Chapter 19: Thermal Properties

ISSUES TO ADDRESS...

- How do materials respond to the application of heat?
- How do we define and measure...
  -- heat capacity?
  -- thermal expansion?
  -- thermal conductivity?
  -- thermal shock resistance?
- How do the thermal properties of ceramics, metals, and polymers differ?

Heat Capacity

The ability of a material to absorb heat

- Quantitatively: The energy required to produce a unit rise in temperature for one mole of a material.

heat capacity (J/mol-K) → $$C = \frac{dQ}{dT}$$ ← energy input (J/mol), temperature change (K)

- Two ways to measure heat capacity:

  C_p : Heat capacity at constant pressure.

  C_v : Heat capacity at constant volume.

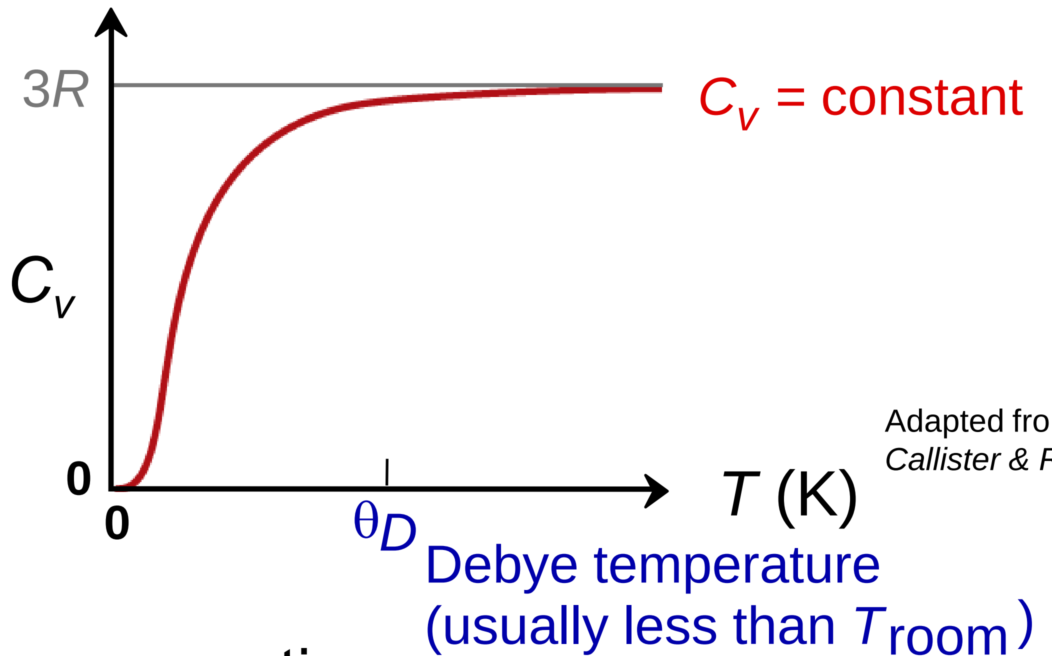
  C_p usually > C_v

- Heat capacity has units of $\frac{\text{J}}{\text{mol} \cdot \text{K}} \left(\frac{\text{Btu}}{\text{lb} - \text{mol} \cdot {}^{\circ}\text{F}} \right)$

Dependence of Heat Capacity on Temperature

- Heat capacity...
  - -- increases with temperature
  - -- for solids it reaches a limiting value of 3*R*

