Outline

- Introduction
- Relative cost of materials
- Example
- Materials selection: Artificial hip joint materials
- Space Shuttle Thermal Protection System

Price and Availability

- Current Prices on the web[a]:
  - Short term trends: fluctuations due to ……../………..
  - Long term trend: prices will increase as rich deposits are depleted.
- Materials require energy to process them:

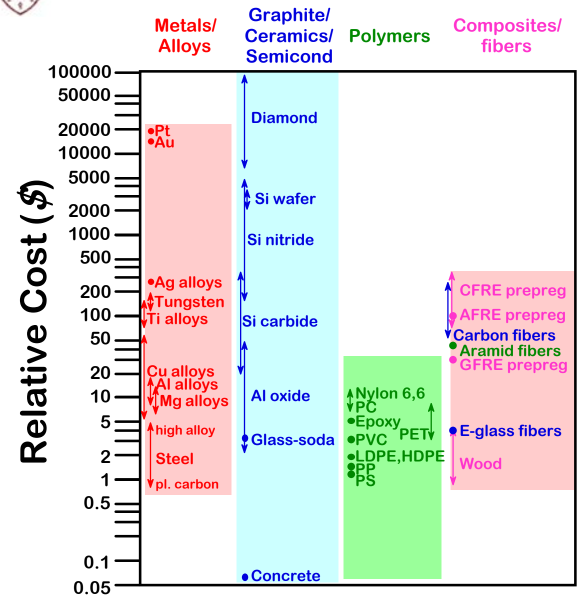
Energy to produce materials (GJ/ton)	
Al	237 (17)[b]
PET	103 (13)[c]
Cu	97 (20)[b]
steel	20[d]
glass	13[e]
paper	9[f]

Energy using recycled material indicated in green.

Cost of energy used in processing materials ($/GJ)[g]	
elect resistance	25
propane	11
natural gas	9
Oil *(~100$/barrel)*	8

a http://www.statcan.ca/
a http://www.metalprices.com
b www.copper.org/applications/automotive/radiators/recyclability.html
c http://members.aol.com/profchm/escalant.html
d http://www.steel.org
e http://www1.eere.energy.gov/industry/glass/
f http://www.cifq.qc.ca/html/english/pates_papiers/index.php
g http://www.bloomberg.com/energy/

Relative Cost of Materials



$$C_m = \frac{\$/kg}{(\$/kg)_{ref\ material}}$$

- Reference material:
  - Rolled A36 plain carbon steel.
- Relative cost, $, fluctuates less over time than actual cost.

Based on data in Appendix C, *Callister, 6e*.
AFRE, GFRE, & CFRE = Aramid, Glass, & Carbon fiber reinforced epoxy composites.

Detailed Study I: Strong, Light Torsion Members

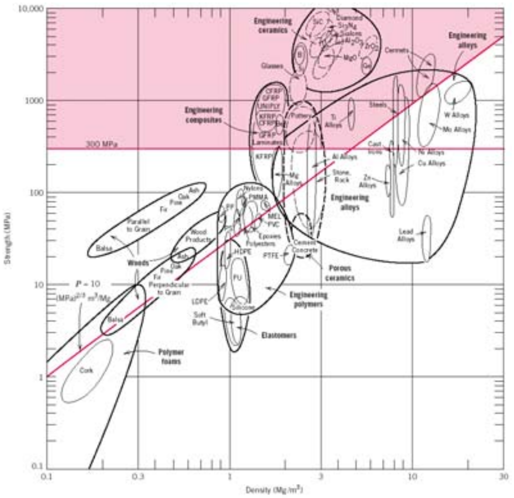
- Maximize the Performance Index:

$$P = \frac{\tau_f^{2/3}}{\rho}$$

- Other factors:

- require $\sigma_f > 300$MPa.

- Rule out ceramics and glasses because K_{Ic} too small.



Strong, Light Torsion Members

- Numerical Data:

material	ρ (Mg/m^3)	τ_f (MPa)	P (MPa)$^{2/3}$m^3/Mg)
CFRE (v_f = 0.65)	1.5	1140	73
GFRE (v_f = 0.65)	2.0	1060	52
Al alloy (2024-T6)	2.8	300	16
Ti alloy (Ti-6Al-4V)	4.4	525	15
4340 steel (oil quench & temper)	7.8	780	11

Data from Table 6.6, *Callister 6e*.

