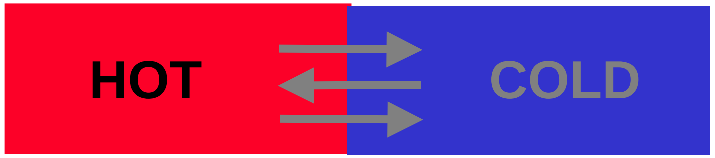
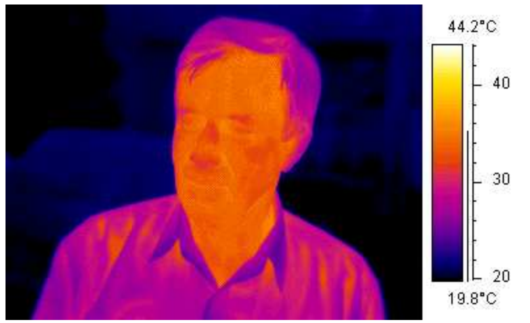
Energy Transport

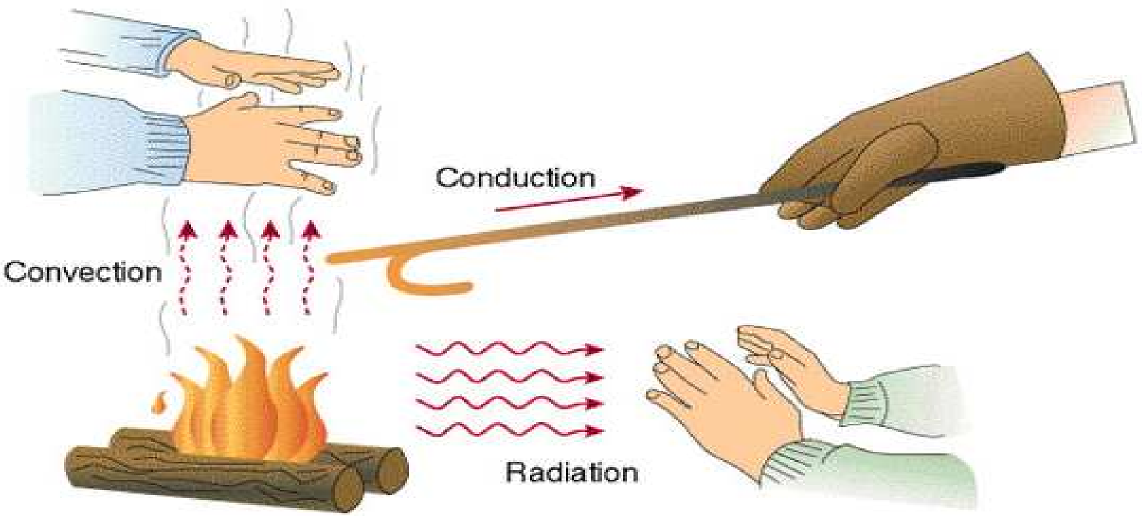
Focus on → heat transfer

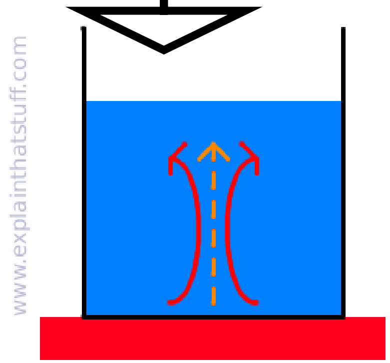


Heat Transfer Mechanisms:

- Conduction
- Radiation
- Convection (mass movement of fluids)







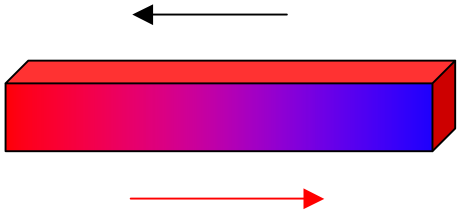
Conduction

Conduction heat transfer occurs only when there is physical contact between bodies (systems) at different temperatures by molecular motion.