R = gas constant
= 8.31 J/mol-K

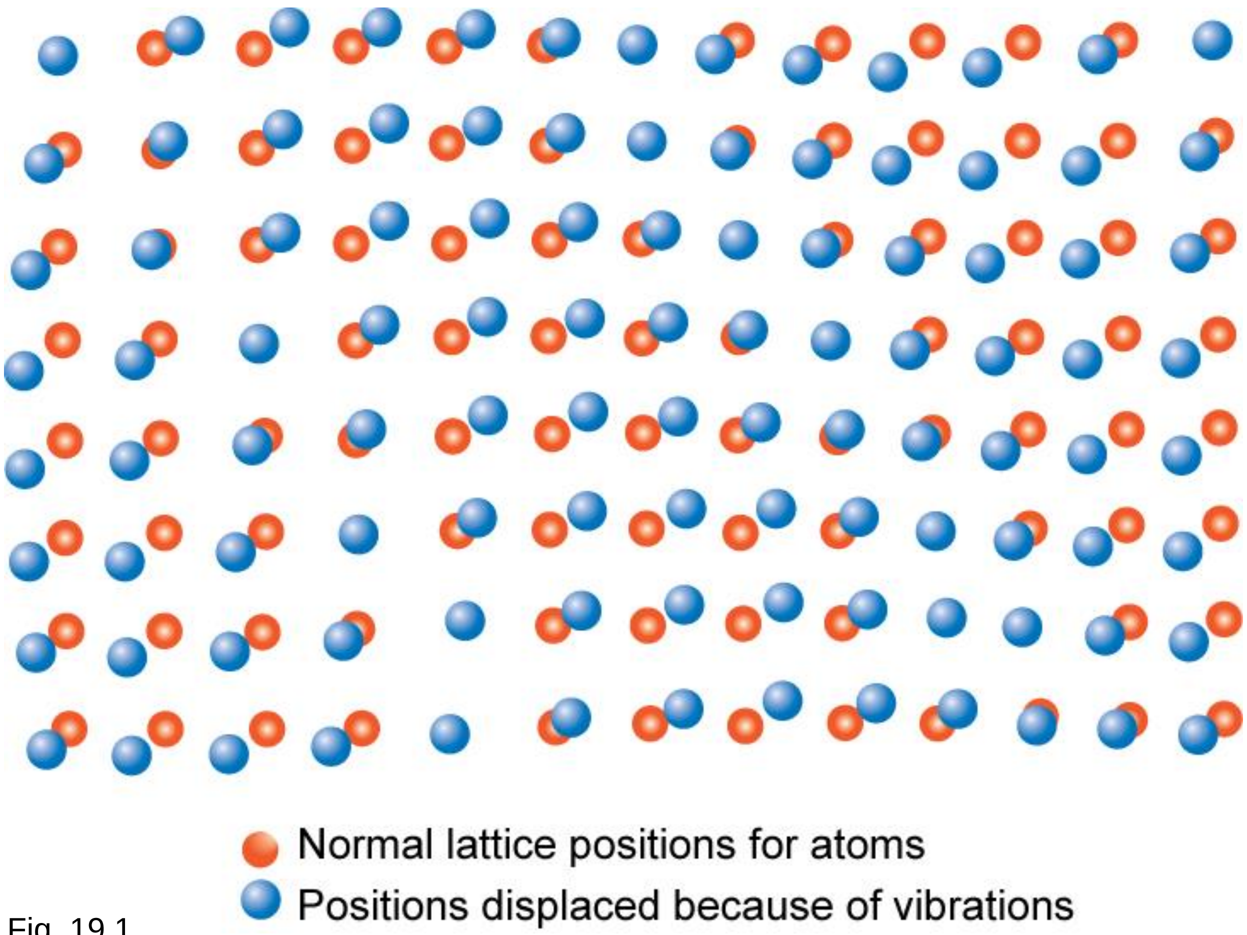


Adapted from Fig. 19.2, *Callister & Rethwisch 8e*.

- From atomic perspective:
  - -- Energy is stored as atomic vibrations.
  - -- As temperature increases, the average energy of atomic vibrations increases.

Atomic Vibrations

Atomic vibrations are in the form of lattice waves or phonons



Adapted from Fig. 19.1, *Callister & Rethwisch 8e*.