- Lightest: Carbon Fiber Reinf. Epoxy (CFRE) member.
- Heaviest: 4340 steel

Strong, Low Cost Torsion Members

Considering (Cost/Mass)*Mass $C_m\rho/\tau^{2/3} = C_m/P$

- Minimize Cost: Cost Index ~ M$ ~ C_m/P (*since M ~ 1/P*)
- Numerical Data:

material	P (MPa)$^{2/3}$m^3/Mg)	C_m	(C_m/P)x100
CFRE (v_f=0.65)	73	80	112
GFRE (v_f=0.65)	52	40	76
Al alloy (2024-T6)	16	15	93
Ti alloy (Ti-6Al-4V)	15	110	748
4340 steel (oil quench & temper)	11	5	46

Data from Table 6.7, *Callister 6e*.

- Lowest cost: 4340 steel (oil quench & temper)
- *Need to consider machining, joining costs also.*

Materials selection: Artificial hip joint materials

- bone is a natural ………….. material
- anisotropic material
- hip → ball and socket type joint
- friction
- large range of rotary motion

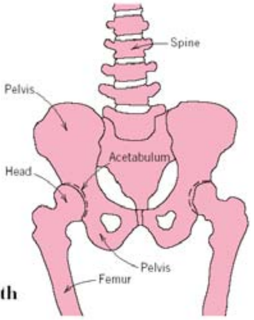


Table 23.3 **Mechanical Characteristics of Human Long Bone Both Parallel and Perpendicular to the Bone Axis**

Property	*Parallel to Bone Axis*	*Perpendicular to Bone Axis*
Elastic modulus, GPa (psi)	17.4 (2.48 × 10^6)	11.7 (1.67 × 10^6)
Ultimate strength, tension, MPa (ksi)	135 (19.3)	61.8 (8.96)
Ultimate strength, compression, MPa (ksi)	196 (28.0)	135 (19.3)
Elongation at fracture	3–4%	—

Materials selection: Artificial hip joint materials

- Susceptible to fracture within the narrow region below the head
- Another problem is a disease when small lumps of bone form on the rubbing surfaces (Osteoarthritis) → very painful
- need ……………….

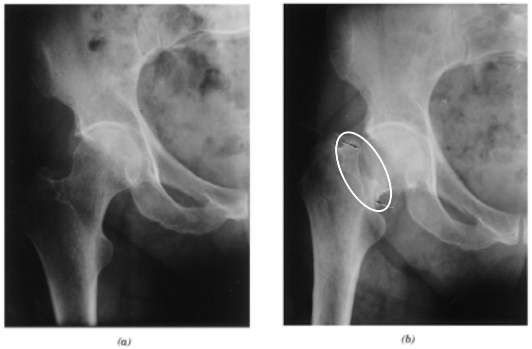
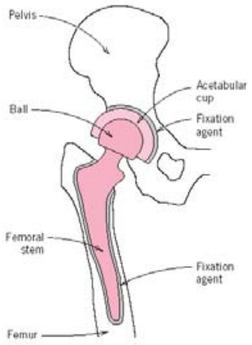


FIGURE 23.12 *X-Rays of (a) a normal hip joint and (b) a fractured hip joint. The arrows in (b) show the two ends of the fracture line through the femoral neck.*

Materials selection: Artificial hip joint materials



Schematic diagram for artificial hip joint

X-ray of an artificial total hip replacement

What are the materials used for artificial hip joint?

What are the materials constraints for hip joint?

Factors for Implant Material Selection

Biocompatibility: minimum degree of rejection by body

Corrosion: warm aqueous solution + 1% NaCl, ………………, require low corrosion rate and minimum corrosion products.

Mechanical: Strength, stiffness, fatigue, fracture toughness.

E.g for *<u>stem</u>* *– 500MPa < Yield and 650 MPa < Tensile strength, 8% < Elongation, Fatigue strength > 400 MPa for 10^7 cycles (approx 10^6 per year)*

Mechanical properties should not be very different from those of bones, otherwise deterioration will take place.

Wear: minimise

Friction: minimise

Density: low for lightweight

Reliability: consistent properties over time

Cost: reasonable

Materials selection: Artificial hip joint materials

- Earlier design: same material for stem and ball → Stainless Steel
- Recently: different materials other than SS.

