Appendix I: Cryogenic Reference Tables

Cryogenic Heat Flow Calculations

The heat flow $\dot{Q}$ conducted across small temperature differences can be calculated using the formula:

$$\dot{Q} = -KA\frac{dT}{dx} \cong -KA\frac{\Delta T}{L} \qquad \textit{Eqn. 1}$$

where *K* is the thermal conductivity, *A* is the cross-sectional area, ΔT is the temperature difference, and *L* is the length of the heat conduction path.

Thermal conduction across significant temperature differences should be calculated using thermal conductivity integrals.

Note that the thermal conductivity and the thermal conductivity integral of a material can depend strongly on composition and fabrication history. Without verification, the data in the accompanying figures should be used only for qualitative heat flow calculations.

Calculating the heat conduction through a body with its ends at greatly different temperatures is made difficult by the strong temperature dependence of the thermal conductivity between absolute zero and room temperature. The use of thermal conductivity integrals (called thermal boundary potentials by Garwin) allows the heat flow to be calculated as

$$\dot{Q} = -G(\Theta_2 - \Theta_1) \qquad \textit{Eqn. 2}$$

where Θ is the integral of the temperature-dependent thermal conductivity, *K*, calculated as

$$\Theta_1 = \int_0^{T_1} KdT \qquad \textit{Eqn. 3}$$

and *G* is a geometry factor calculated as

$$\frac{1}{G} = \int_{x_1}^{x_2} \frac{dx}{A} \qquad \textit{Eqn. 4}$$

where *A(x)* is the cross sectional area at position *x* along the path of heat flow. Note that *G=A/L* in the case of a body of length *L* and uniform cross-sectional area *A*.

Equation 1 is only applicable to bodies within which a common thermal conductivity integral function applies.

Reference: R. L. Garwin, Rev. Sci. Instrum. 27 (1956) 826.