Specific Heat: Comparison

increasing c_p

Material	c_p (J/kg-K) at room T
• Polymers	
Polypropylene	1925
Polyethylene	1850
Polystyrene	1170
Teflon	1050
• Ceramics	
Magnesia (MgO)	940
Alumina (Al_2O_3)	775
Glass	840
• Metals	
Aluminum	900
Steel	486
Tungsten	138
Gold	128

c_p (specific heat): (J/kg-K)

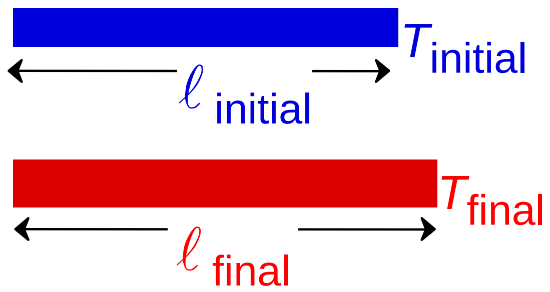
C_p (heat capacity): (J/mol-K)

- Why is c_p significantly larger for polymers?

Selected values from Table 19.1, *Callister & Rethwisch 8e*.

Thermal Expansion

Materials change size when temperature is changed

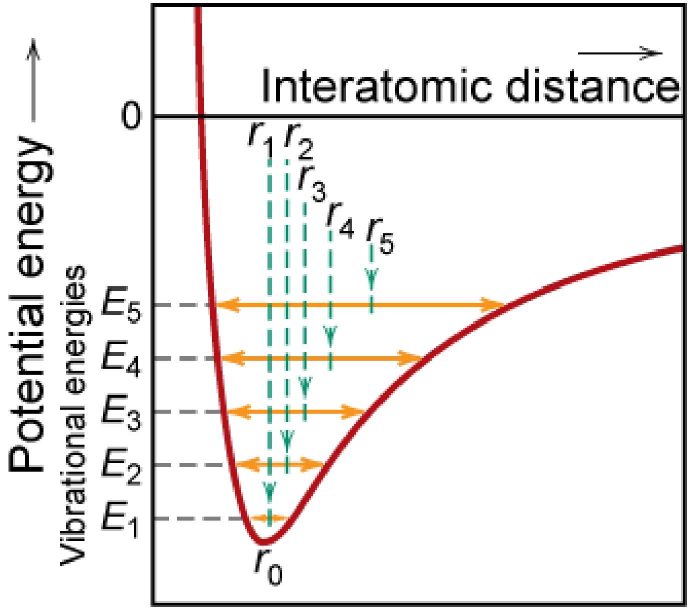


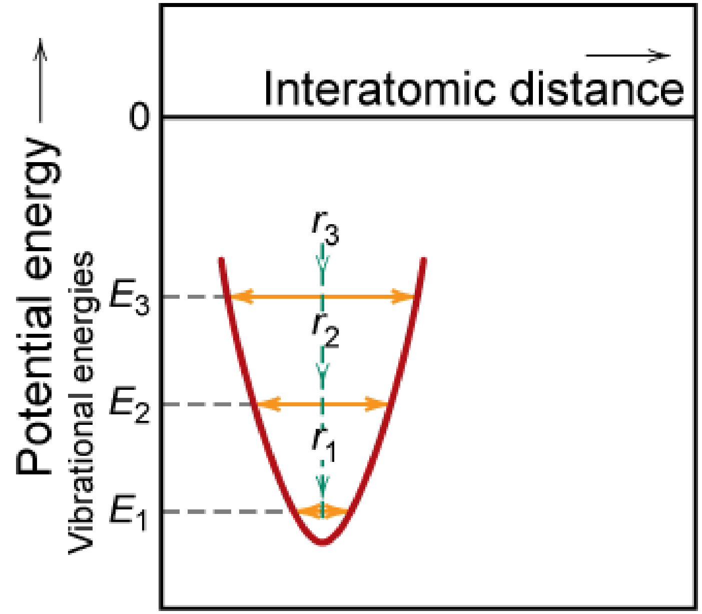
$$T_{final} > T_{initial}$$

$$\frac{l_{final} - l_{initial}}{l_{initial}} = \alpha_l (T_{final} - T_{initial})$$

linear coefficient of thermal expansion (1/K or 1/ºC)

