Lecture #2

Cryogenic Properties of Materials & Refrigeration (Part 1)

I) Cryogenic Properties of Materials

- Material properties change significantly with temperature

- Many materials are unsuitable for cryogenic use

- Material selection must always be done carefully. Testing may be required.

- **Some suitable materials for cryogenic use include:**

  a) **Austenitic stainless steels e.g. 304, 304L, 316, 321**
  b) **Aluminum alloys e.g. 6061, 6063, 1100**
  c) **Copper e.g. OFHC, ETP and phosphorous deoxidized**
  d) **Brass**
  e) **Fiber reinforced plastics such as G –10 and G –11**
  f) **Niobium &Titanium (frequently used in superconducting RF systems)**
  g) **Invar (Ni /Fe alloy) useful in making washers due to its lower coefficient of expansion**
  h) **Indium (used as an O ring material)**
  i) **Kapton and Mylar (used in Multilayer Insulation and as electrical insulation**
  j) **Quartz (used in windows)**

- **Unsuitable materials include:**

  a) Martensitic stainless steels - Undergoes ductile to brittle transition when cooled down.

  b) Cast Iron – also becomes brittle

  c) Carbon steels – also becomes brittle. Sometimes used in 300 K vacuum vessels but care must be taken that breaks in cryogenic lines do not cause the vacuum vessels to cool down and fail

  d) Rubber, Teflon and most plastics although plastic insulated wires are frequently OK as long as the wire is not repeatedly flexed which could lead to cracking of the insulation.

- **Thermal Contraction**

Large amounts of contraction can occur when materials are cooled to cryogenic temperatures. Points to consider:

a) Impact on alignment
b) Development of interferences or gaps due to dissimilar materials
c) Increased strain and possible failure
d) Impact on wiring
e) Most contraction occurs above 77 K

