# 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

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

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**

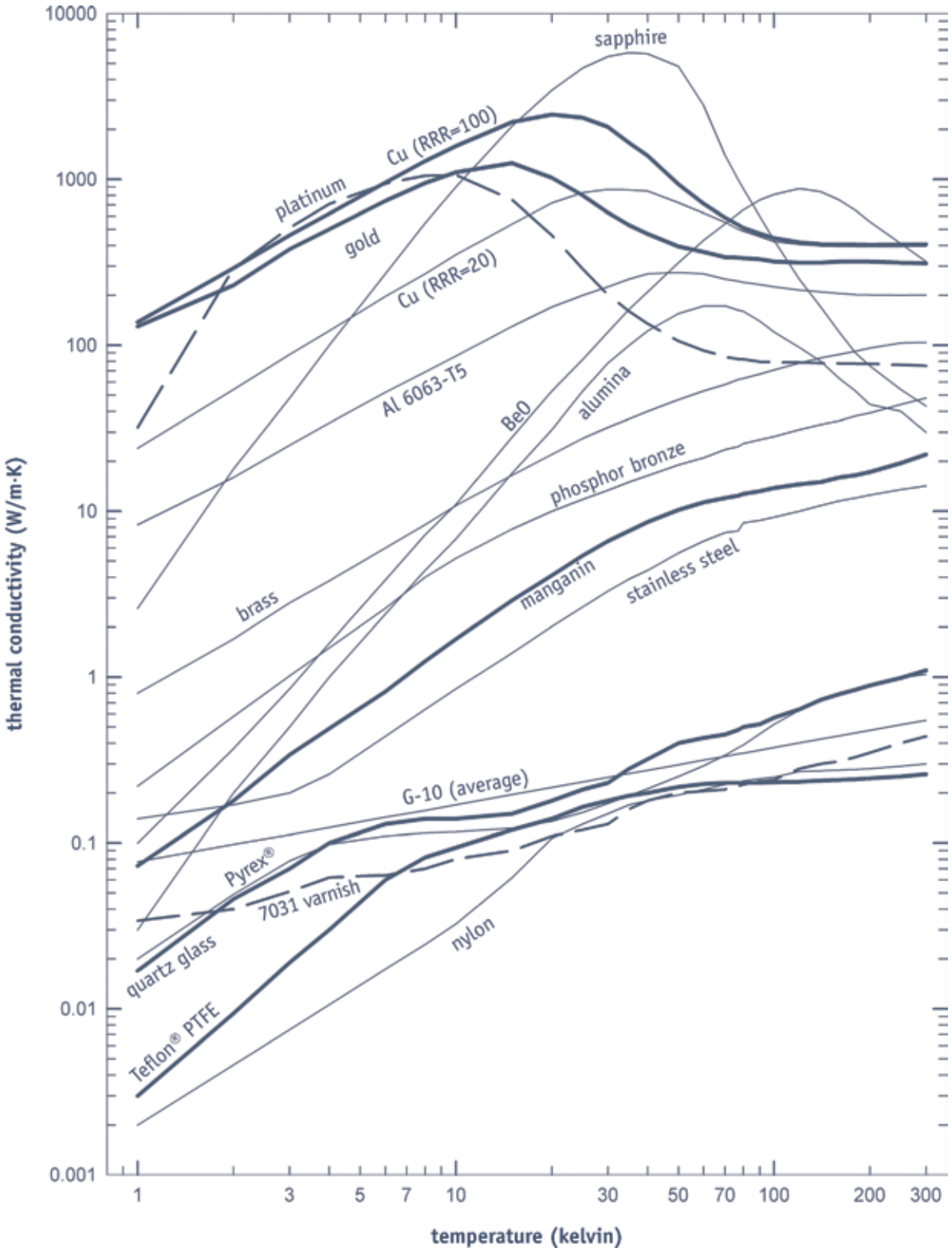
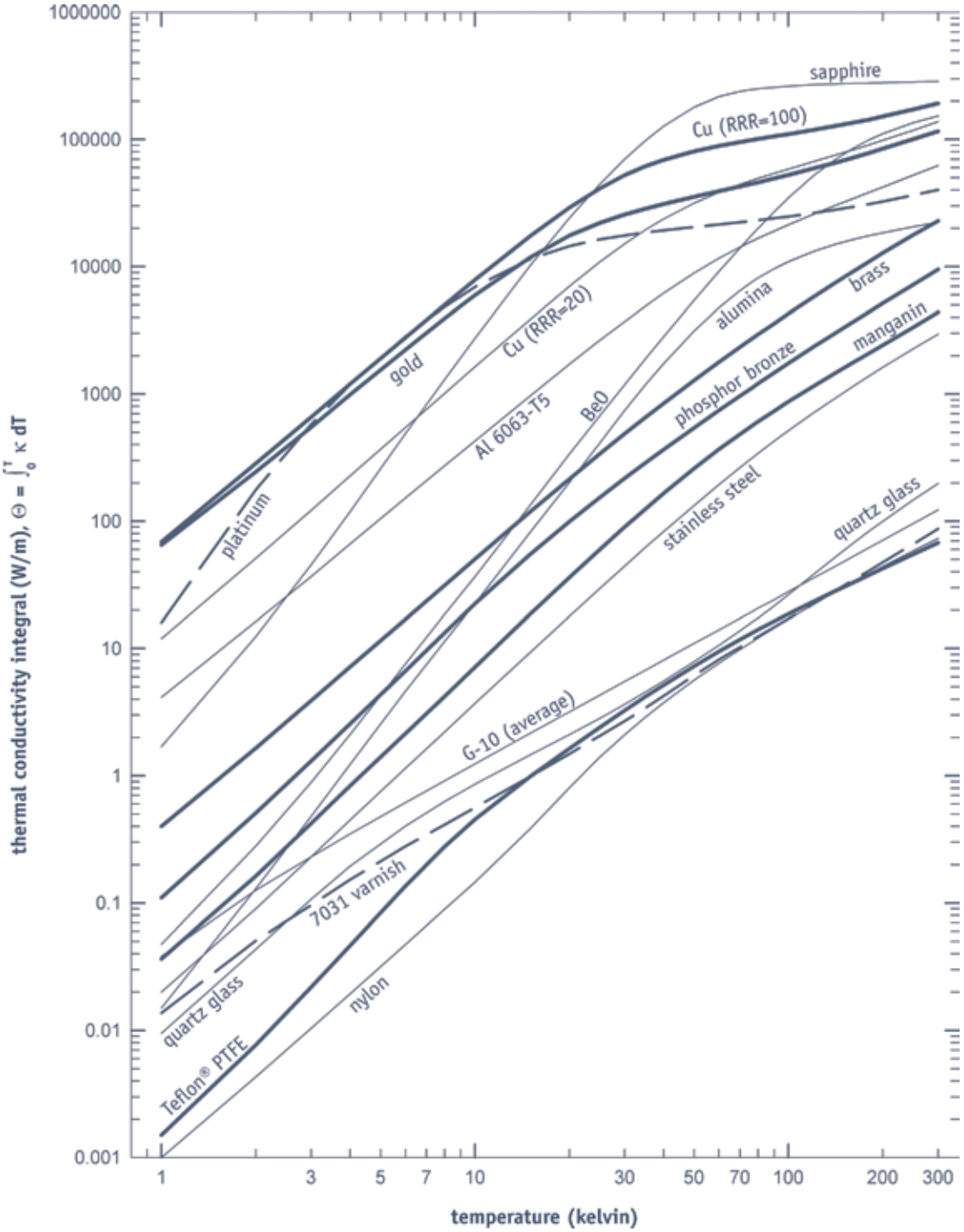