Atomic Perspective: Thermal Expansion





Asymmetric curve:
- -- increase temperature,
- -- increase in interatomic separation
- -- thermal expansion

Symmetric curve:
- -- increase temperature,
- -- no increase in interatomic separation
- -- no thermal expansion

Adapted from Fig. 19.3, *Callister & Rethwisch 8e*.

Coefficient of Thermal Expansion: Comparison

increasing α_ℓ

Material	α_ℓ (10^{-6}/°C) at room *T*
• Polymers	
Polypropylene	145-180
Polyethylene	106-198
Polystyrene	90-150
Teflon	126-216
• Metals	
Aluminum	23.6
Steel	12
Tungsten	4.5
Gold	14.2
• Ceramics	
Magnesia (MgO)	13.5
Alumina (Al_2O_3)	7.6
Soda-lime glass	9
Silica (cryst. SiO_2)	0.4

Polymers have larger α_ℓ values because of weak secondary bonds

- **Q: Why does α_ℓ generally decrease with increasing bond energy?**

Selected values from Table 19.1, *Callister & Rethwisch 8e*.

Thermal Expansion: Example

Ex: A copper wire 15 m long is cooled from 40 to -9ºC. How much change in length will it experience?

- Answer: For Cu $\alpha_\ell = 16.5 \text{ x } 10^{-6}\ (^\circ\text{C})^{-1}$

rearranging Equation 19.3b

$$\Delta\ell = \alpha_\ell \ell_0 \Delta T = [16.5 \text{ x } 10^{-6} (1/^\circ\text{C})](15 \text{ m})[40^\circ\text{C} - (-9^\circ\text{C})]$$

$$\Delta\ell = 0.012 \text{ m} = 12 \text{ mm}$$

Thermal Conductivity

The ability of a material to transport heat.

Fourier's Law

$$q = -k\frac{dT}{dx}$$

heat flux (J/m^2-s)

temperature gradient

thermal conductivity (J/m-K-s)

$T_2 > T_1$

- Atomic perspective: Atomic vibrations and free electrons in hotter regions transport energy to cooler regions.

Thermal Conductivity: Comparison

increasing k

Material	k (W/m-K)	Energy Transfer Mechanism
• Metals		
Aluminum	247	atomic vibrations and motion of free electrons
Steel	52	
Tungsten	178	
Gold	315	
• Ceramics		
Magnesia (MgO)	38	atomic vibrations
Alumina (Al_2O_3)	39	
Soda-lime glass	1.7	
Silica (cryst. SiO_2)	1.4	
• Polymers		
Polypropylene	0.12	vibration/rotation of chain molecules
Polyethylene	0.46-0.50	
Polystyrene	0.13	
Teflon	0.25	

Selected values from Table 19.1, *Callister & Rethwisch 8e*.

Thermal Stresses

- Occur due to:
  -- restrained thermal expansion/contraction
  -- temperature gradients that lead to differential dimensional changes

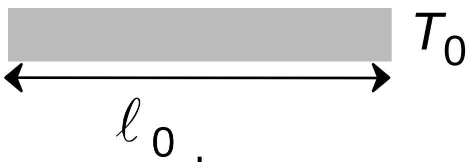
Thermal stress $= \sigma$

$$= E\alpha_\ell (T_0 - T_f) = E\alpha_\ell \Delta T$$

Example Problem

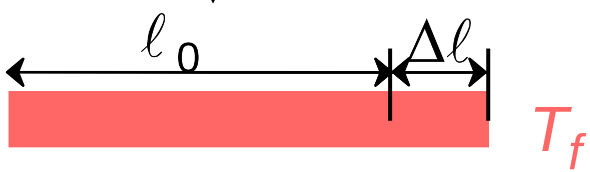
-- A brass rod is stress-free at room temperature (20ºC).
-- It is heated up, but prevented from lengthening.
-- At what temperature does the stress reach -172 MPa?