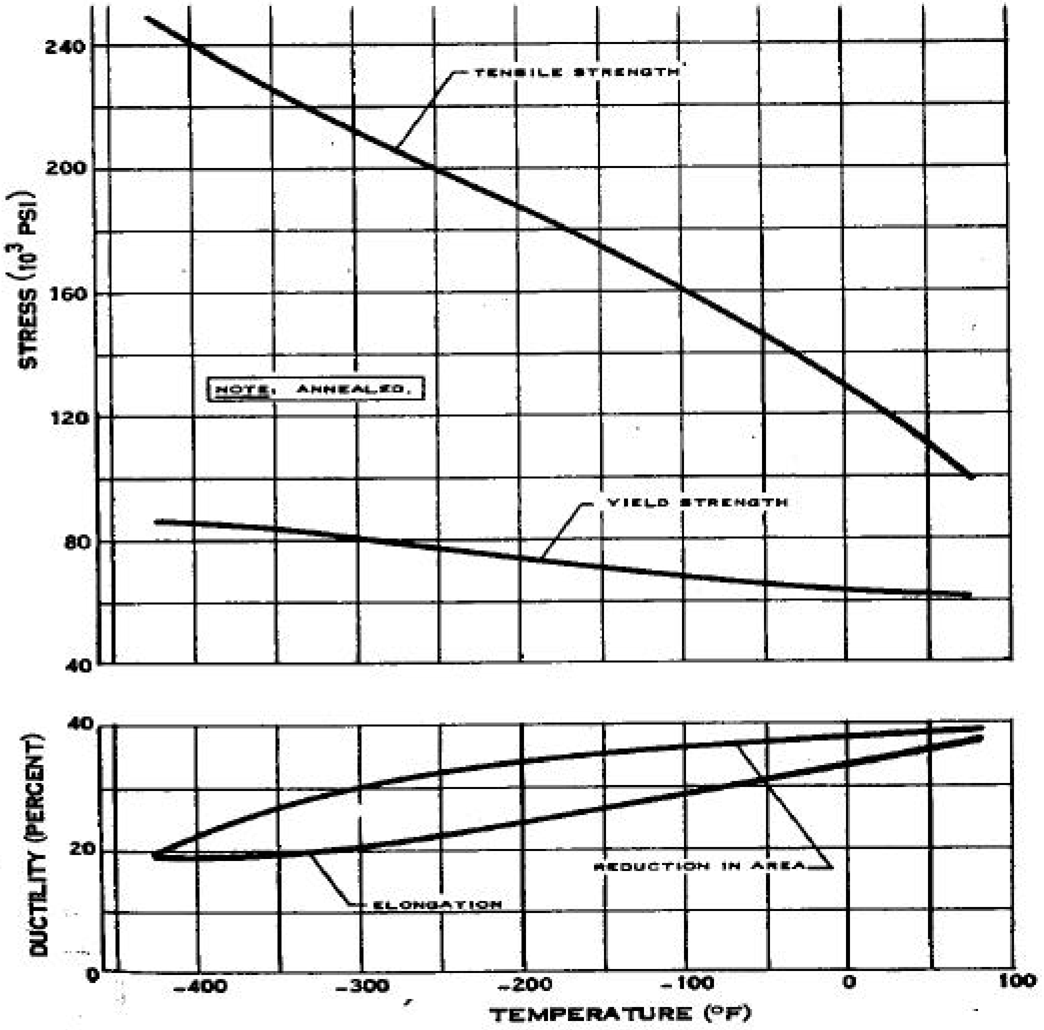
Table 2.1 Integral Thermal Contraction

Material	DL / L (300 – 100)	DL / L (100 – 4)
Stainless Steel	296 x 10^{-5}	35 x 10^{-5}
Copper	326 x 10^{-5}	44 x 10^{-5}
Aluminum	415 x 10^{-5}	47 x 10^{-5}
Iron	198 x 10^{-5}	18 x 10^{-5}
Invar	40 x 10^{-5}	-
Brass	340 x 10^{-5}	57 x 10^{-5}
Epoxy/ Fiberglass	279 x 10^{-5}	47 x 10^{-5}
Titanium	134 x 10^{-5}	17 x 10^{-5}

Strength

- Tends to increase at low temperatures (as long as there is no ductile to brittle transition
- 300 K values are typically used for conservative design

Fig. 2.1 Typical Properties of 304 Stainless Steel
From <u>Cryogenic Materials Data Handbook (Revised)</u>
Schwartzberg et al (1970)



Specific Heat

$$C = Q / DT$$

- **Decreases with temperature**

Result:

- **Systems cooldown faster as they get colder**
- **At cryogenic temperatures, small heat leaks may cause large temperature rises**

