Announcements

- Quiz in lecture on Wednesday
  - Chapter 18 Electrical Properties
  - Chapter 19 Thermal Properties
  - Also an anonymous end-of-term survey
- Also on Wednesday
  - Hand out a study guide for the final exam

Polymers

- **Polymers**
  - **14.7, 14.9**
  - **15.1 – 15.5**
  - **Jones, Ch. 8**
  - **Lecture notes**

WebCT Quiz#4

- **2. Creep (50 point(s)) A major design consideration is taking into account creep. Consider the following material options commonly used for microelectronics. For each indicate whether creep is a design concern for the material at the temperature of interest. In each case, *how big of a concern* is it and why?**
  - **For the board - Option 1 is standard FR4 board with a polymer-glass composite and Cu. Option 2 is a ceramic with patterned Al and Cu conductors.**
  - **For the solders - Option 1 is eutectic Pb-Sn solder (Callister Fig. 9.9). Option 2 is eutectic Au-Sn (80wt% Au, Callister Fig. 9.36).**

$0.4\,T_m$

Kelvins

WebCT Quiz#4

- **3. Minimize Creep (40 point(s)) Consider that the company is constrained to using the materials identified in the previous problem as having the biggest issues with creep. Based on your knowledge of steady state creep behavior, identify two design changes that could be implemented to minimize the creep strain rate (Besides changing materials). Discuss how these changes could be implemented.**

stress exponent (material parameter)

$$\boxed{\dot{\varepsilon}_s} = K_2 \sigma^{\boxed{n}} \exp\left(-\frac{\boxed{Q_c}}{RT}\right)$$

activation energy for creep (material parameter)

strain rate

material const.

applied stress

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)

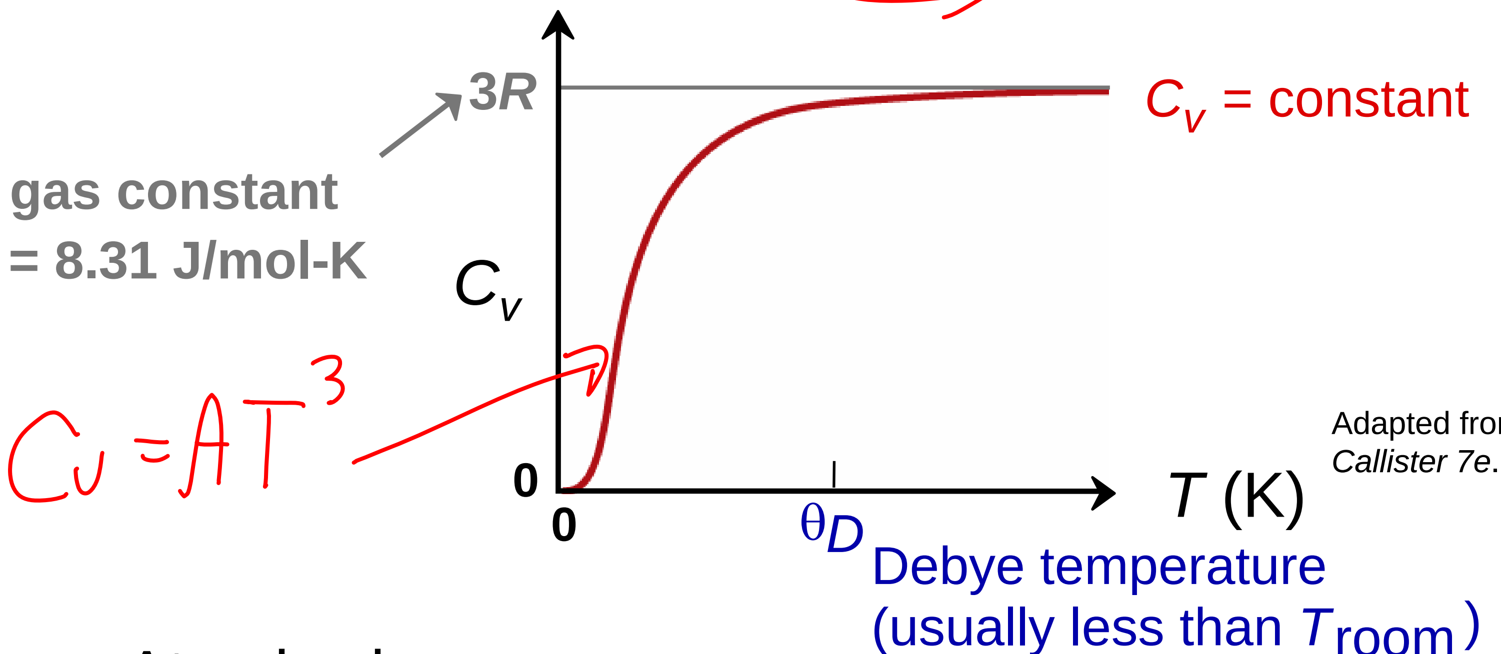
- Two ways to measure heat capacity:
  - C_p : Heat capacity at constant pressure.
  - C_v : Heat capacity at constant volume.

$$C_p > C_v$$

- Specific heat has typical units of $\dfrac{\text{J}}{\text{kg}\cdot\text{K}}$

Heat Capacity vs T

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



Adapted from Fig. 19.2, *Callister 7e*.

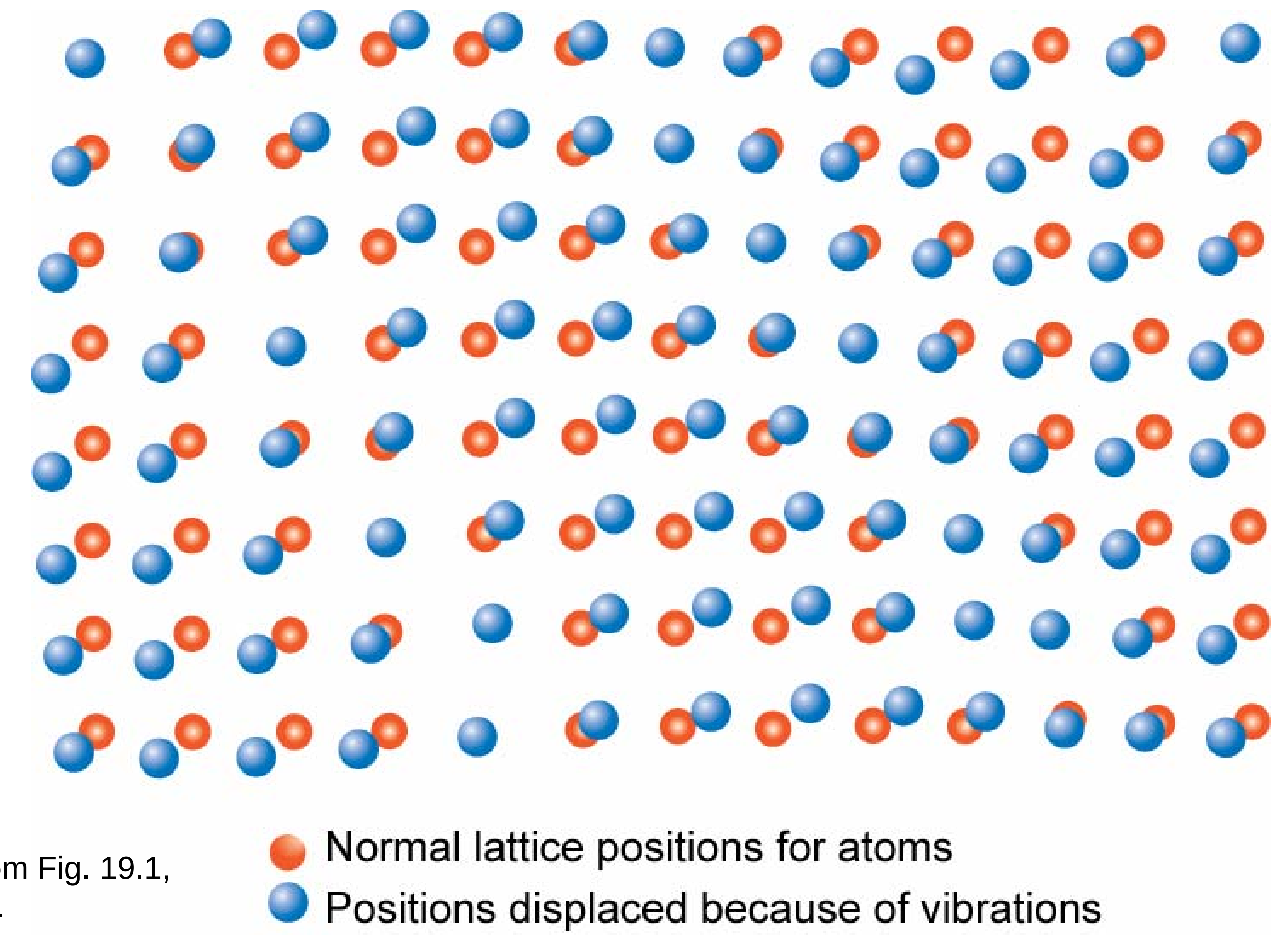
- Atomic view:
  -- Energy is stored as atomic vibrations.
  -- As T goes up, so does the avg. energy of atomic vibr.

Energy Storage

phonons

How is the energy stored?

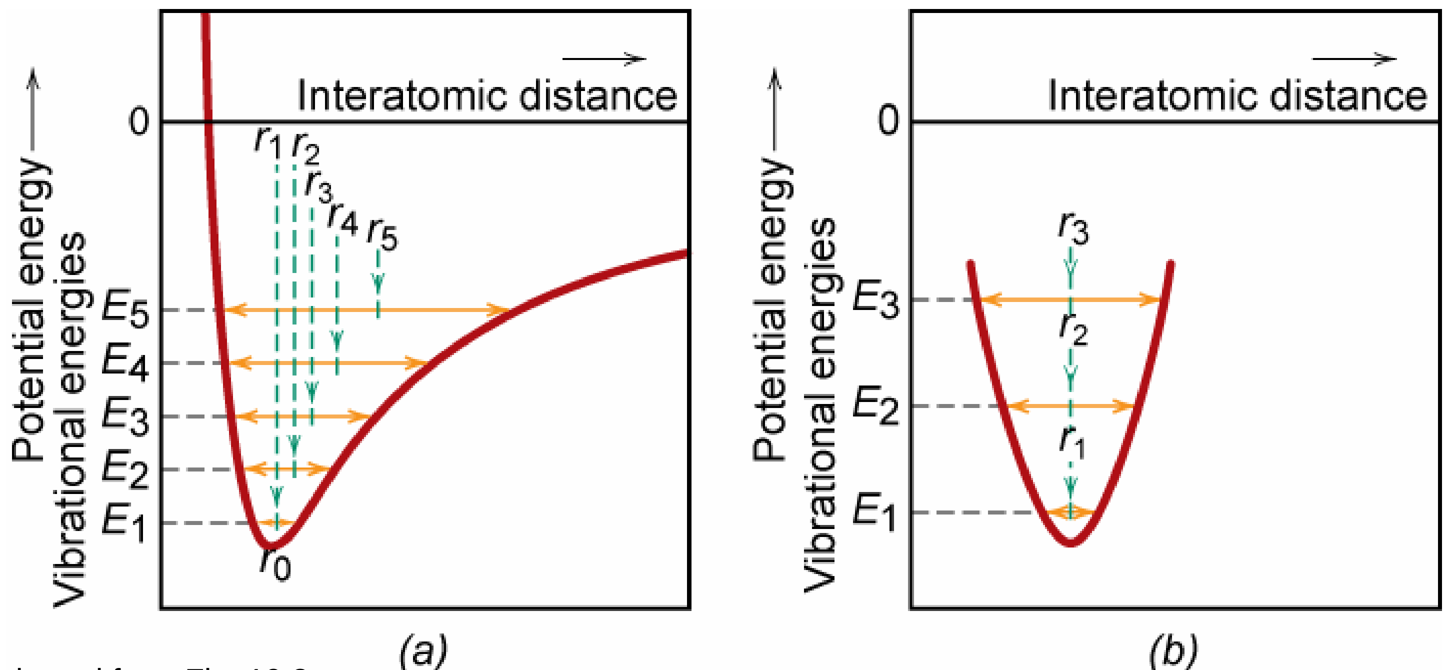
Phonons – thermal waves - vibrational modes



Adapted from Fig. 19.1, *Callister 7e*.

Energy Storage

- Other small contributions to energy storage
  - Electron energy levels
    - Dominate for ceramics & plastics
  - Energy storage in vibrational modes



Adapted from Fig. 19.3, *Callister 7e*.

Heat Capacity: 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: (J/kg-K)

C_p: (J/mol-K)

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

① Less dense

② More vibrational modes

Selected values from Table 19.1, *Callister 7e*.

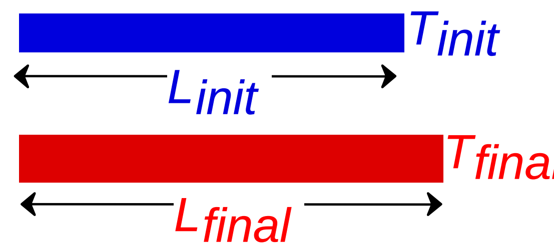
Thermal Expansion

- **Materials change size when heating.**

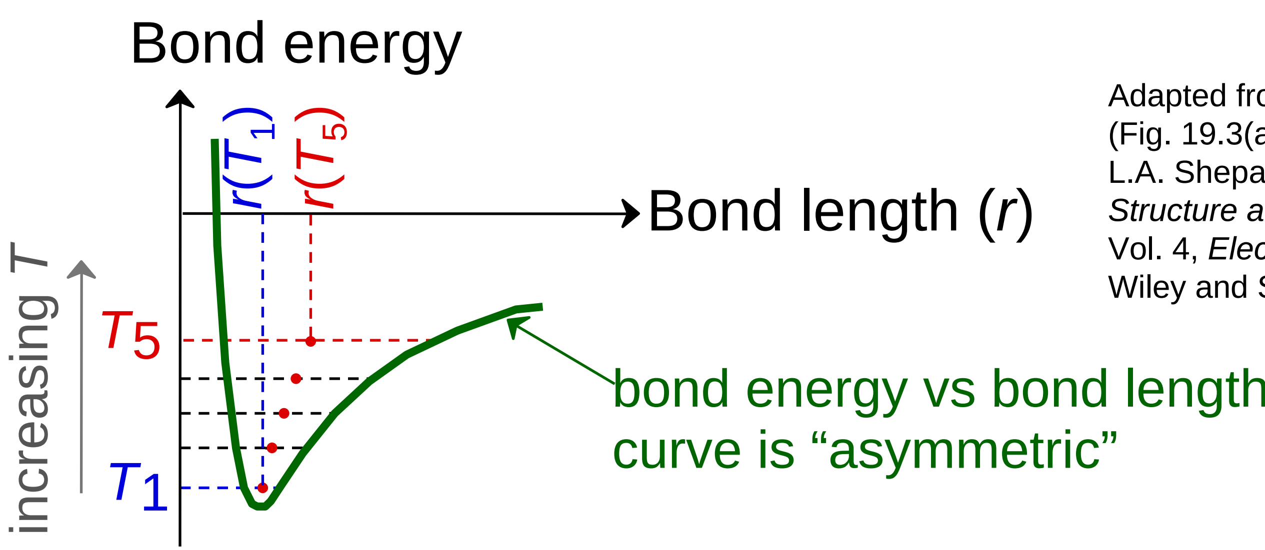
$$\frac{L_{final} - L_{initial}}{L_{initial}} = \alpha(T_{final} - T_{initial})$$

ε

coefficient of thermal expansion (1/K or 1/°C)



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



Adapted from Fig. 19.3(a), *Callister 7e*. (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_ℓ (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

ppm/K

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

Si ~ 2

Selected values from Table 19.1, *Callister 7e*.

Thermal Expansion: Example

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

$\varepsilon = \alpha \Delta T$

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

rearranging Eqn 19.3b

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

$T_F - T_i$

$\boxed{\Delta\ell = 0.012\,\mathrm{m}} \leftarrow (-9 - 40)$

$\Delta\ell = -0.012$ m

Thermal Conductivity

1820

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

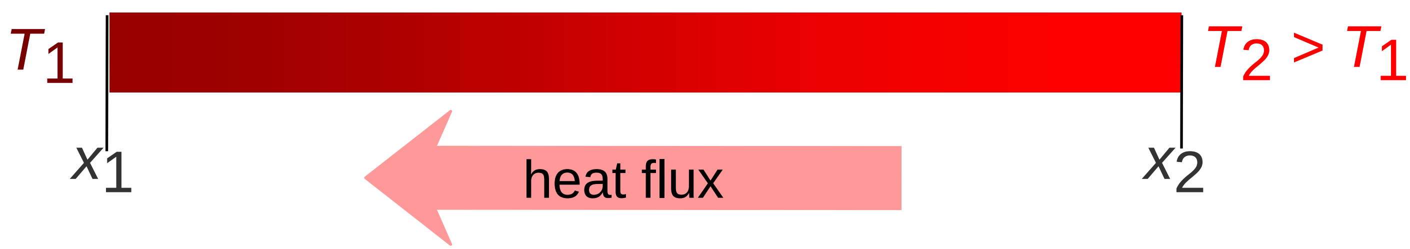
$$q = -k\frac{dT}{dx}$$

heat flux (J/m^2-s) W/m^2

temperature gradient

"**Fourier's Law**"

thermal conductivity (J/m-K-s) → $W/m\cdot K$



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

Thermal Conductivity: Comparison

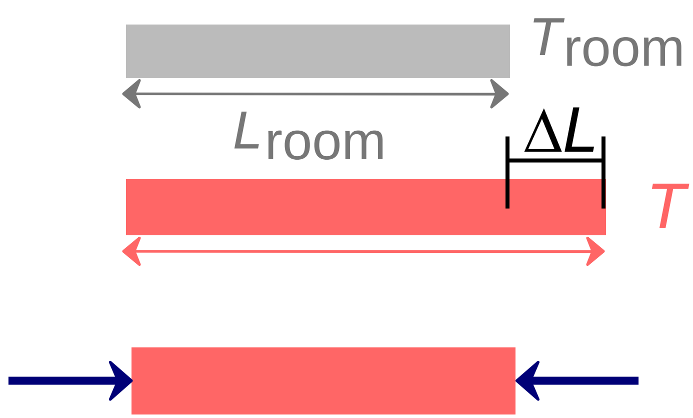
increasing k

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 7e*.

Thermal Stress

- **Occurs due to:**
  - -- uneven heating/cooling
  - -- mismatch in thermal expansion.
- **Example Problem 19.1, *Callister 7e*.**
  - -- A brass rod is stress-free at room temperature (20°C).
  - -- It is heated up, but prevented from lengthening.
  - -- At what T does the stress reach -172 MPa?



compressive σ keeps $\Delta L = 0$

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

$$\underbrace{\sigma}_{-172\text{ MPa}} = E(-\varepsilon_{thermal}) = -\overbrace{E}^{100\text{GPa}}\overbrace{\alpha}^{20\times 10^{-6}\,/°\text{C}}(T - \underbrace{T_{room}}_{20°\text{C}})$$

Answer: 106°C

Thermal Protection System

- Application:

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

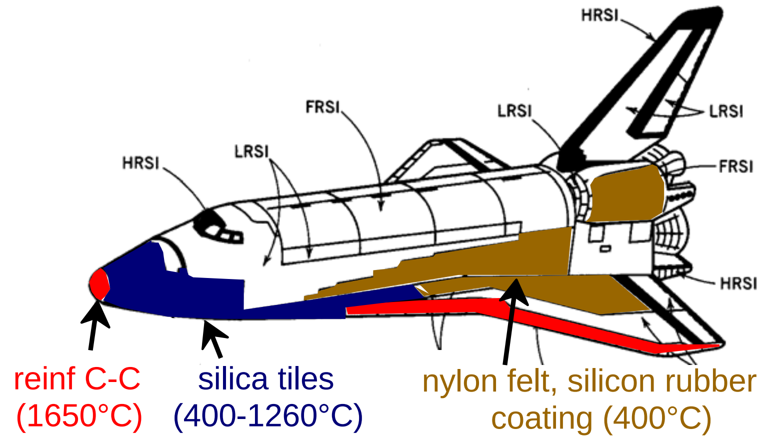


Fig. 19.2W, *Callister 6e*. (Fig. 19.2W adapted from L.J. Korb, C.A. Morant, R.M. Calland, and C.S. Thatcher, "The Shuttle Orbiter Thermal Protection System", *Ceramic Bulletin*, No. 11, Nov. 1981, p. 1189.)

- Silica tiles (400-1260°C):

--large scale application

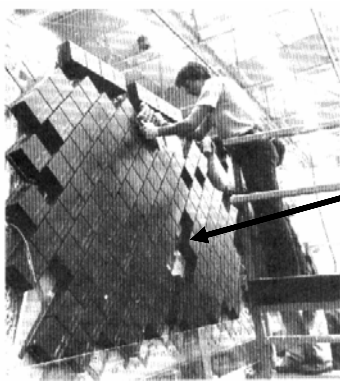
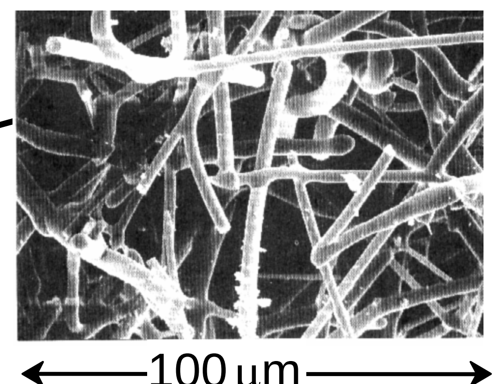


Fig. 19.3W, *Callister 5e*. (Fig. 19.3W courtesy the National Aeronautics and Space Administration.)

--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.