FIGURE 23.14 *(Callister 5th ed.) Photograph showing two artificial total hip replacement designs.*

Materials selection: Artificial hip joint materials

Table 23.4 Mechanical and Corrosion Characteristics of Three Metal Alloys That Are Commonly Used for the Femoral Stem Component of the Prosthetic Hip

Alloy	*Elastic Modulus [GPa (psi)]*	*0.2% Yield Strength [MPa (ksi)]*	*Tensile Strength [MPa (ksi)]*	*Elongation at Fracture (%)*	*Fatigue Strength or Limit, 10^7 Cycles [MPa (ksi)]*	*Corrosion Rate (mpy)[a]*
316L Stainless steel (cold worked)	196 (28.4×10^6)	700 (102)	875 (127)	12	383 (55.5)	0.001–0.002
MP35N (hot forged)	230 (33.4×10^6)	1000 (145)	1200 (174)	13	500 (72.5)	0.0012–0.002
Ti-6Al-4V (hot forged)	120 (17.4×10^6)	950 (138)	1075 (156)	13	580 (84.1)	0.007–0.04

[a] mpy means mils per year, or 0.001 in./yr

Old inactive person

The most biocompatible

(**MP35N** = 35% Co - 35% Ni - 20% Cr - 10% Mo)

- **<u>Recent development</u>**: ceramic for the ball *(Al_2O_3 → harder and more wear resistant)*

<u>Acetabular cup</u> - usually UHMWPE *(inert, excellent wear resistance and low friction with the ball materials)*

<u>Fixation</u> is with PMMA cement *(not great because it is brittle. Using porous material where bone tissues grow is better)*

Space shuttle Thermal Protection System

Cost is not as important as for normal commercial applications

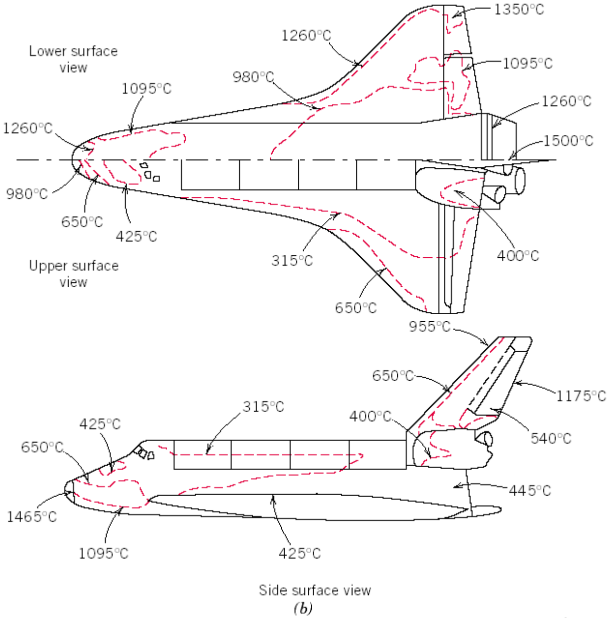


FIGURE 23.15 *(Callister 5th ed.)* Approximate maximum outer surface temperature profiles for the Space Shuttle Orbiter during reentry: (*a*) upper and lower views; (*b*) side view.

Space Shuttle Thermal Protection System

1. Maintain the temperature on the inner airframe below certain temp. *[eg., 175°C]* for a maximum outer surface temperature of 1465°C.

2. Remain usable for 100 missions, with a maximum turnaround time of 160 h.

3. Provide and maintain an aerodynamically smooth outer surface.

4. Be constructed of ……………. materials.

5. Withstand temperature extremes between -110°C and 1465°C.

6. Be resistant to severe thermal gradients and rapid temperature changes.

7. Be able to withstand stresses and vibrations that are experienced during launch, as well as thermally induced stresses imposed during temperature changes.

8. Experience a **minimum absorption of moisture** and other contaminants during storage between missions.

9. Be made to adhere to the airframe that is constructed of an aluminum alloy.

Space Shuttle Thermal Protection System

- Materials developed previously by the aerospace industry are unsuitable for the space shuttle
- They are **too dense** or **nonreusable**

Is there a single material which satisfies all these requirements?

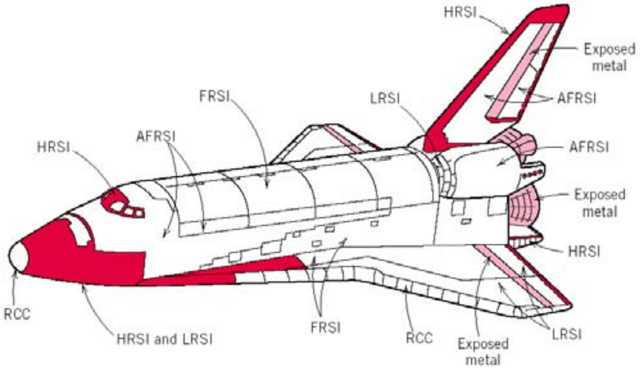


***FIGURE 23.16** Locations of the various components of the thermal protection system on the Space Shuttle Orbiter.*

- FRSI, felt reusable surface insulation;
- AFRSI, advanced flexible reusable surface insulation;
- LRSI, low-temperature reusable surface insulation;
- HRSI, high-temperature reusable surface insulation;
- RCC, reinforced carbon–carbon composite