Figure 1 *– Thermal Conductivity of Selected Materials*

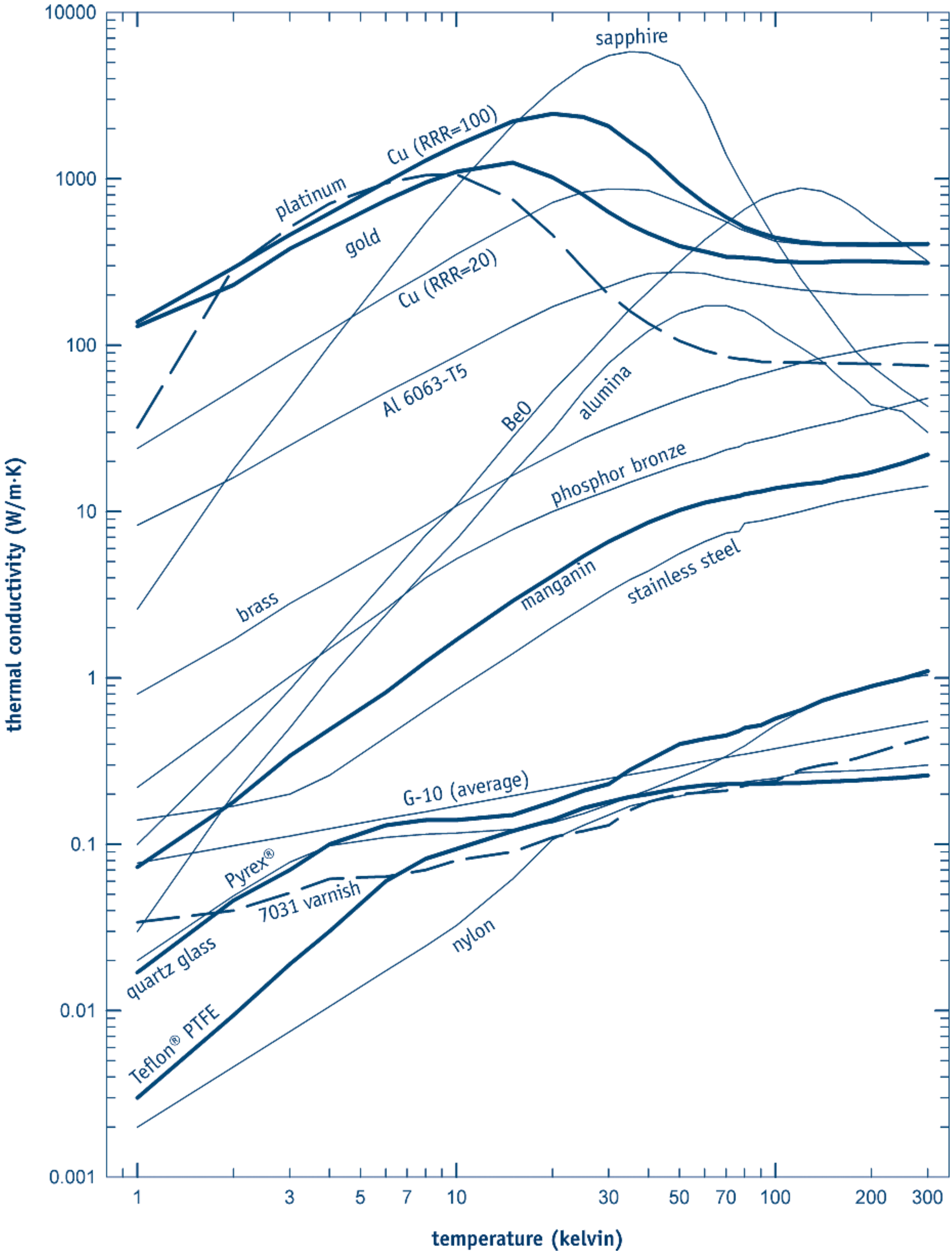

Figure 2 *– Thermal Conductivity Integral of Selected Materials*

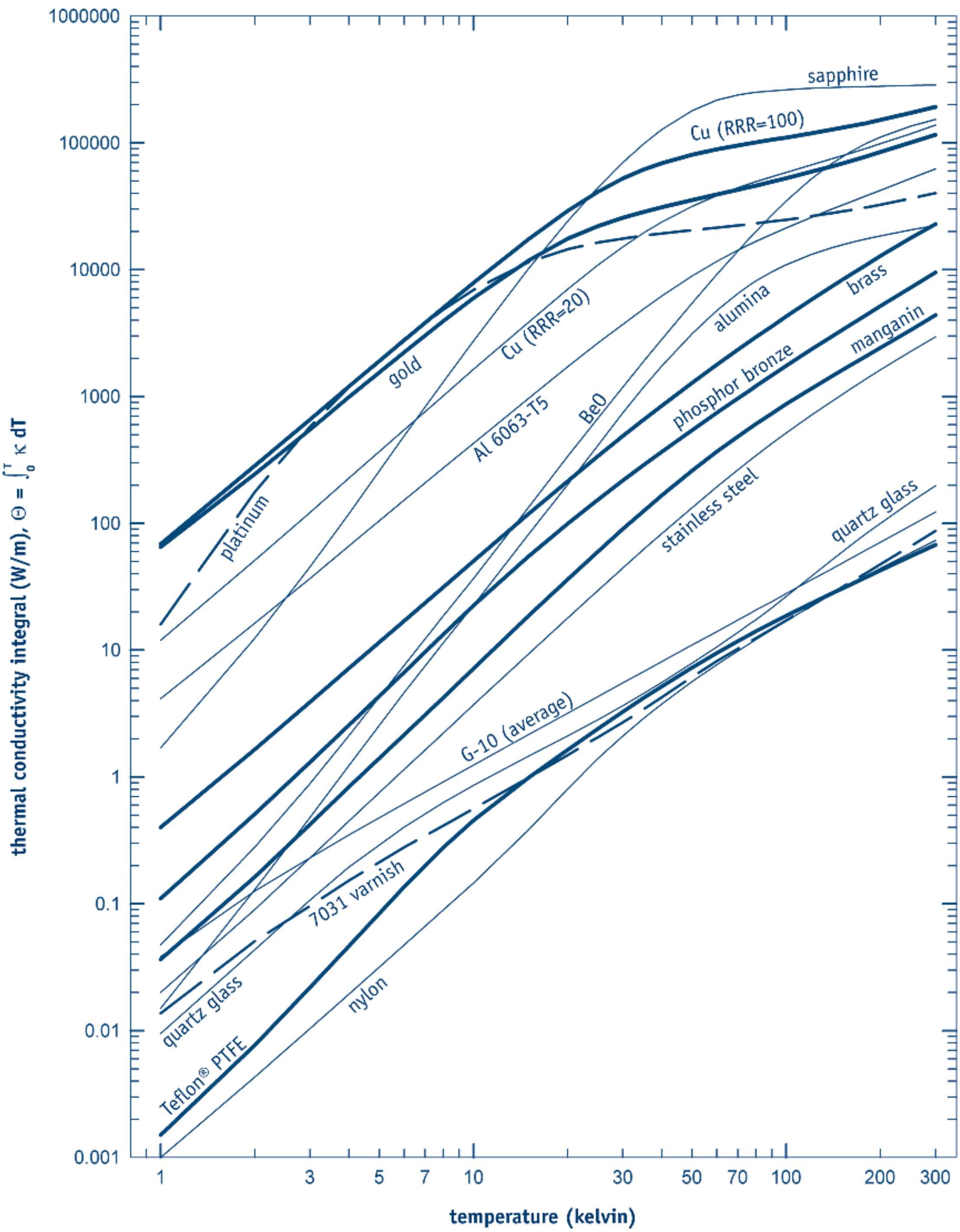

Table 1 – Thermodynamic Properties for Various Cryogenic Liquids

	Temperature (K)			Pressure			Latent Heat of Vaporization	
	Triple point	Normal boiling point	Critical point	Triple point (kPa)	Critical point (kPa)	Critical density (kg/m^3)	L (J/g)	Density (g/ml)
Helium	2.1768[a]	4.222	5.1953	5.048	227.46	69.64	20.6	0.13
Hydrogen	13.8	20.28	32.94	7.042	1283.8	31.36	441	0.07
Neon	24.5561	27.09	44.44	43.35	2703	483.23	86	1.20
Nitrogen	63.15	77.36	126.26	12.46	3399	313.11	199	0.81
Oxygen	54.36	90.19	154.58	0.148	5043	436.14	213	1.14
Argon	83.8	87.28	150.86	68.9	4906	535.70	162	1.40
Krypton	115.76	119.77	209.39	73.2	5496	910.75	108	2.40
Xenon	161.36	165.04	289.74	81.6	5821	1100	96	3.10
CO_2	216.58	—	304.21	518.16	7384	466.51	571	1.56
Methane	90.69	111.63	190.55	11.7	4599	162.65	510	0.42
Ethane	90.35	184.55	305.33	0.0011	4871	206.73	489	0.55
Propane	85.47	231.07	369.85	0.1×10^{-6}	4248	220.49	425	0.58
Ammonia	195.49	239.81	406.65	0.0662	11627	237.57	1371	0.68

[a] *Triple point values for helium are those of the lambda point*

Table 2 – Gamma Radiation-Induced Calibration Offsets as a Function of Temperature for Several Types of Cryogenic Temperature Sensors