Solution:



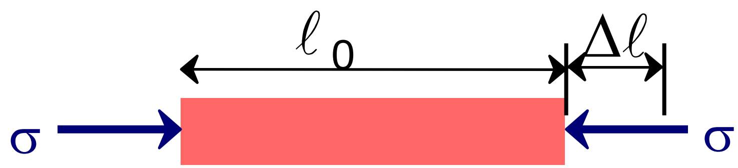
Original conditions

Step 1: Assume unconstrained thermal expansion



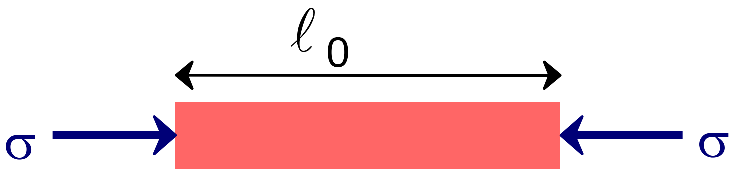
$$\frac{\Delta \ell}{\ell_{\text{room}}} = \varepsilon_{\text{thermal}} = \alpha_{\ell}(T_f - T_0)$$

Step 2: Compress specimen back to original length



$$\varepsilon_{\text{compress}} = \frac{-\Delta \ell}{\ell_{\text{room}}} = -\varepsilon_{\text{thermal}}$$

Example Problem (cont.)



The thermal stress can be directly calculated as

$$\sigma = E(\varepsilon_{compress})$$

Noting that $\varepsilon_{compress} = -\varepsilon_{thermal}$ and substituting gives

$$\sigma = -E(\varepsilon_{thermal}) = -E\alpha_{\ell}(T_f - T_0) = E\alpha_{\ell}(T_0 - T_f)$$

Rearranging and solving for T_f gives

$$T_f = T_0 - \frac{\sigma}{E\alpha_{\ell}}$$

20ºC

-172 MPa (since in compression)

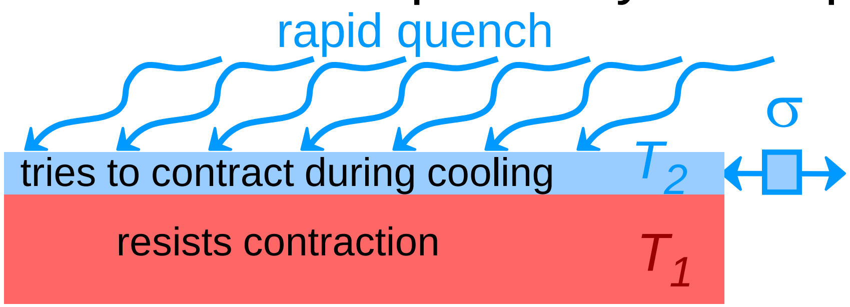
100 GPa

$20 \times 10^{-6}/^{\circ}C$

Answer: 106ºC

Thermal Shock Resistance

- Occurs due to: nonuniform heating/cooling
- Ex: Assume top thin layer is rapidly cooled from T_1 to T_2



Tension develops at surface

$$\sigma = -E\alpha_{\ell}(T_1 - T_2)$$

Temperature difference that can be produced by cooling:

$$(T_1 - T_2) = \frac{\text{quench rate}}{k}$$

Critical temperature difference for fracture (set $\sigma = \sigma_f$)

$$(T_1 - T_2)_{\text{fracture}} = \frac{\sigma_f}{E\alpha_{\ell}}$$

set equal

- $$(\text{quench rate})_{\text{for fracture}} = \text{Thermal Shock Resistance } (TSR) \propto \frac{\sigma_f k}{E\alpha_{\ell}}$$
- Large *TSR* when $\frac{\sigma_f k}{E\alpha_{\ell}}$ is large

Thermal Protection System

- Application:

Chapter-opening photograph, Chapter 23, *Callister 5e* (courtesy of the National Aeronautics and Space Administration.)