Space Shuttle Thermal Protection System

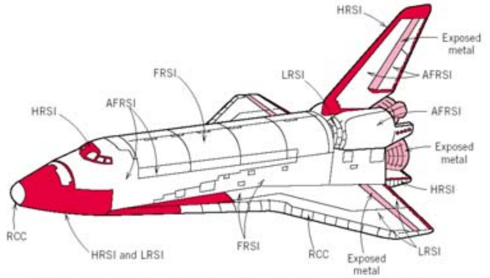


Table 23.5 Thermal Protection Systems Employed on the Space Shuttle Orbiter

Material Generic Name	*Minimum Operating Temperature, °C (°F)*	*Maximum Operating Temperature, °C (°F)*	*Material Composition*	*Orbiter Locations*
Felt reusable surface insulation (FRSI)	−130 (−200)	400 (750)	Nylon felt, silicone rubber coating	Wing upper surface, upper sides, cargo bay doors
Advanced flexible reusable surface insulation (AFRSI)	−130 (−200)	815 (1500)	Quartz batting sandwiched between quartz and glass fabrics	Upper surface regions
Low-temperature reusable surface insulation (LRSI)	−130 (−200)	650 (1200)	Silica tiles, borosilicate glass coating	Upper wing surfaces, tail surfaces, upper vehicle sides
High-temperature reusable insulation (HRSI)	−130 (−200)	1260 (2300)	Silica tiles, borosilicate glass coating with SiB_4 added	Lower surfaces and sides, tail leading and trailing edges
Reinforced carbon–carbon (RCC)	No lower limit identified	1650 (3000)	Pyrolized carbon–carbon, coated with SiC	Nose cap and wing leading edges

Space Shuttle Thermal Protection System

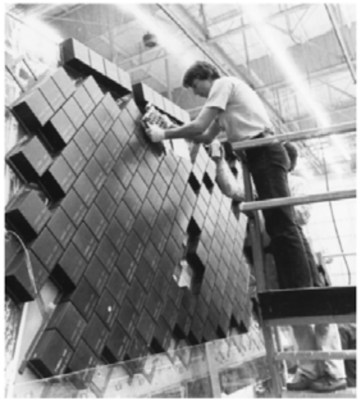
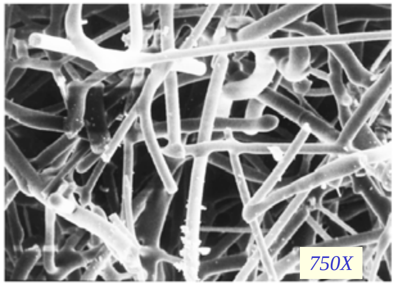


***FIGURE 23.17** Photograph showing the installation of thermal protection ceramic tiles on the Space Shuttle Orbiter.*

- For regions that are exposed to higher temperature (400 to 1260°C);
- ceramic tiles (more complex) are used
- because ceramics are thermal insulators and can withstand high temperature.
- 24,300 tiles (70% or the exterior area)
- each tile is different



SEM micrograph of a Space Shuttle Orbiter ceramic tile showing silica fibers after sintering

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Space Shuttle Thermal Protection System

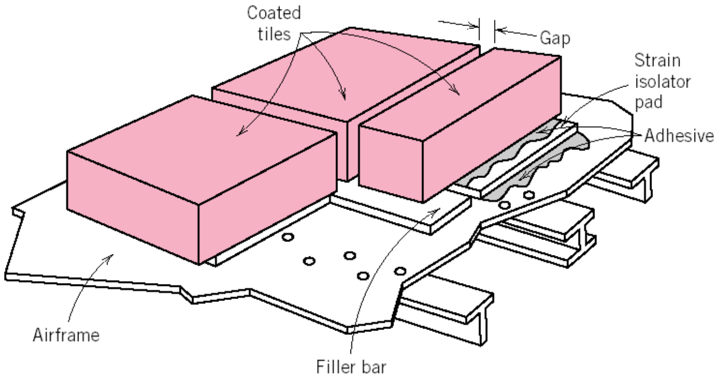

FIGURE 23.19 *(Callister 5th ed.)* Schematic cross section of the tile component of the Space Shuttle Orbiter's thermal protection system.

Next time:

Materials Codes