		Radiation-induced offset (mK) at temperature				
	Model	4.2 K	20 K	77 K	200 K	300 K
Platinum[b]	PT-103	NA	–15	–10[d]	10[d]	10[d]
Rhodium-iron[b]	RF-100-AA	2[d]	15[d]	15[d]	5[d]	5[d]
Cernox™[b]	CX-1050-SD	–10	–10[d]	–5[d]	25[d]	25[d]
Carbon-glass[b]	CGR-1-1000	–30	–140	–700	–1300	–3400
Germanium[b]	GR-1400-AA	–5	–20	–25	NA	NA
Ruthenium oxide[b]	RO600	20	150	[d]	[d]	NA
GaAlAs diode[b]	TG-120P	–15	–25	2200	2500	400
Silicon diode[b]	DT-470-SD	25	1000	1300	1000	2700
Silicon diode[b]	DT-500P-GR-M	350	50	20	250	300
Silicon diode[b]	SI-410-NN	600	2000	300	450	1400
Platinum[c]	PT-103	NA	–50	5[d]	50	75
Rhodium-iron[c]	RF-800-4	5[d]	15[d]	25	10[d]	–15[d]
Rhodium-iron[c]	RF-100-AA	–5[d]	–5[d]	5[d]	–10[d]	5[d]
Carbon-glass[c]	CGR-1-1000	–25	–175	–1400	–4200	–6500
Germanium[c]	GR-1400-AA	2[d]	2[d]	5[d]	NA	NA
GaAlAs diode[c]	TG-120P	–50	–75	700	600	–250
Silicon diode[c]	DT-470-SD	+20	–200	1500	11000	18000
Silicon diode[c]	DT-500P-GR-M	10[d]	10[d]	–5[d]	–5[d]	–100

[b] *Sensors were irradiated* in situ *at 4.2 K with a cobalt-60 gamma source at a dose rate of 3,000 Gy/hr to a total dose of 10,000 Gy (1×10^6 rad)*
[c] *Sensors were irradiated at room temperature with a cesium-137 gamma source at a dose of 30 Gy/hr to a total dose of 10,000 Gy (1×10^6 rad)*
[d] *Deviations smaller than calibration uncertainty*

Table 3 – Vapor Pressure of Some Gases at Selected Temperatures in Pascals (Torr)

	4 K	20 K	77 K	150 K	Triple[e] Point Temperature
Water	[f]	[f]	[f]	1.33×10^{-4} (10^{-7})	273 K
Carbon dioxide	[f]	[f]	1.33×10^{-5} (10^{-8})	1333 (10)	217 K
Argon	[f]	1.33×10^{-10} (10^{-13})	21332 (160)	[h]	84 K
Oxygen	[f]	1.33×10^{-10} (10^{-13})	19998 (150)	[h]	54 K
Nitrogen	[f]	1.33×10^{-8} (10^{-11})	97325 (730)	[g]	63 K
Neon	[f]	4000 (30)	[g]	[g]	25 K
Hydrogen	1.33×10^{-4} (10^{-7})	101,325 (760)	[g]	[g]	14 K

Note: estimates – useful for comparison purposes only (1 Torr = 133.3 Pa)
[e] Solid and vapor only at equilibrium below this temperature; no liquid
[f] Less than 10^{-13} Torr
[g] Greater than 1 atm
[h] Above the critical temperature, liquid does not exist

Table 4 – Thermal Contraction of Selected Materials Between 293 K and 4 K

Material	Contraction (per 10^4)
Teflon®	214
Nylon	139
Stycast® 1266	115
SP22 Vespel®	63.3
Stycast® 2850FT	50.8
Stycast® 2850GT	45
Al	41.4
Brass (65% Cu/35% Zn)	38.4
Cu	32.6
Stainless steel	30
Quartz a-axis	25
Quartz c-axis	10
Quartz mean, for typical transducer	15
Titanium	15.1
Ge	9.3
Pyrex®	5.6
Si	2.2

Table 5 – Electrical Resistivity of Alloys (in $\mu\Omega \cdot$cm)

Material	Resistivity (295 K)	(4.2 K)
Brass	7.2	4.3
Constantan	52.5	44
CuNi (80% Cu/20% Ni)	26	23
Evanohm®	134	133
Manganin	48	43
Stainless steel	71 to 74	49 to 51

Table 6 – Defining Fixed Points of the ITS-90

<table>
<tr><th>Temperature (T_{90}/K)</th><th>Substance[i]</th><th>State[j]</th><th colspan="4">Defining Instrument</th></tr>
<tr><td>0.65 to 3</td><td></td><td></td><td rowspan="2">He vapor pressure thermometer</td><td></td><td></td><td></td></tr>
<tr><td>3 to 5</td><td>He</td><td>V</td><td rowspan="5">Constant volume gas thermometer</td><td></td><td></td></tr>
<tr><td>13.8033</td><td>e-He_2</td><td>T</td><td></td><td rowspan="14">Platinum resistance thermometer</td><td></td></tr>
<tr><td>*~17*</td><td>*e-He_2 (or He)*</td><td>*V (or G)*</td><td></td><td></td></tr>
<tr><td>*~20.3*</td><td>*e-He_2 (or He)*</td><td>*V (or G)*</td><td></td><td></td></tr>
<tr><td>24.5561</td><td>Ne</td><td>T</td><td></td><td></td></tr>
<tr><td>54.3584</td><td>O_2</td><td>T</td><td></td><td></td><td></td></tr>
<tr><td>83.8058</td><td>Ar</td><td>T</td><td></td><td></td><td></td></tr>
<tr><td>234.3156</td><td>Hg</td><td>T</td><td></td><td></td><td></td></tr>
<tr><td>273.16</td><td>H_2O</td><td>T</td><td></td><td></td><td></td></tr>
<tr><td>302.9146</td><td>Ga</td><td>M</td><td></td><td></td><td></td></tr>
<tr><td>429.7485</td><td>In</td><td>F</td><td></td><td></td><td></td></tr>
<tr><td>505.078</td><td>Sn</td><td>F</td><td></td><td></td><td></td></tr>
<tr><td>692.677</td><td>Zn</td><td>F</td><td></td><td></td><td></td></tr>
<tr><td>933.473</td><td>Al</td><td>F</td><td></td><td></td><td></td></tr>
<tr><td>1234.93</td><td>Ag</td><td>F</td><td></td><td></td><td rowspan="3">Radiation</td></tr>
<tr><td>1337.33</td><td>Au</td><td>F</td><td></td><td></td><td></td></tr>
<tr><td>1357.77</td><td>Cu</td><td>F</td><td></td><td></td><td></td></tr>
</table>

[i] *All substances except 3He are of natural isotopic composition;*
e-H_2 is hydrogen at the equilibrium concentration of the ortho- and para-molecular forms

[j] *For complete definitions and advice on the realization of these various states, see "Supplementary Information for the ITS-90"; the symbols have the following meanings: V – Vapor pressure point; T – Triple point; G – Gas thermometer point; M – Melting point; F – Freezing point*

Table 7 – Saturated Vapor Pressure of Helium

T (K)	P (Pa)
5.1	211600
5	196000
4.9	181000
4.8	167000
4.7	154300
4.6	141900
4.5	130300
4.4	119300
4.3	108900
4.2	99230
4.1	90140
4	81620
3.9	73660
3.8	66250
3.7	59350
3.6	52960
3.5	47040

T (K)	P (Pa)
3.4	41590
3.3	36590
3.2	32010
3.1	27840
3	24050
2.9	20630
2.8	17550
2.7	14810
2.6	12370
2.5	10230
2.4	8354
2.3	6730
2.2	5335
2.1	4141
2	3129
1.9	2299
1.8	1638

T (K)	P (Pa)
1.7	1128
1.6	746.4
1.5	471.5
1.4	282.0
1.3	157.9
1.27	130.7
1.24	107.3
1.21	87.42
1.18	70.58
1.15	56.45
1.12	44.68
1.09	34.98
1.06	27.07
1.03	20.67
1	15.57