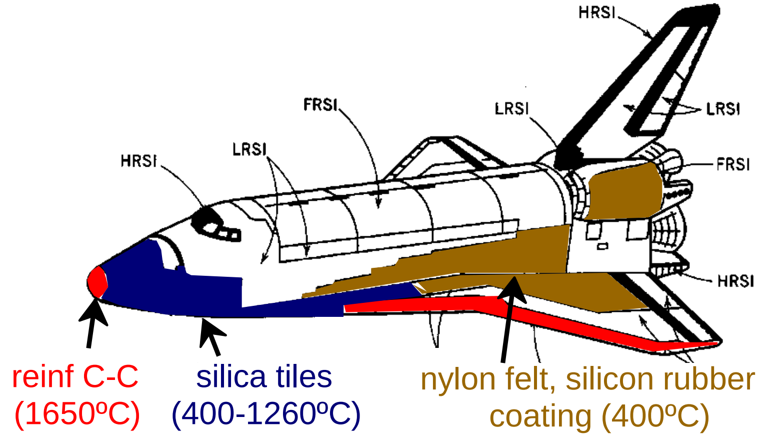


Fig. 19.2W, *Callister 6e*. (Fig. 19.2W adapted from L.J. Korb, C.A. Morant, R.M. Calland, and C.S. Thatcher, "The Shuttle Orbiter Thermal Protection System", *Ceramic Bulletin*, No. 11, Nov. 1981, p. 1189.)

- Silica tiles (400-1260ºC):
  -- large scale application

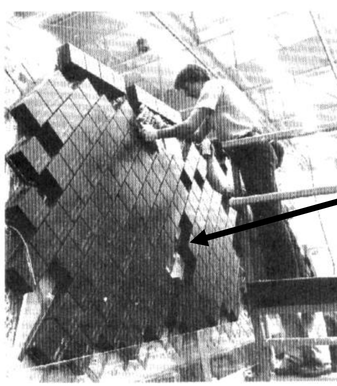
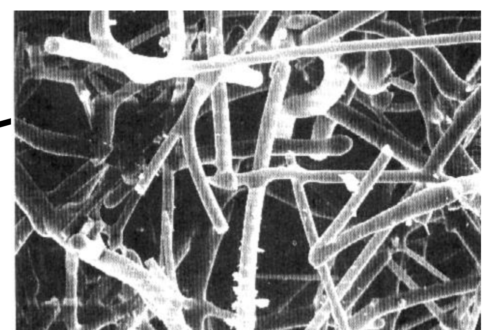


Fig. 19.3W, *Callister 5e*. (Fig. 19.3W courtesy the National Aeronautics and Space Administration.)

-- microstructure:



100 µm

~90% porosity!
SiO2 fibers bonded to one another during heat treatment.

Fig. 19.4W, *Callister 5e*. (Fig. 219.4W courtesy Lockheed Aerospace Ceramics Systems, Sunnyvale, CA.)

Summary

The thermal properties of materials include:

- **Heat capacity:**
  -- energy required to increase a mole of material by a unit T
  -- energy is stored as atomic vibrations
- **Coefficient of thermal expansion:**
  -- the size of a material changes with a change in temperature
  -- polymers have the largest values
- **Thermal conductivity:**
  -- the ability of a material to transport heat
  -- metals have the largest values
- **Thermal shock resistance:**
  -- the ability of a material to be rapidly cooled and not fracture
  -- is proportional to $\dfrac{\sigma_f k}{E\alpha_\ell}$

ANNOUNCEMENTS

Reading:

Core Problems:

Self-help Problems: