CHAPTER 19:
THERMAL PROPERTIES

ISSUES TO ADDRESS...

- **How does a material respond to heat?**
- **How do we define and measure...**
  --heat capacity
  --coefficient of thermal expansion
  --thermal conductivity
  --thermal shock resistance
- **How do ceramics, metals, and polymers rank?**

HEAT CAPACITY

- **General:** **The ability of a material to absorb heat.**
- **Quantitative:** **The energy required to increase the temperature of the material.**

heat capacity (J/mol-K)

$$C = \frac{dQ}{dT}$$

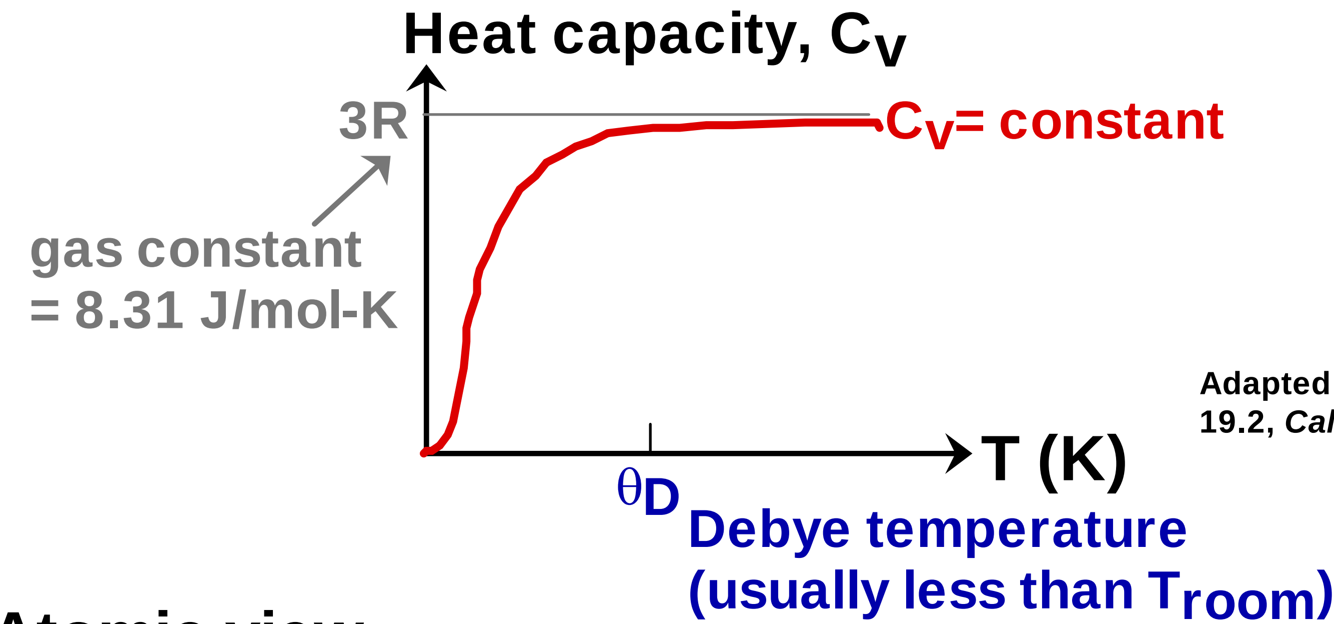
energy input (J/mol)

temperature change (K)

- **Two ways to measure heat capacity:**
  - **-- C_p : Heat capacity at constant pressure.**
  - **-- C_v : Heat capacity at constant volume.**

HEAT CAPACITY VS T

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



Adapted from Fig. 19.2, *Callister 6e*.

- **Atomic view:**
  --Energy is stored as atomic vibrations.
  --As T goes up, so does the avg. energy of atomic vibr.

HEAT CAPACITY: COMPARISON

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	128
Gold	138

increasing c_p

c_p: (J/kg-K)

C_p: (J/mol-K)

- **Why is c_p significantly larger for polymers?**

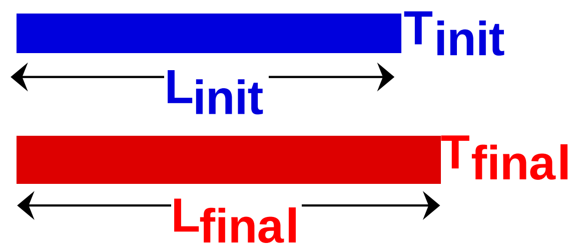
Selected values from Table 19.1, *Callister 6e*.

THERMAL EXPANSION

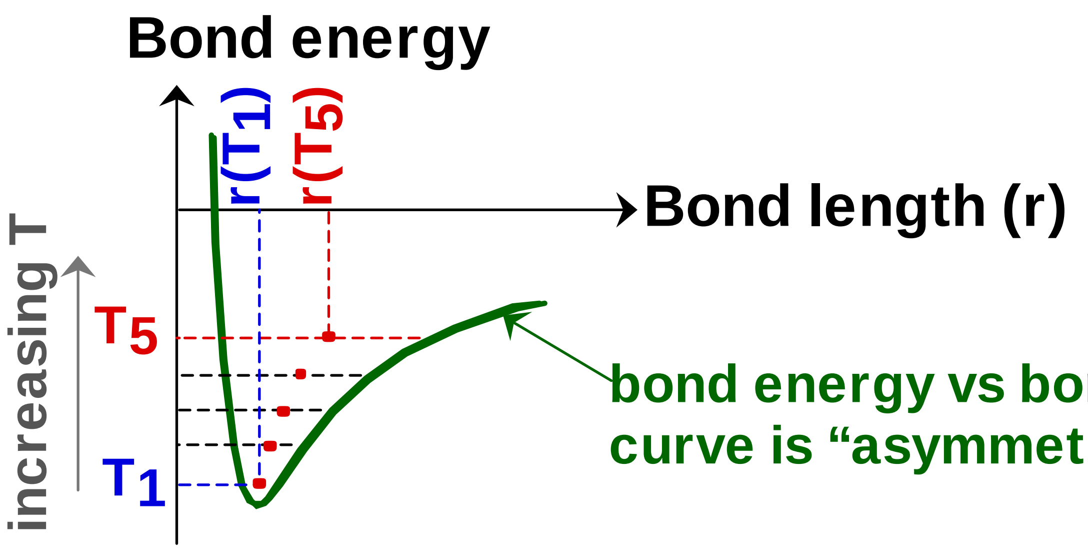
- **Materials change size when heating.**

$$\frac{L_{final} - L_{initial}}{L_{initial}} = \alpha (T_{final} - T_{initial})$$

coefficient of thermal expansion (1/K)



- **Atomic view: Mean bond length increases with T.**



bond energy vs bond length curve is "asymmetric"

Adapted from Fig. 19.3(a), *Callister 6e*. (Fig. 19.3(a) adapted from R.M. Rose, L.A. Shepard, and J. Wulff, *The Structure and Properties of Materials*, Vol. 4, *Electronic Properties*, John Wiley and Sons, Inc., 1966.)

THERMAL EXPANSION: COMPARISON

Material	α (10^{-6}/K) 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

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

Selected values from Table 19.1, *Callister 6e*.

THERMAL CONDUCTIVITY

- **General:** The ability of a material to transfer heat.
- **Quantitative:**

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

heat flux (J/m^2-s) → q

thermal conductivity (J/m-K-s) → k

temperature gradient → $\frac{dT}{dx}$

- **Atomic view:** Atomic vibrations in hotter region carry energy (vibrations) to cooler regions.

THERMAL CONDUCTIVITY: COMPARISON

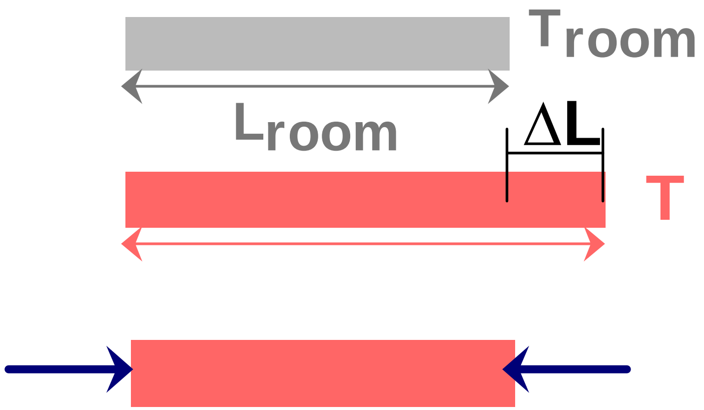
increasing k

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

Selected values from Table 19.1, *Callister 6e*.

EX: THERMAL STRESS

- **Occurs due to:**
  --uneven heating/cooling
  --mismatch in thermal expansion.
- **Example Problem 19.1, p. 666, *Callister 6e*.**
  --A brass rod is stress-free at room temperature (20C).
  --It is heated up, but prevented from lengthening.
  --At what T does the stress reach -172MPa?



compressive σ keeps $\Delta L = 0$

$$\frac{\Delta L}{L_{room}} = \varepsilon_{thermal} = \alpha(T - T_{room})$$

100GPa (E) **20×10^{-6} /C** (α)

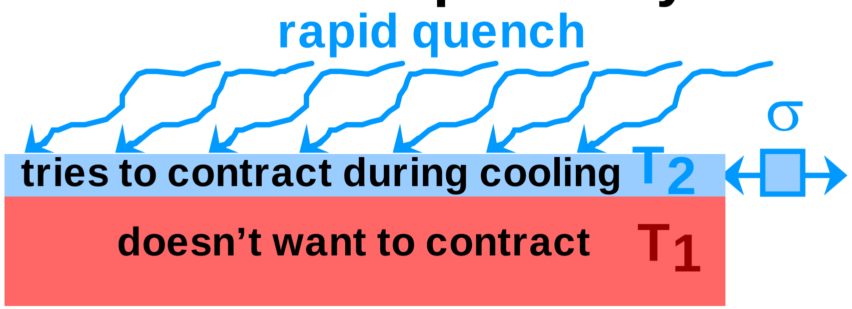
$$\sigma = E(-\varepsilon_{thermal}) = -E\alpha(T - T_{room})$$

-172MPa (σ) **20C** (T_{room})

Answer: 106C

THERMAL SHOCK RESISTANCE

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



Tension develops at surface

$$\sigma = -E\alpha(T_1 - T_2)$$

Temperature difference that can be produced by cooling:

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

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

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

set equal

- **Result:** $(\text{quench rate})_{\text{for fracture}} \propto \dfrac{\sigma_f k}{E\alpha}$
- **Large thermal shock resistance when** $\dfrac{\sigma_f k}{E\alpha}$ **is large.**

THERMAL PROTECTION SYSTEM

- **Application:**

Fig. 23.0, *Callister 5e*. (Fig. 23.0 courtesy the National Aeronautics and Space Administration.

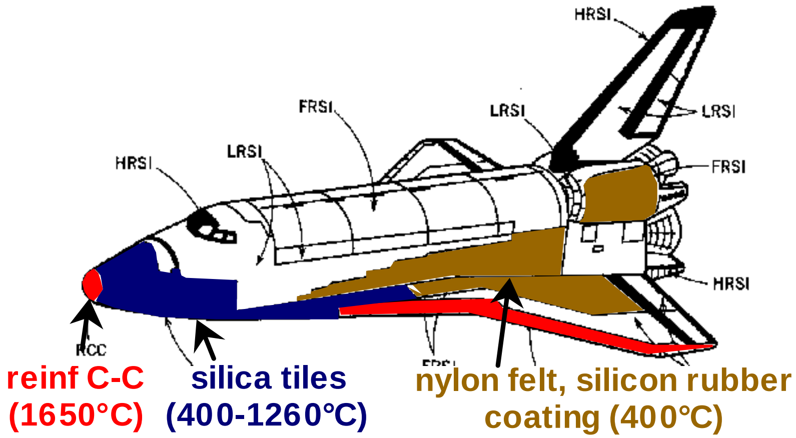


Fig. 19.2W, *Callister 6e*. (Fig. 19.2W adapted from L.J. Korb, C.A. Morant, R.M. Calland, and C.S. Thatcher, "The Shuttle Orbiter Thermal Protection System", *Ceramic Bulletin*, No. 11, Nov. 1981, p. 1189.)

- **Silica tiles (400-1260C):**
  --large scale application

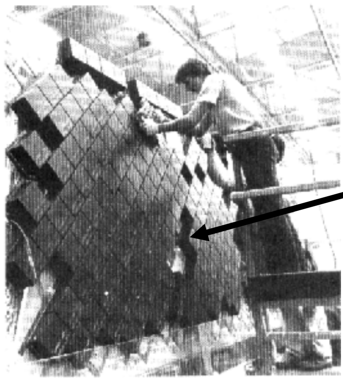
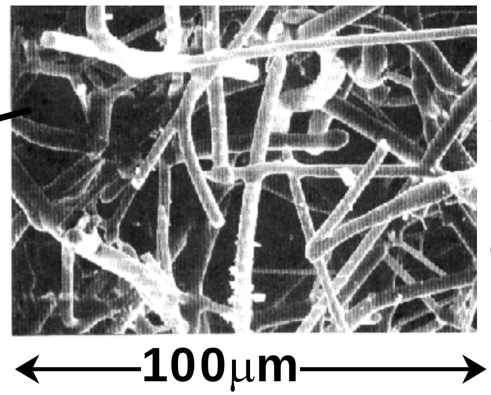


Fig. 19.3W, *Callister 5e*. (Fig. 19.3W courtesy the National Aeronautics and Space Administration.

--microstructure:



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

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

SUMMARY

- **A material responds to heat by:**
  --increased vibrational energy
  --redistribution of this energy to achieve thermal equil.
- **Heat capacity:**
  --energy required to increase a unit mass by a unit T.
  --polymers have the largest values.
- **Coefficient of thermal expansion:**
  --the stress-free strain induced by heating by a unit T.
  --polymers have the largest values.
- **Thermal conductivity:**
  --the ability of a material to transfer heat.
  --metals have the largest values.
- **Thermal shock resistance:**
  --the ability of a material to be rapidly cooled and not crack. Maximize $\sigma_f k/E\alpha$.