**Figure 2—Thermal conductivity integral of selected materials**



## 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 | $0.1 \times 10^{-6}$ | 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] |
| Cernox®[b] | CX-1050-SD | –10 | –10[d] | –5[d] | 25[d] | 25[d] |
| Germanium[b] | GR-1400-AA | –5 | –20 | –25 | NA | NA |
| Ruthenium oxide[b] | RO600 | 20 | 150 | [d] | [d] | NA |
| 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 |
| Germanium[c] | GR-1400-AA | 2[d] | 2[d] | 5[d] | NA | NA |
| 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 ($1 \times 10^6$ 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 ($1 \times 10^6$ rad)*
[d] *Deviations smaller than calibration uncertainty*

## Table 3—Vapor pressure of some gases at selected temperatures in Pascal (Torr)

| | 4 K | 20 K | 77 K | 150 K | Triple[e] point temperature |
|---|---|---|---|---|---|
| Water | [f] | [f] | [f] | $1.33 \times 10^{-4}$ ($10^{-7}$) | 273 K |
| Carbon dioxide | [f] | [f] | $1.33 \times 10^{-5}$ ($10^{-8}$) | 1333 (10) | 217 K |
| Argon | [f] | $1.33 \times 10^{-10}$ ($10^{-13}$) | 21332 (160) | [h] | 84 K |
| Oxygen | [f] | $1.33 \times 10^{-10}$ ($10^{-13}$) | 19998 (150) | [h] | 54 K |
| Nitrogen | [f] | $1.33 \times 10^{-8}$ ($10^{-11}$) | 97325 (730) | [g] | 63 K |
| Neon | [f] | 4000 (30) | [g] | [g] | 25 K |
| Hydrogen | $1.33 \times 10^{-4}$ ($10^{-7}$) | 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

| | 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 μΩ·cm)

| | 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

| Temperature ($T_{90}$/K) | Substance[i] | State[j] | Defining instrument |
|---|---|---|---|
| 0.65 to 3 | 3He | Vapor pressure point | He vapor pressure thermometer |
| 3 to 5 | He | Vapor pressure point | He vapor pressure thermometer |
| 13.8033 | e-$He_2$ | Triple point | Constant volume gas thermometer |
| *~17* | *e-$He_2$ (or He)* | *Vapor pressure point or gas thermometer point* | Constant volume gas thermometer |
| *~20.3* | *e-$He_2$ (or He)* | *Vapor pressure point or gas thermometer point* | Constant volume gas thermometer |
| 24.5561 | Ne | Triple point | Constant volume gas thermometer |
| 54.3584 | $O_2$ | Triple point | Platinum resistance thermometer |
| 83.8058 | Ar | Triple point | Platinum resistance thermometer |
| 234.3156 | Hg | Triple point | Platinum resistance thermometer |
| 273.16 | $H_2O$ | Triple point | Platinum resistance thermometer |
| 302.9146 | Ga | Melting point | Platinum resistance thermometer |
| 429.7485 | In | Freezing point | Platinum resistance thermometer |
| 505.078 | Sn | Freezing point | Platinum resistance thermometer |
| 692.677 | Zn | Freezing point | Platinum resistance thermometer |
| 933.473 | Al | Freezing point | Platinum resistance thermometer |
| 1234.93 | Ag | Freezing point | Platinum resistance thermometer |
| 1337.33 | Au | Freezing point | Radiation |
| 1357.77 | Cu | Freezing point | Radiation |

[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"*

## Table 7—Saturated vapor pressure of helium

| T (K) | P (Pa) | T (K) | P (Pa) | T (K) | P (Pa) |
|---|---|---|---|---|---|
| 5.1 | 211600 | 3.4 | 41590 | 1.7 | 1128 |
| 5 | 196000 | 3.3 | 36590 | 1.6 | 746.4 |
| 4.9 | 181000 | 3.2 | 32010 | 1.5 | 471.5 |
| 4.8 | 167000 | 3.1 | 27840 | 1.4 | 282.0 |
| 4.7 | 154300 | 3 | 24050 | 1.3 | 157.9 |
| 4.6 | 141900 | 2.9 | 20630 | 1.27 | 130.7 |
| 4.5 | 130300 | 2.8 | 17550 | 1.24 | 107.3 |
| 4.4 | 119300 | 2.7 | 14810 | 1.21 | 87.42 |
| 4.3 | 108900 | 2.6 | 12370 | 1.18 | 70.58 |
| 4.2 | 99230 | 2.5 | 10230 | 1.15 | 56.45 |
| 4.1 | 90140 | 2.4 | 8354 | 1.12 | 44.68 |
| 4 | 81620 | 2.3 | 6730 | 1.09 | 34.98 |
| 3.9 | 73660 | 2.2 | 5335 | 1.06 | 27.07 |
| 3.8 | 66250 | 2.1 | 4141 | 1.03 | 20.67 |
| 3.7 | 59350 | 2 | 3129 | 1 | 15.57 |
| 3.6 | 52960 | 1.9 | 2299 | | |
| 3.5 | 47040 | 1.8 | 1638 | | |