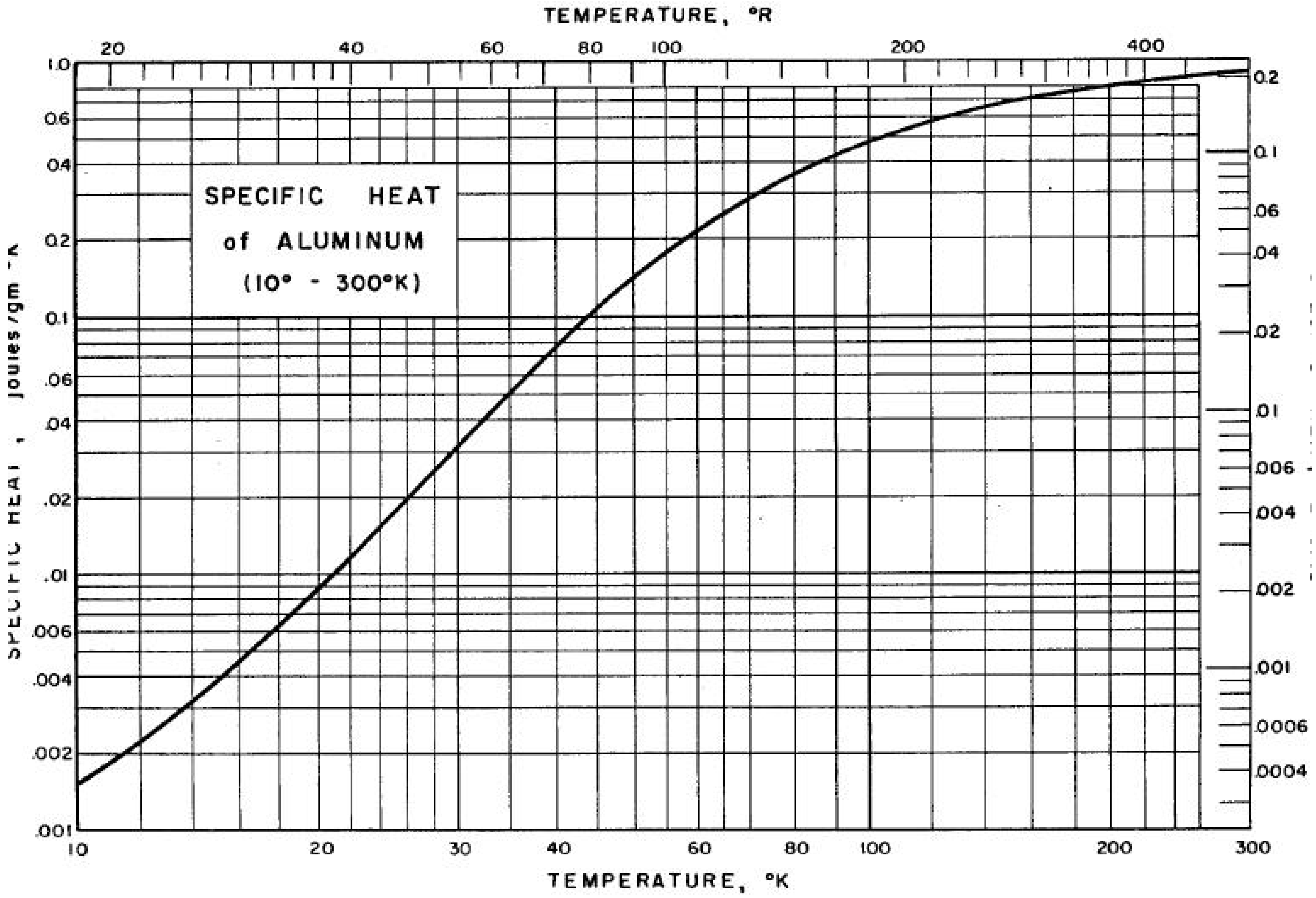


Figure 2.2
Specific Heat of Aluminum
From Properties of Materials at Low Temperatures (Phase1)
V.J. Johnson – Editor
Pergamon Press (1961)

Thermal Conductivity

- **Varies significantly with temperature**
- **Temperature dependence must be considered when calculating heat transfer rates.**

Solution: use thermal conductivity integrals

Conduction heat transfer