Heat transfer through solid bodies is by conduction alone, whereas the heat may transfer from a solid surface to a fluid partly by conduction and partly by convection.

$$\vec{\nabla}\, T\ \left(\frac{\partial T}{\partial x}\right)$$

Furier's law



$$\vec{q} = -\lambda\, \vec{\nabla} T$$

$$\vec{q}$$

- Thermal conductivity (Fourier 1822)

Thermal Conductivity of Solids

Solids transmit thermal energy by two modes:

- **elastic vibrations of the lattice moving through the crystal in the form of waves**

- **free electrons moving through the lattice also carry energy similar to the case in gases (this is observed in metals)**

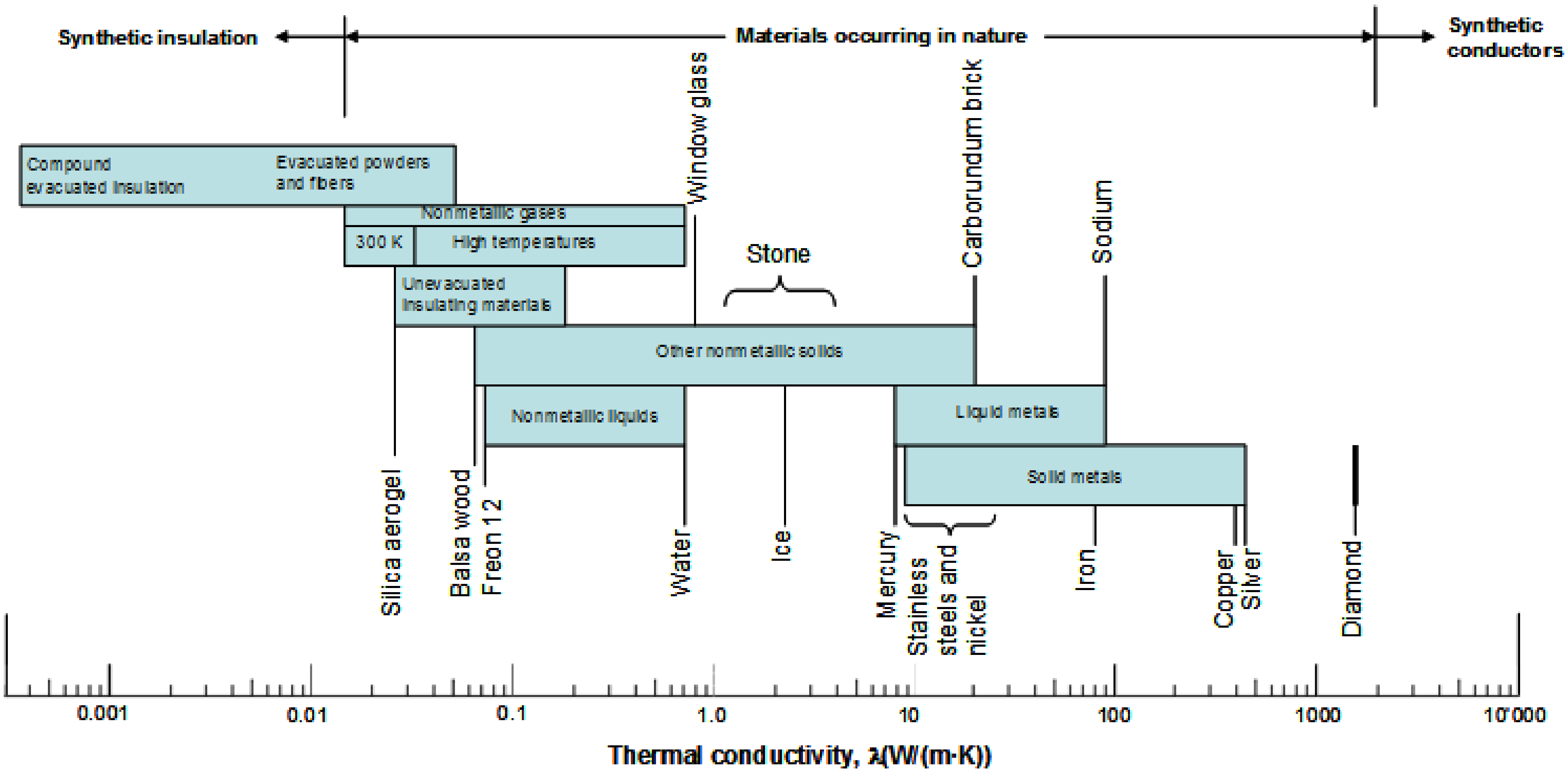
$$\lambda_{total} = \lambda_{\mathbf{phon}} + \lambda_e$$

Thermal conductivity:

$$\lambda = \frac{1}{3} C v \ell$$

Specific heat Velocity Mean free path

Thermal Conductivity of Solids

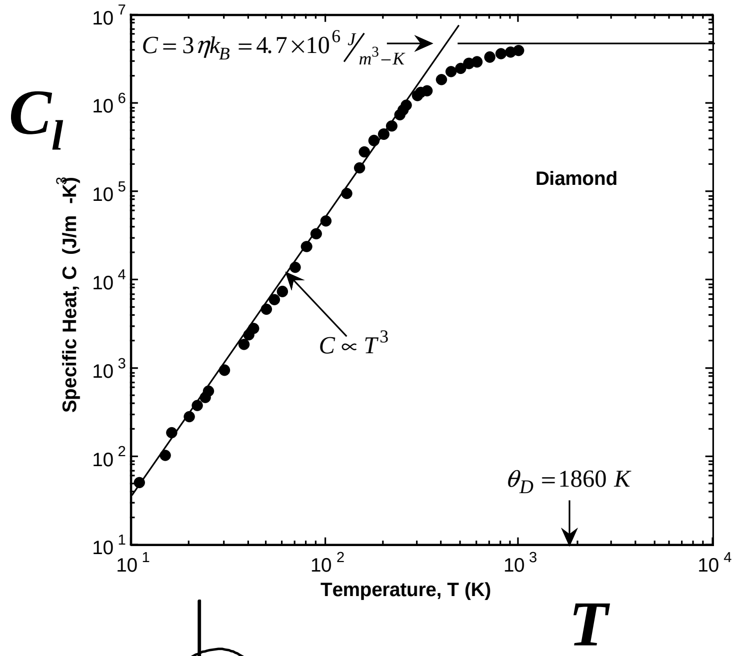


Specific Heat of Solids

- The heat is stored via
  - Lattice vibrations
  - Electrons (metals)

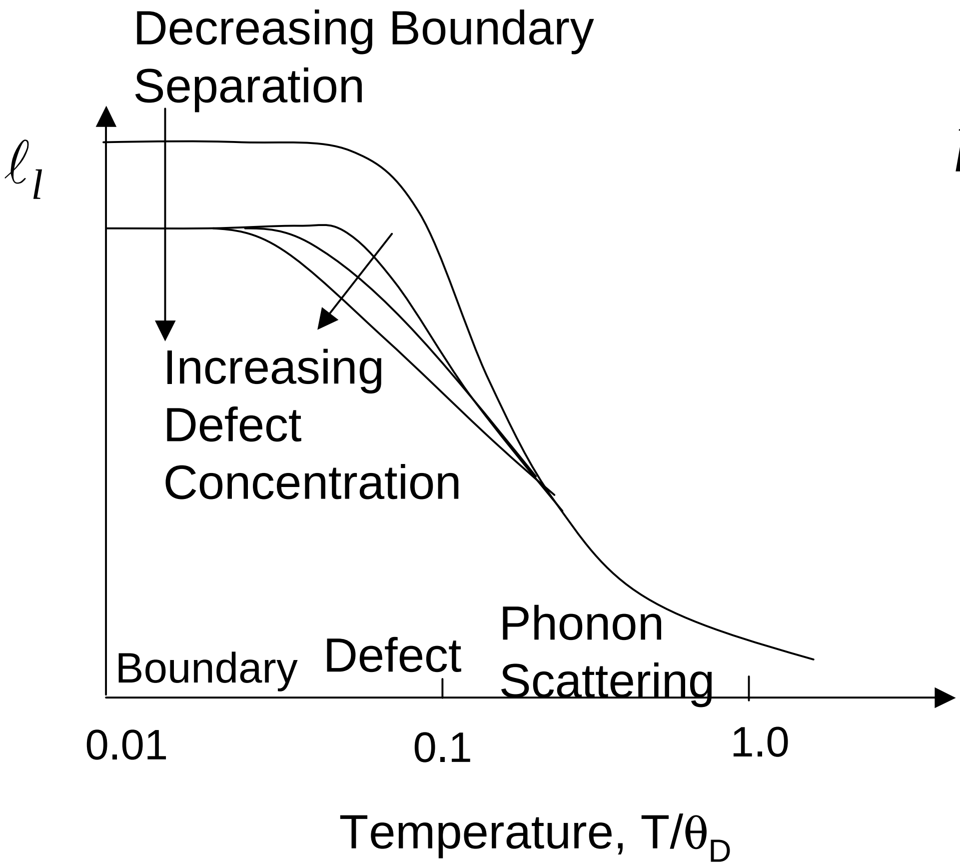
Phonon Thermal Conductivity

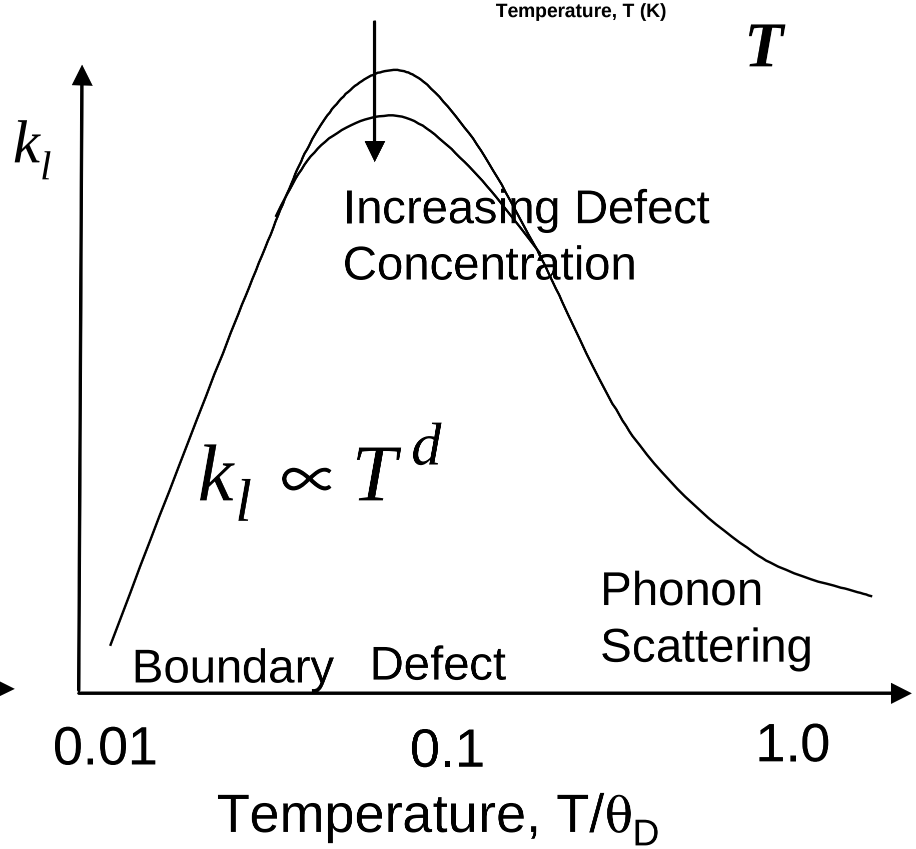
Kinetic Theory $$k_l = \frac{1}{3} C_l v_s \ell_l$$



$$\frac{1}{\ell_l} = \frac{1}{\ell_{defect}} + \frac{1}{\ell_{boundary}} + \frac{1}{\ell_{phonon}}$$

