d
```

Ex: Yield_stress_9percentNiSteel(20) = $1.0669 \cdot 10^{3}$ MPa... Yield stress at 20 K

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Yield stress of kMonel: Ref: Barron.

Yield stress in MPa, T in K

Digitized with Plot Digitizer, and then Curve fitted with EXCEL.

```
Yield_stress_kMonel(T) := | return "T must be between 0 K and 350 K !!" if T<0
                          | return "T must be between 0 K and 350 K !!" if T>350
                          | a ← 0.000000015041
                          | b ← - 0.000011053
                          | c ← 0.0048733
                          | d ← - 1.6876
                          | e ← 1091.2
                          | a·T^4 + b·T^3 + c·T^2 + d·T + e
```

Ex: Yield_stress_kMonel(20) = $1.0593 \cdot 10^3$ MPa... Yield stress at 20 K

Yield stress of C1020C Steel: Ref: Barron.

Yield stress in MPa, T in K

Digitized with Plot Digitizer, and then Curve fitted with EXCEL.

```
Yield_stress_C1020CSteel(T) := | return "T must be between 0 K and 350 K !!" if T<0
                               | return "T must be between 0 K and 350 K !!" if T>350
                               | a ← 0.00000002715
                               | b ← - 0.00002784
                               | c ← 0.011711
                               | d ← - 3.0361
                               | e ← 711.24
                               | a·T^4 + b·T^3 + c·T^2 + d·T + e
```

Ex: Yield_stress_C1020CSteel(20) = 654.984 MPa... Yield stress at 20 K

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Prob. 2.4.11 Write Mathcad Functions for Young's Modulus of various materials.

Young's Mod. Ey of SS 304: Ref: Barron.

Young's Mod. in GPa, T in K

Digitized with Plot Digitizer, and then Curve fitted with EXCEL.

```
Youngs_Mod_Ey_SS304(T) := | return "T must be between 0 K and 350 K !!" if T<0
                          | return "T must be between 0 K and 350 K !!" if T>350
                          | a ← 0.000000038231
                          | b ← - 0.000023528
                          | c ← - 0.12801
                          | d ← 201.37
                          | a·T^3 + b·T^2 + c·T + d
```

Ex: Youngs_Mod_Ey_SS304(20) = 198.8007 GPa... at 20 K

Young's Mod. Ey of AL-2024-T4: Ref: Barron.

Young's Mod. in GPa, T in K

Digitized with Plot Digitizer, and then Curve fitted with EXCEL.

```
Youngs_Mod_Ey_AL_2024_T4(T) := | return "T must be between 0 K and 350 K !!" if T<0
                               | return "T must be between 0 K and 350 K !!" if T>350
                               | a ← 0.00000024395
                               | b ← - 0.000031441
                               | c ← - 0.071171
                               | d ← 88.637
                               | a·T^3 + b·T^2 + c·T + d
```

Ex: Youngs_Mod_Ey_AL_2024_T4(20) = 87.203 GPa... at 20 K

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Young's Mod. Ey of BeCu: Ref: Barron.

Young's Mod. in GPa, T in K

Dgitized with Plot Digitizer, and then Curve fitted with EXCEL.

```
Youngs_Mod_Ey_BeCu(T) := | return "T must be between 0 K and 350 K !!"  if T<0
                         | return "T must be between 0 K and 350 K !!"  if T>350
                         | a ← -0.000000045324
                         | b ← 0.000024745
                         | c ← -0.049673
                         | d ← 133.4
                         | a·T^3 + b·T^2 + c·T + d
```

Ex: Youngs_Mod_Ey_BeCu(20) = 132.4161 GPa... at 20 K

Young's Mod. Ey of kMonel: Ref: Barron.

Young's Mod. in GPa, T in K

Digitized with Plot Digitizer, and then Curve fitted with EXCEL.

```
Youngs_Mod_Ey_kMonel(T) := | return "T must be between 0 K and 350 K !!"  if T<0
                           | return "T must be between 0 K and 350 K !!"  if T>350
                           | a ← -0.000000025449
                           | b ← 0.000012554
                           | c ← -0.042499
                           | d ← 192.68
                           | a·T^3 + b·T^2 + c·T + d
```

Ex: Youngs_Mod_Ey_kMonel(20) = 191.8348 GPa... at 20 K

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Young's Mod. Ey of Titanium: Ref: Barron.

Young's Mod. in GPa, T in K

Digitized with Plot Digitizer, and then Curve fitted withCurve Expert.

$$\text{Youngs\_Mod\_Ey\_Ti}(T) := \left| \begin{array}{l} \text{return "T must be between 0 K and 350 K !!" if } T<0 \\ \text{return "T must be between 0 K and 350 K !!" if } T>350 \\ a \leftarrow 118.465 \\ b \leftarrow -0.037787399 \\ c \leftarrow 0.00018471178 \\ d \leftarrow -0.00000072610257 \\ e \leftarrow 8.9385205 \cdot 10^{-10} \\ a + b \cdot T + c \cdot T^2 + d \cdot T^3 + e \cdot T^4 \end{array} \right.$$

Ex: $\text{Youngs\_Mod\_Ey\_Ti}(20) = 117.7775$ GPa... at 20 K

Young's Mod. Ey of C1020 Steel: Ref: Barron.

Young's Mod. in GPa, T in K

Digitized with Plot Digitizer, and then Curve fitted with EXCEL.

$$\text{Youngs\_Mod\_Ey\_C1020\_Steel}(T) := \left| \begin{array}{l} \text{return "T must be between 0 K and 350 K !!" if } T<0 \\ \text{return "T must be between 0 K and 350 K !!" if } T>350 \\ a \leftarrow -0.000000029236 \\ b \leftarrow 0.0000095092 \\ c \leftarrow -0.047625 \\ d \leftarrow 219.75 \\ a \cdot T^3 + b \cdot T^2 + c \cdot T + d \end{array} \right.$$

Ex: $\text{Youngs\_Mod\_Ey\_C1020\_Steel}(20) = 218.8011$ GPa... at 20 K

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Young's Mod. Ey of 9 % Ni Steel: Ref: Barron.

Young's Mod. in GPa, T in K

Digitized with Plot Digitizer, and then Curve fitted with EXCEL.

```
Youngs_Mod_Ey_9percentNiSteel(T) := | return "T must be between 0 K and 350 K !!"  if T<0
                                    | return "T must be between 0 K and 350 K !!"  if T>350
                                    | a ← 0.000000075177
                                    | b ← -0.000023851
                                    | c ← -0.081419
                                    | d ← 214.53
                                    | a·T^3 + b·T^2 + c·T + d
```

Ex: Youngs_Mod_Ey_9percentNiSteel(20) = 212.8927 GPa... at 20 K

Prob. 2.4.12 Write Mathcad Functions for Bulk Modulus (B) and Shear Modulus (G) in terms of Young's Modulus and Poisson ratio **(ν)**, for various materials.

Solution:

Bulk Modulus:

$$\text{Bulk\_Mod\_B}(\text{Youngs\_Mod\_Ey}, \text{Poisson\_ratio\_nu}) := \frac{\text{Youngs\_Mod\_Ey}}{3\cdot(1 - 2\cdot\text{Poisson\_ratio\_nu})}$$

Ex: Bulk_Mod_B(198.801, 0.305) = 169.915 GPa at 20 K

Shear Modulus:

$$\text{Shear\_Mod\_G}(\text{Youngs\_Mod\_Ey}, \text{Poisson\_ratio\_nu}) := \frac{\text{Youngs\_Mod\_Ey}}{2\cdot(1 + \text{Poisson\_ratio\_nu})}$$

Ex: Shear_Mod_G(198.801, 0.305) = 76.169 GPa at 20 K

==

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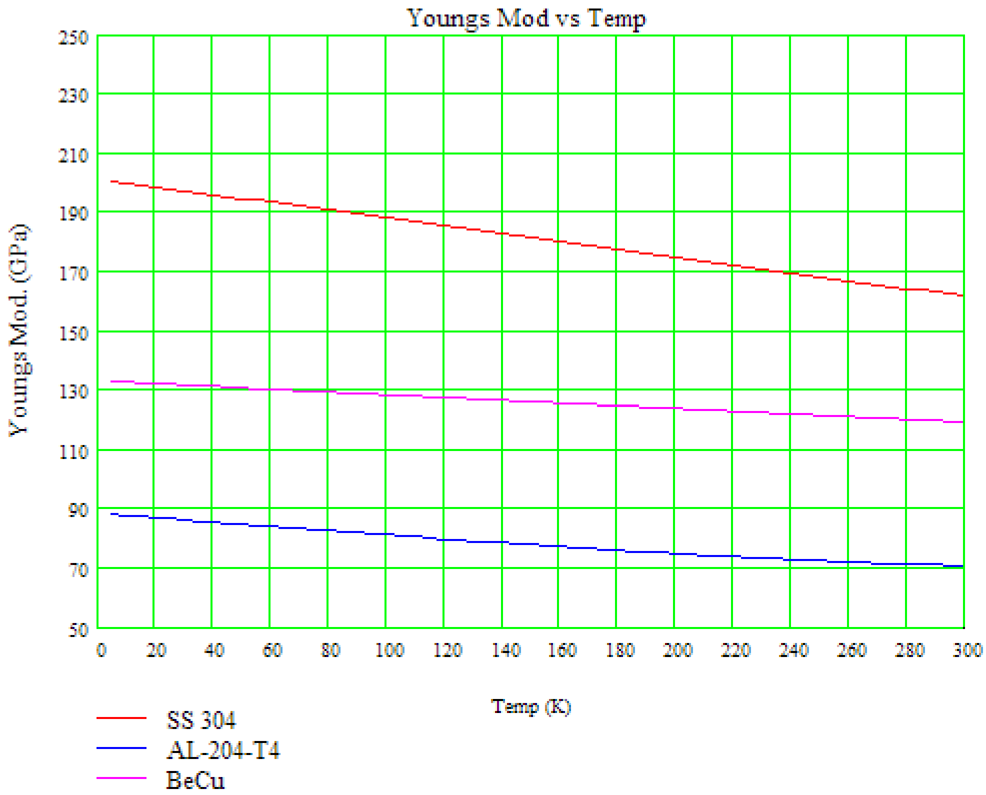
Prob. 2.4.13 Plot Youngs Mod., Bulk Mod. and Shear Mod. for SS 304, AL-2024-T4 and BeCu as temp varies from 5 K to 300K.

Solution:

T := 5, 10.. 300 ...define a range variable



For Bulk Mod. And Shear Mod.:

Poisson Ratio Data:

nu_SS304 := 0.305 nu_AL := 0.32 nu_BeCu := 0.285

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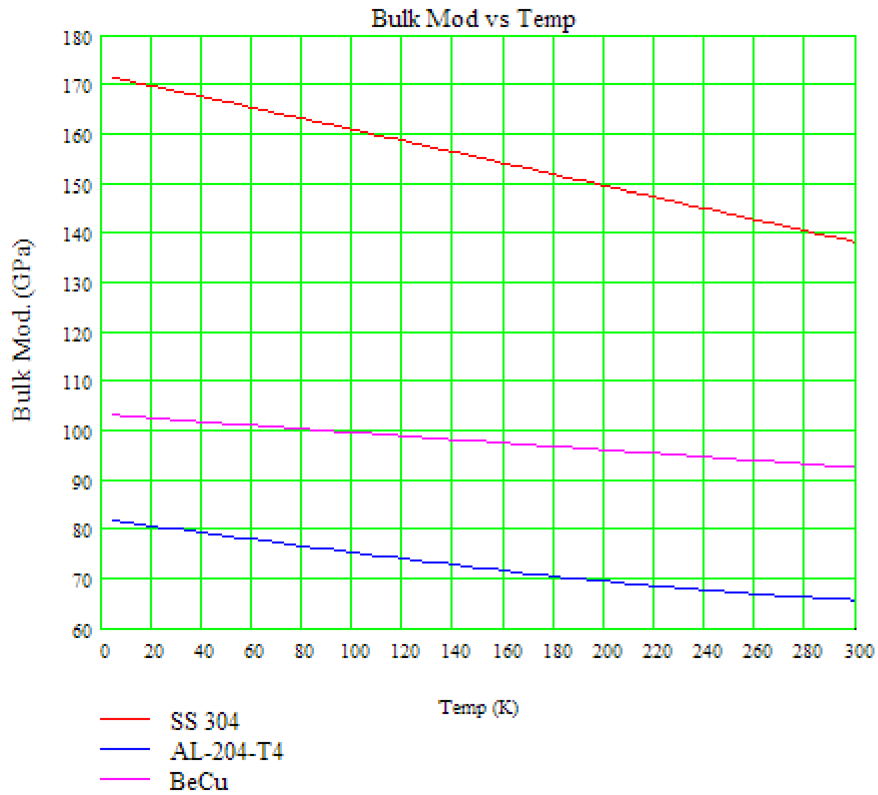

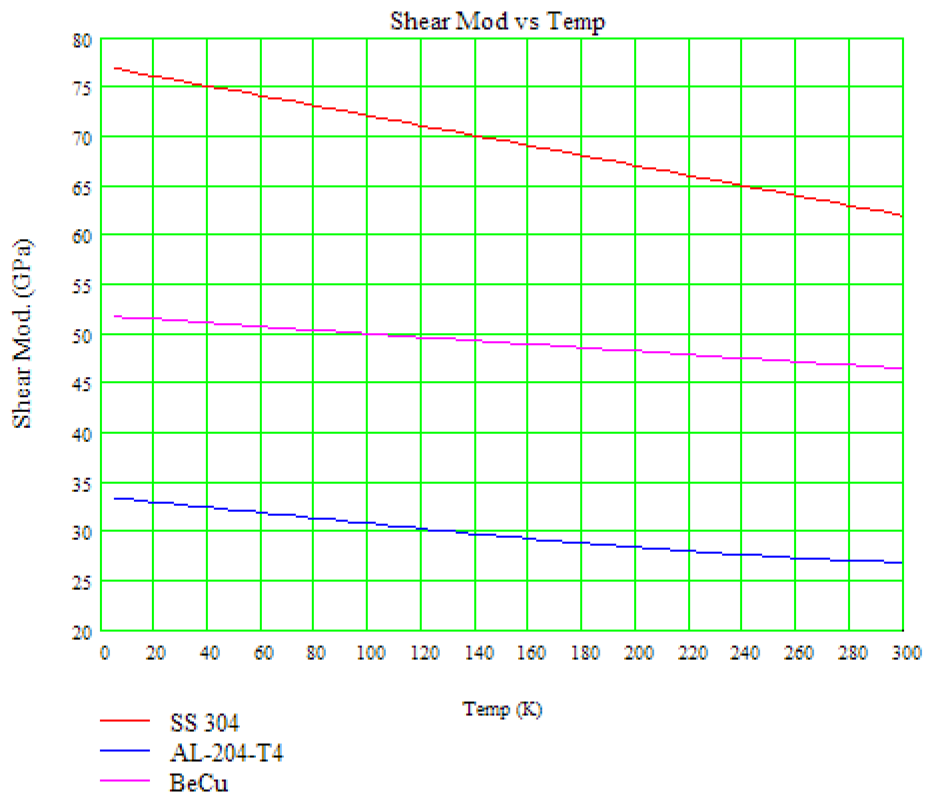

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