$$Q = \frac{-1}{\int_{x_1}^{x_2} \frac{dx}{A(x)}} \left(\int_{T_1}^{T_2} K(T)\, dT \right)$$

Expand

$$Q = \frac{-1}{\int_{x_1}^{x_2} \frac{dx}{A(x)}} \left(\int_{0}^{T_2} K(T)\, dT - \int_{0}^{T_1} K(T)\, dT \right)$$

or :

$$Q = -G(\theta_2 - \theta_1)$$

where the geometry factor G is defined by
:

$$G = \frac{1}{\int_{x_1}^{x_2} \frac{dx}{A(x)}}$$

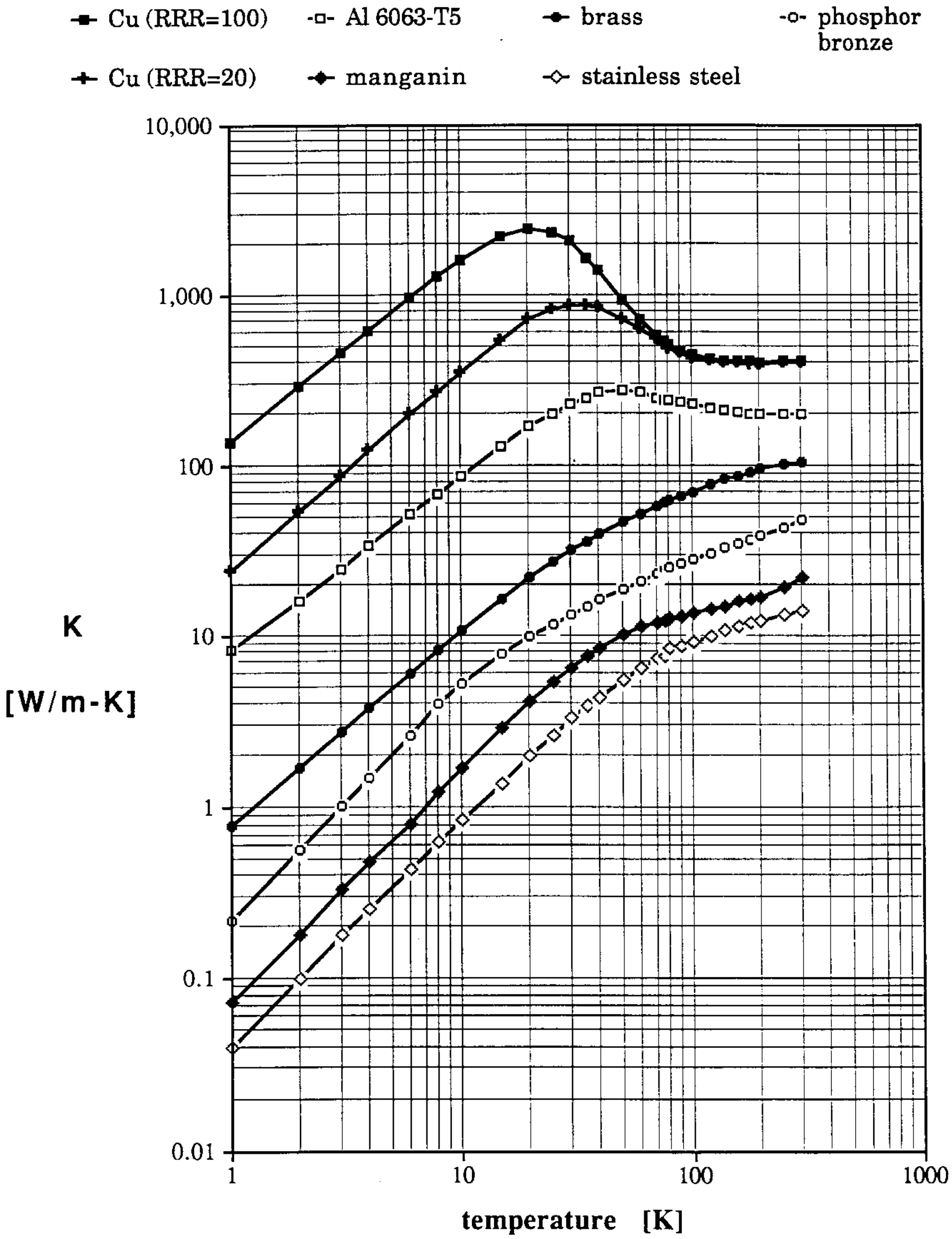
and the thermal conductivity integrals are defined as:

$$\theta_i = \int_0^{T_i} K(T)\,dT$$

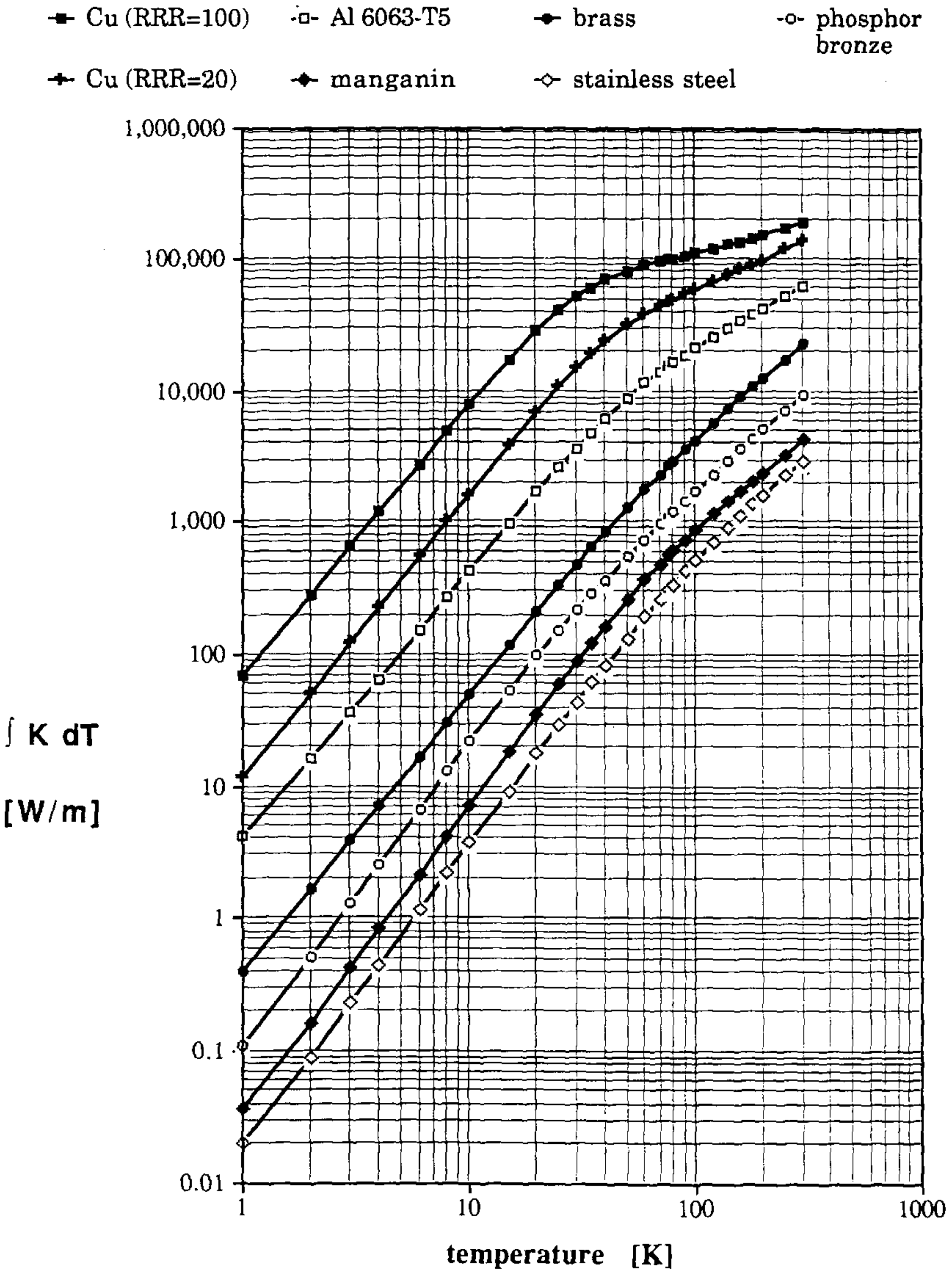
Advantages:

- **Simple**
- **Only end point temperatures are important the actual temperature distribution is not.**

Thermal Conductivities of Metals



Thermal Conductivity Integrals of Metals



Electrical Resistivity

- **Drops due to reduced phonon electron scattering**

- **RRR = resistivity at 300 K / resistivity at 4.2 K. An indication of material purity**

- **“cryogenic” magnets**
  i.e. nonsuperconducting but lower resistance – not too commonly used

- **Superconductivity**

  One of the major reasons cryogenics is used in high energy physics

  A whole separate course

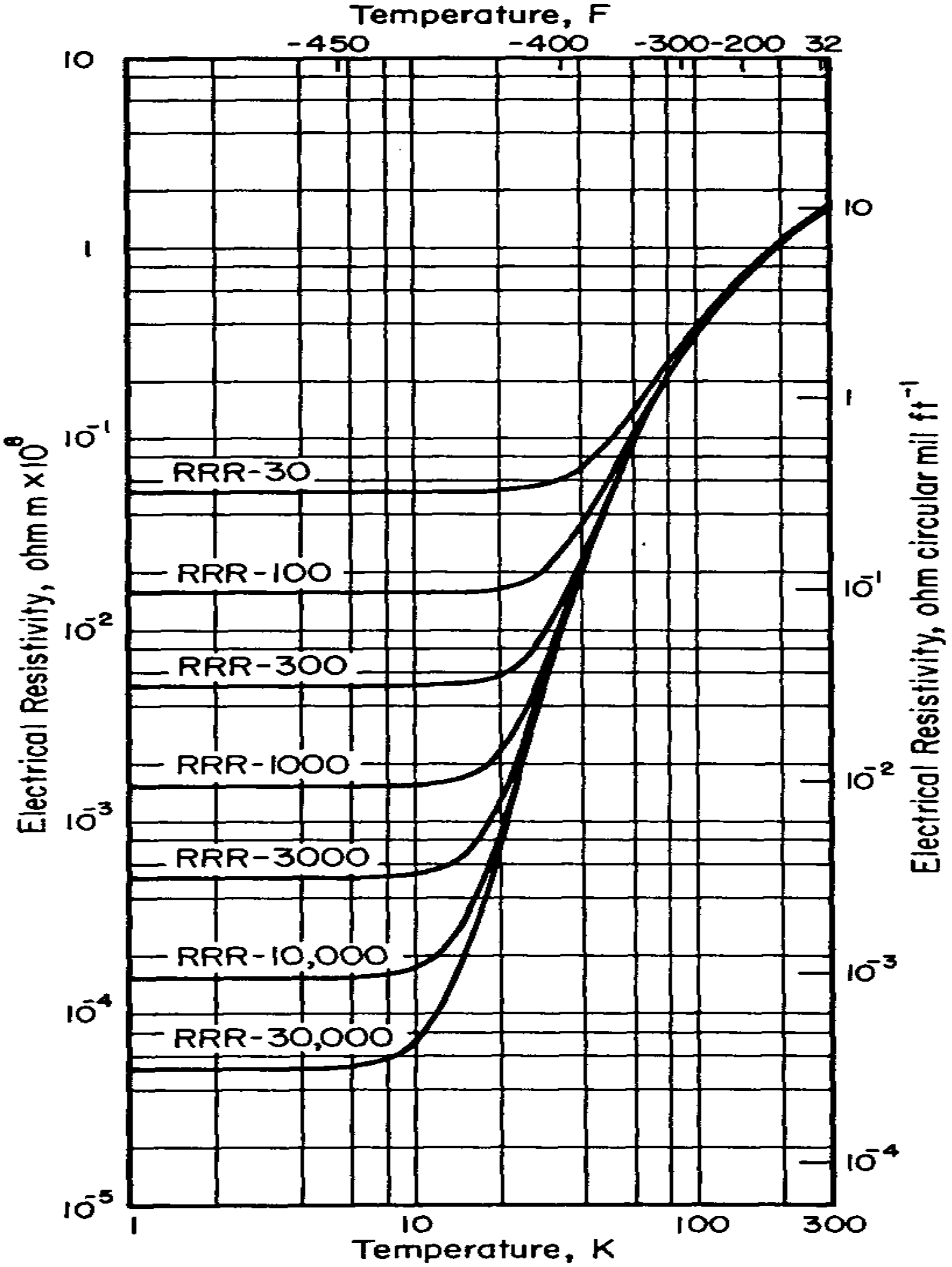
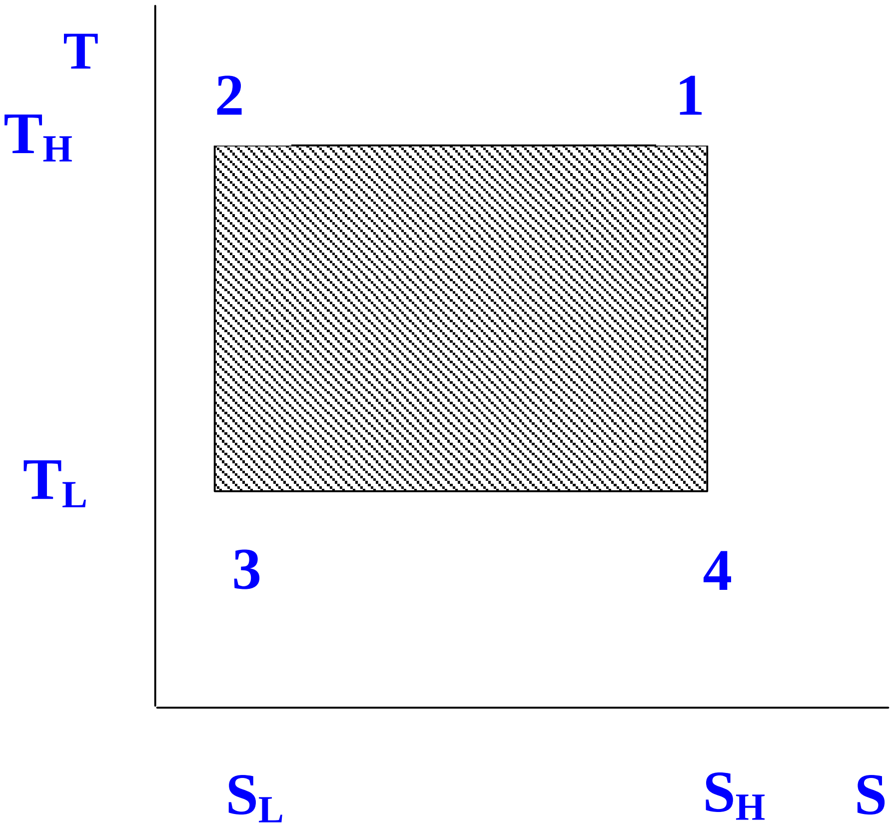


Figure 2.5 Electrical Resistivity of Copper
From Handbook of Materials for Superconducting Machinery
Batttelle Columbus Laboratories (1974)

II) Refrigeration

- Refrigerators
  - Closed cycle
  - Balanced
- Liquefiers
  - Open cycle
  - Unbalanced
- Both refrigerators and liquefiers use the same thermodynamic principles
- Large plants can typically be run in either refrigeration or liquefaction mode or both

An Ideal refrigeration cycle: the Carnot Cycle



Performance Measurements

- **Coefficient of Performance (COP).**

The COP is the heat removed at low temperature divided by the work done at high temperature.