Matthiessen Rule:



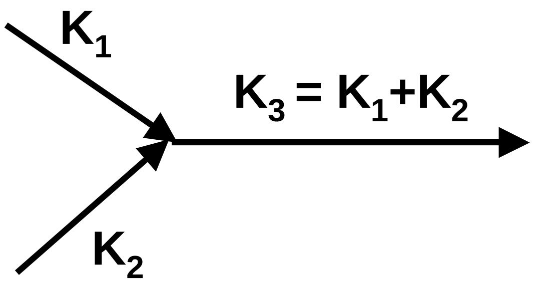


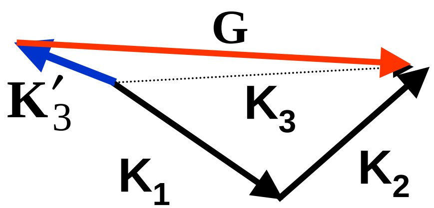
Thermal Conductivity of Solids

Each lattice vibration (there is always a spectrum of vibrations) may be described as a traveling wave carrying energy and obeying the laws of quantum mechanics. By analogy with light theory, the waves in a crystal exhibit the characteristics of particles and are called phonons.

Two types of phonon-phonon interaction are observed in solids:

- Normal or N-type
- Umklapp (U-process) collision





U-Process

$$\mathbf{K}_3' = \mathbf{K}_1 + \mathbf{K}_2 - \mathbf{G}$$

$$\omega_3' = \omega_1 + \omega_2$$

Momentum Conservation: $\hbar \mathbf{K}_3 = \hbar \mathbf{K}_1 + \hbar \mathbf{K}_2$

Energy Conservation: $\hbar\omega_3 = \hbar\omega_1 + \hbar\omega_2$

Phonon Thermal Conductivity

Thermal Conductivity of Solids

Phonons are also scattered by

- differences in isotopic masses
- chemical impurities
- dislocations
- second phases

Alloying, phase mixing

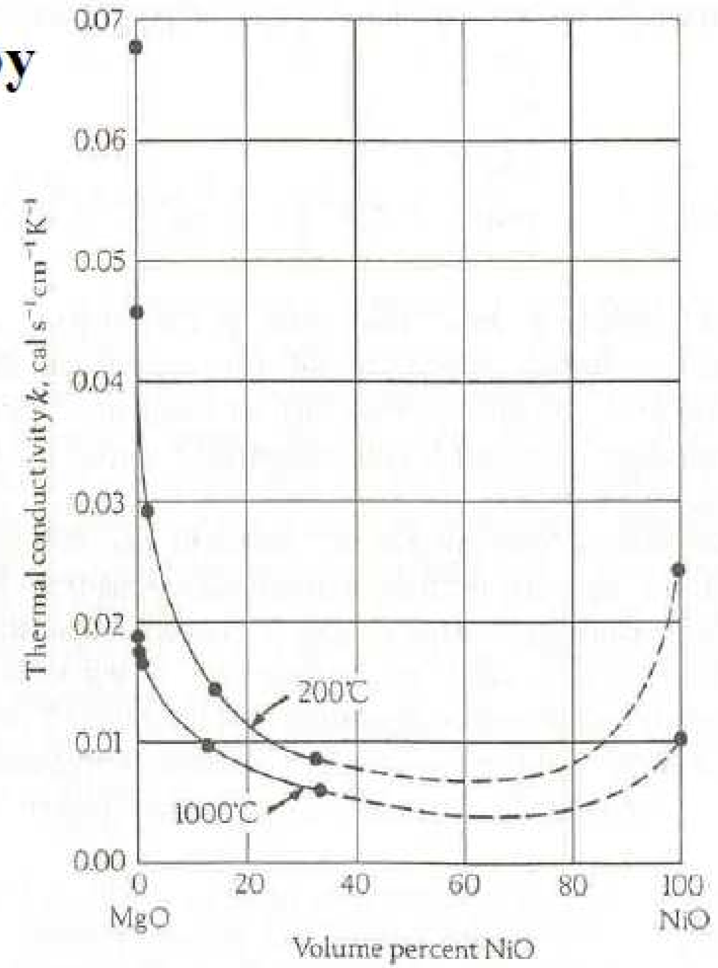


Fig. 6.5 Thermal conductivity in the solid-solution system MgO-NiO. (From Kingery *et al.*, *ibid.*, page 623.) Note: 1 cal s^{-1} cm^{-1} K^{-1} = 418.4 W m^{-1} K^{-1}.

Phonon Thermal Conductivity- Impurities

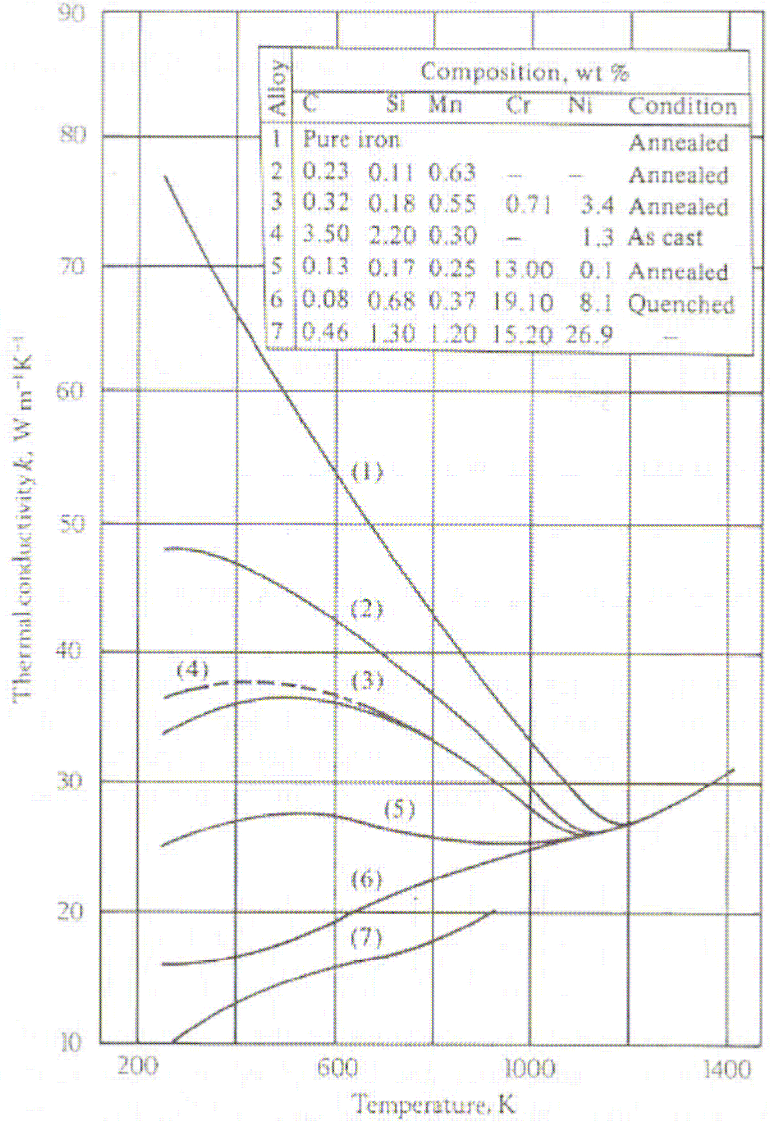
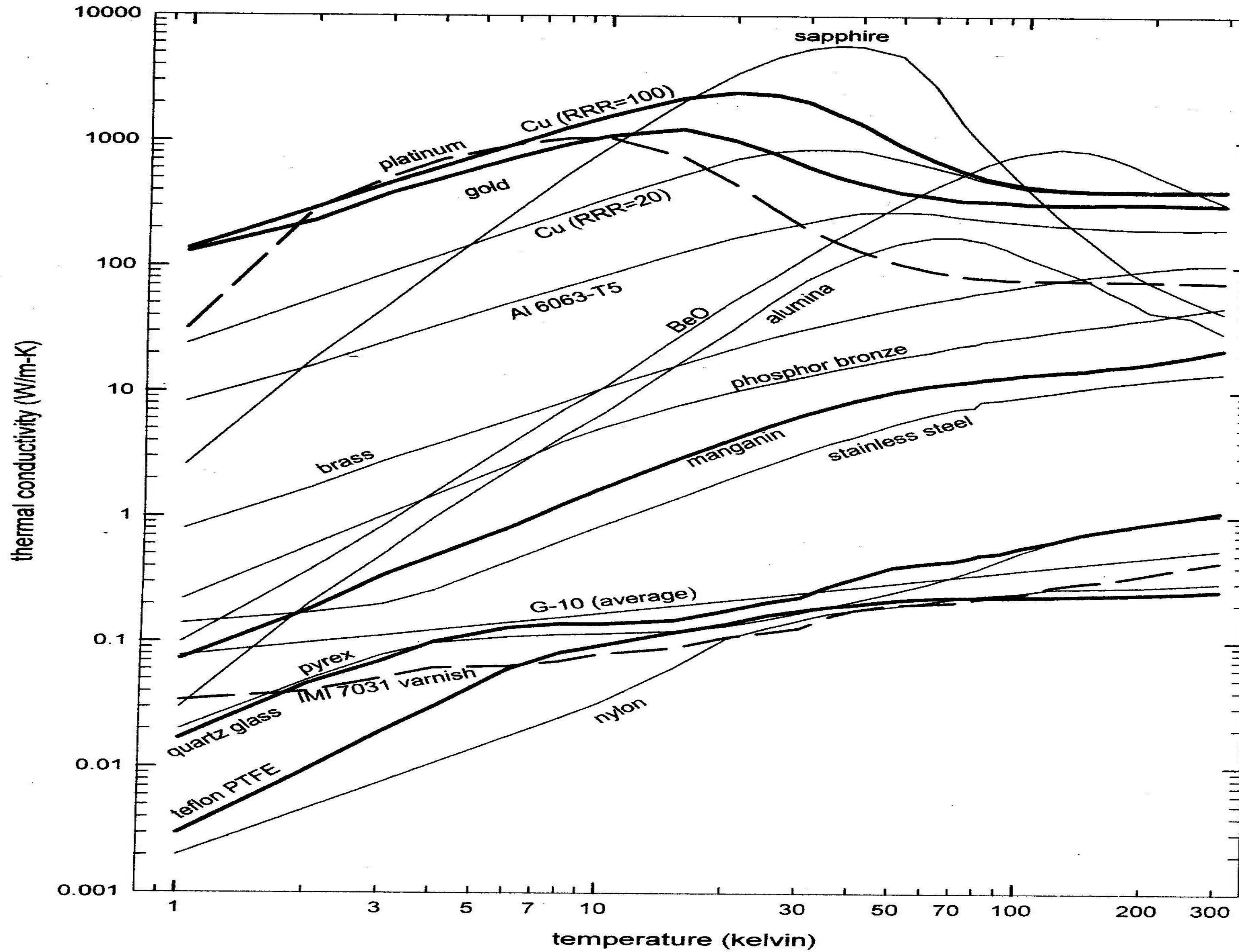
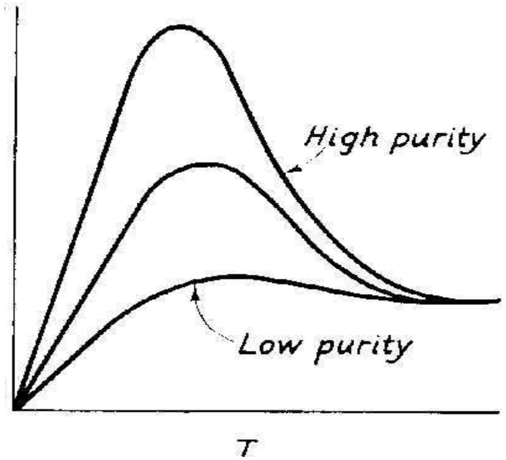


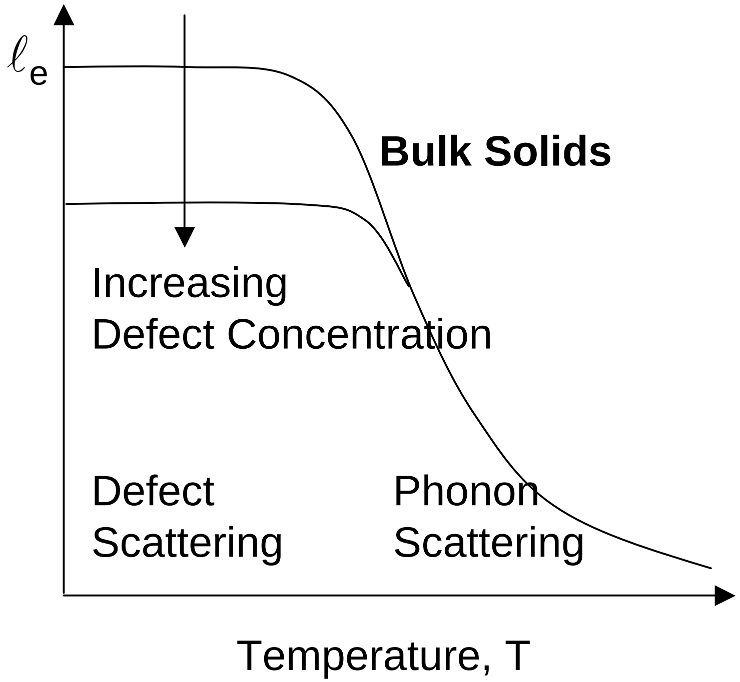
Fig. 6.8 Thermal conductivities of pure iron and iron-base alloys. (From Schack, *ibid.*)


sapphire
Cu (RRR=100)
platinum
gold
Cu (RRR=20)
Al 6063-T5
BeO
alumina
phosphor bronze
brass
manganin
stainless steel
G-10 (average)
pyrex
IMI 7031 varnish
quartz glass
nylon
teflon PTFE
10000
1000
100
10
1
0.1
0.01
0.001
thermal conductivity (W/m-K)
1
3
5
7
10
30
50
70
100
200
300
temperature (kelvin)

Electronic Thermal Conductivity

Thermal Conductivity





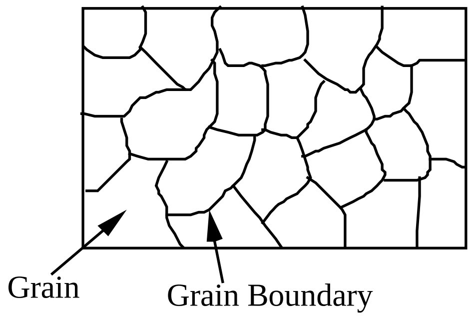
Specific Heat

$$C_e = \frac{\pi^2}{2}\left(\frac{k_B T}{E_F}\right)\eta_e k_B$$ in 3D

$$k_e = \frac{1}{3} C_e v_F \ell_e = \frac{1}{3} C_e v_F^2 \tau_e$$

Electron Scattering Mechanisms

- Defect Scattering
- Phonon Scattering
- Boundary Scattering



Electrical conductivity