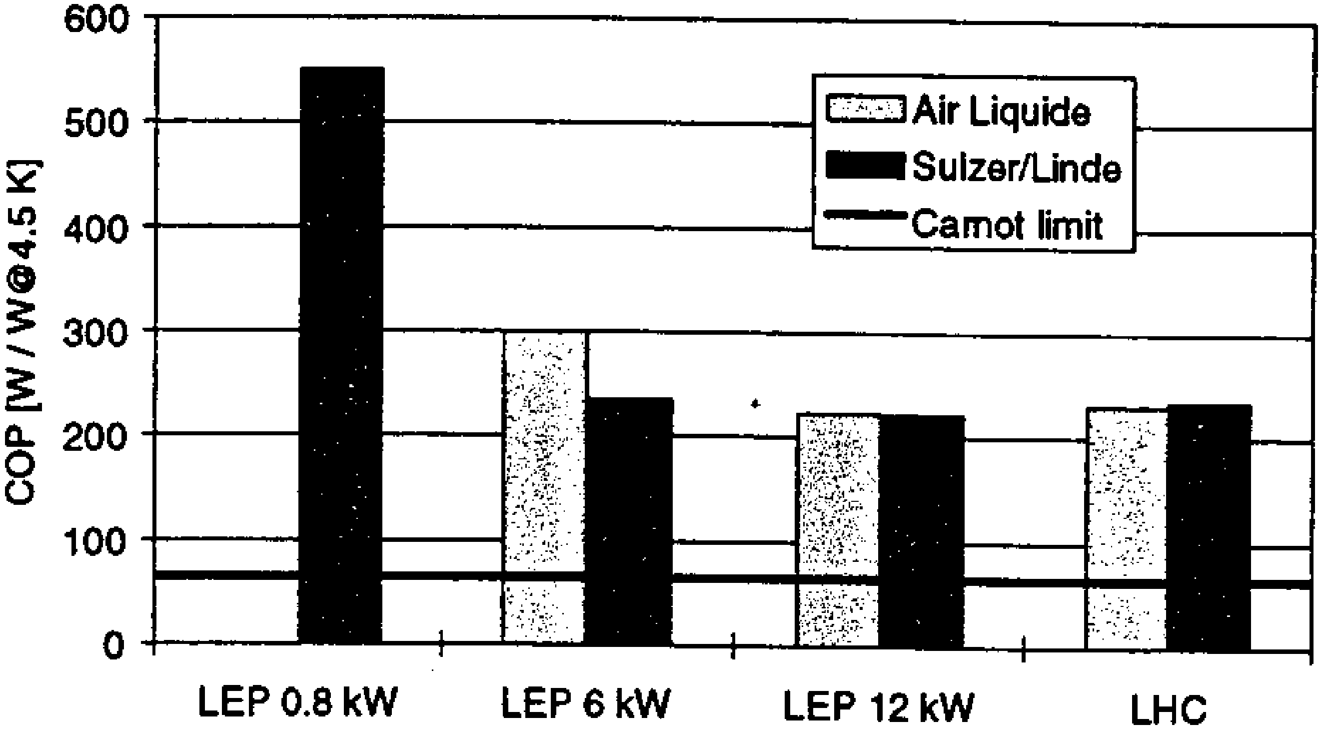
In the case of the ideal Carnot cycle:

$$COP = (T_L) /(T_H - T_L)$$

> **Moral : Intercept heat at as high a temperature as possible**

- **Figure of Merit (FOM). The FOM is the work required for an ideal Carnot cycle divided by the work required for real system.**
  - **An ideal Carnot refrigerator requires 70 watts of work to provide 1 W of cooling at 4.2 K**

- **The modern LHC refrigerators require ~ 220 Watts of work to provide 1 Watt of cooling at 4.2 K. This equals a FOM of ~ 30 %**



600
500
400
300
200
100
0
COP [W / W@4.5 K]
Air Liquide
Sulzer/Linde
Carnot limit
LEP 0.8 kW
LEP 6 kW
LEP 12 kW
LHC

Real Refrigerators

4 Principal ways to cool a fluid

1. Expand it through a valve (internal work –isenthalpic)

2. Make it do external work on a turbine or piston (isentropic)

3. Cool it with another fluid via a heat exchanger

4. Reduce the pressure and thus temperature of a saturated liquid

Isenthalpic Expansion (also known as Joule – Thomson expansion)

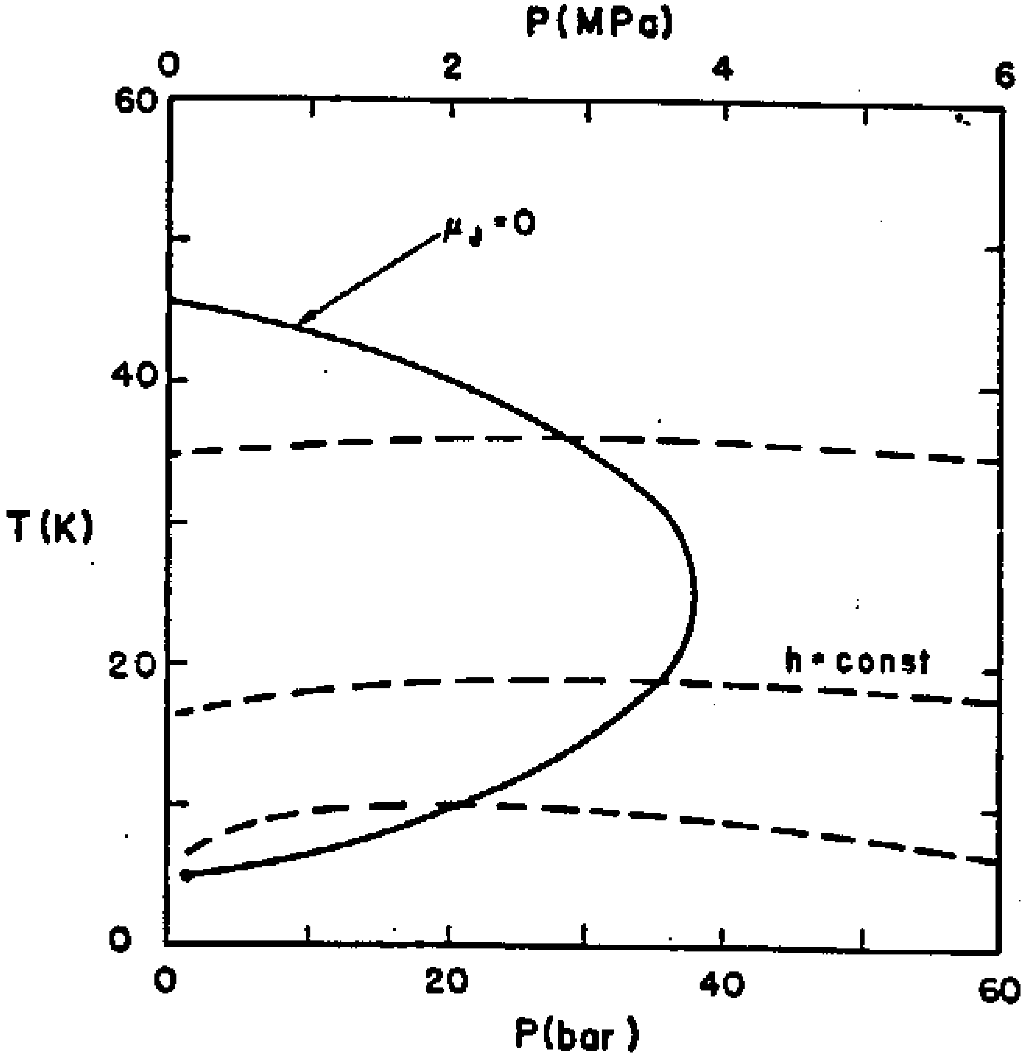
- **Generally smaller DT for a given DP than isentropic expansion (recall TS diagram)**

- **Handles two-phase mixtures of fluid and gas without a problem**

- **Simple**

- **You must be below the inversion temperature for the given pressure or you will heat the fluid instead of cool it.**

Nitrogen: Tmax >300 K.
He :Tmax ~ 45 K.


P(MPa)
0
2
4
6
60
40
20
0
T(K)
$\mu_J = 0$
h = const
0
20
40
60
P(bar)

Isentropic Expansion

- Generally more efficient (larger DT for a given DP) than isenthalpic expansion
- Doesn’t work well with two-phase mixtures (particularly in turbines though there are exceptions)
- Works at any temperature
- Requires complicated though well understood machinery
- Turbine work may sometimes be used to generate electricity

Almost all machines use Joule-Thomson expansion as a final cooling step.