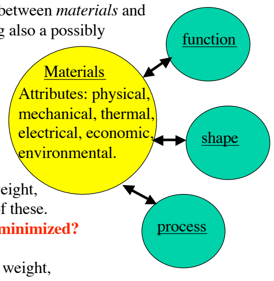
Materials Selection and Design

For selection, one must establish a link between *materials* and *function*, with shape and process playing also a possibly important role (now ignored.)



AREAS OF DESIGN CONCERN

Function- support a load, contain a pressure, transmit heat, etc.

What does component do?

Objective- make thing cheaply, light weight, increase safety, etc., or combinations of these.

What is to be maximized or minimized?

Constraints- make thing cheaply, light weight, increase safety, etc., or combinations of these.

What is non-negotiable conditions to be met?

What is negotiable but desired conditions?

Following "Materials Selection in Mechanical Design", M. Ashby

Design & Selection: Materials Indices

Structural elements perform physical functions (carry load or heat, store energy,..), and so they must satisfy certain functional requirements specified by the design, such as specified tensile load, max. heat flux, spring restoring force, etc.

Material index is a combination of materials properties that characterizes the Performance of a material in a given application.

Performance of a structural element may be specified by the **functional requirements, the geometry, and the material's properties.**

PERFORMANCE:

P[(Functional needs, F); (Geometric, G); **(Material Property, M)**]

For OPTIMUM design, we need to MAXIMIZE or MINIMIZE the functional P.

Consider only the simplest cases where these factors form a *separable equation.*

$$P = f_1(F)\, f_2(G)\, \mathbf{f_3(M)}$$

Examples of Materials Indices

Function, Objective, and Constraint	Index	
Tie, minimum weight, stiffness	E/ρ	
Beam, minimum weight, stiffness	$E^{1/2}/\rho$	
Beam, minimum weight, strength	$\sigma^{2/3}/\rho$	
Beam, minimum cost, stiffness	$E^{1/2}/C_m\rho$	C_m =cost/mass
Beam, minimum cost, strength	$\sigma^{2/3}/C_m\rho$	
Column, minimum cost, buckling load	$E^{1/2}/C_m\rho$	
Spring, minimum weight for given energy storage	$\sigma_{YS}{}^2/E\rho$	
Thermal insulation, minimum cost, heat flux	$1/(\alpha\, C_m\rho)$	α =thermal cond
Electromagnet, maximum field, temperature rise	$\kappa\, C_p\rho$	κ =elec. cond

Design & Selection: Materials Indices

PERFORMANCE: (using separable form) $P = f_1(F)\, f_2(G)\, \mathbf{f_3(M)}$

When separable, the optimum subset of materials can be identified

- without solving the complete design problem,
- knowing details of F and G.

There is then enormous simplification and performance can be optimized by focusing on $f_3(M)$, which is the materials index

S= safety factor should always be included!

Price and Availability of Materials

- Current Prices on the web[(a)]: *TRENDS*
  - -Short term: fluctuations due to supply/demand.
  - -Long term: prices increase as 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)]

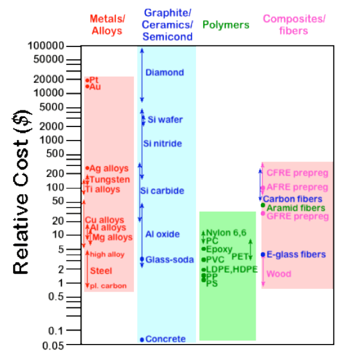
Recycling indicated in green.

- Cost of energy used in processing materials ($/GJ)[(g)]

elect resistance	25
propane	11
natural gas	9
oil	8

a http://www.statcan.ca/english/pgdb/economy/primary/prim44.htm
a http://www.metalprices.com
b http://www.automotive.copper.org/recyclability.htm
c http://members.aol.com/profchm/escalant.html
d http://www.steel.org.facts/power/energy.htm
e http://eren.doe.gov/EE/industry_glass.html
f http://www.aifq.qc.ca/english/industry/energy.html#1
g http://www.wren.doe.gov/consumerinfo/rebriefs/cb5.html

Relative Cost (in $) of Materials



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

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

Based on data in Appendix C, *Callister, 6e.*

Materials Selection Examples in Mechanical Design with Separable Performance Factor

PERFORMANCE: functional needs , geometry, and materials index

P = $f_1(F)\, f_2(G)\, \mathbf{f_3(M)}$ ---> optimize the material index $\mathbf{f_3(M)}$.

Example 1: Material Index for a Light, Strong, Tie-Rod
Example 2: Material Index for a Light, Stiff Beam in Tension
Example 3: Material Index for a Light, Stiff Beam in Deflection
Example 4: Torsionally stressed shaft (Callister Chapter 6)
Example 5: Material Index for a Cheap, Stiff Support Column
Example 6: Selecting a Slender but strong Table Leg
Example 7: Elastic Recovery of Springs
Example 8: Safe Pressure Vessel (some from M.F. Ashby)

Example 1: Material Index for a Light, Strong, Tie-Rod

A Tie-rod is common mechanical component.
***Functional needs:* F, L, σ_f**
- Tie-rod must carry tensile force, **F**.
- NO failure. Stress must be less than σ_f. (f=YS, UTS)
- **L** is usually fixed by design, can vary ***Area A***.
- While strong, need to be lightweight, or low mass.

-Strength relation:

$$\frac{F}{A} \leq \frac{\sigma_f}{S}$$

- Mass of rod:

$$m = \rho L A$$

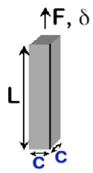
- **Eliminate the "free" design parameter, A:**

$$m \geq (FS)(L)\left(\frac{\rho}{\sigma_f}\right)$$

minimize for small m

Or Maximize Materials Index: $M = \frac{\sigma_f}{\rho}$
For light, strong, tie-rod

Example 1': square rod (it's all the same!)



- Carry F without failing; fixed initial length L.
  - -Strength relation: $\frac{\sigma_f}{S} = \frac{F}{c^2}$
  - - Mass of bar: $M = \rho L c^2$
- Eliminate the "free" design parameter, c:

$$M = (FLS)\frac{\rho}{\sigma_f}$$

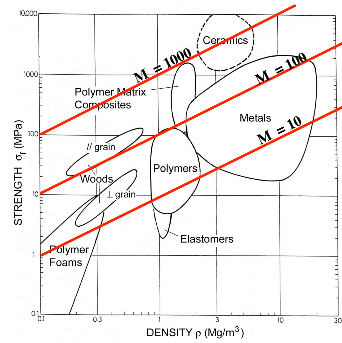
specified by application → (FLS); minimize for small M → $\frac{\rho}{\sigma_f}$

- Maximize the Materials Performance Index:

(strong, light tension members) $M_{index} = \frac{\sigma_f}{\rho}$

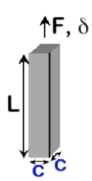
Maximize $M = \sigma_f/\rho$ Consider $\log \sigma_f$ vs $\log \rho$

For fixed M: $\log M = \log \sigma_f - \log \rho$ = constant = C



- What are units of $M=\sigma_f/\rho$?
- For fixed M, look at $\log \sigma_f = (1/1) \log \rho + C$
- For fixed M, you look for lines of slope = 1.
- Along each line materials have the same M values! But NOT the same materials properties (σ_f or ρ) e.g. some less dense (lighter).

Example 2: Material Index for a Light, Stiff Beam in Tension



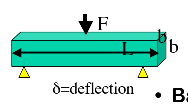
- Bar must not lengthen by more than δ under force F; must have initial length L.
  - - Stiffness relation: $\frac{F}{c^2} = E\frac{\delta}{L}$ $(\sigma = E\varepsilon)$
  - - Mass of bar: $m = \rho L c^2$
- Eliminate the "free" design parameter, c:

$$m = \frac{FL^2}{\delta}\frac{\rho}{E}$$

specified by application → $\frac{FL^2}{\delta}$; minimize for small m → $\frac{\rho}{E}$

- Maximize the Materials Index: $M = \frac{E}{\rho}$ (stiff, light tension members)

Example 3: Material Index for a Light, Stiff Beam in Deflection



Bending is common mode of loading, e.g., golf clubs, wing spars, floor joists.

- Bar with initial length L must not deflect by more than δ under force F.
  - - Stiffness relation: $\frac{F}{\delta} \geq \frac{C_1 E\mathbf{I}}{L^3} = \frac{C_1 E}{L^3}\left(\frac{b^4}{12}\right) = \frac{C_1 E}{L^3}\left(\frac{A^2}{12}\right)$
  - - Mass of bar: $m = b^2 L\rho = AL\rho$
- Eliminate the "free" design parameter, A:

$$m \geq \left(\frac{12S}{C_1 L}\right)^{1/2}(L^3)\left(\frac{\rho}{E^{1/2}}\right)$$

specified by application → $\left(\frac{12S}{C_1 L}\right)^{1/2}$; minimize for small m → $\left(\frac{\rho}{E^{1/2}}\right)$

Maximize → Light, Stiff Beam: $M = \frac{E^{1/2}}{\rho}$

If only beam height can change (not A), then M= $(E^{1/3}/\rho)$ (Car door) $I \propto b^3 w$

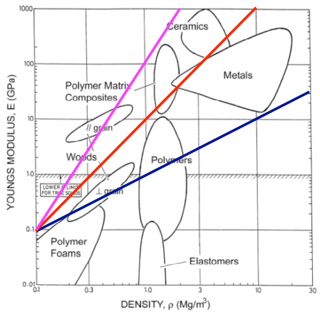
If only beam width can change (not A), then M= (E/ρ)

Performance of Square Beam vs. Fixed Height or Width

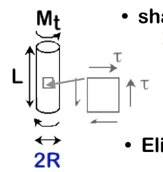
Light, Stiff Plate E/ρ

Light, Stiff Beam $E^{1/2}/\rho$

Light, Stiff Panel $E^{1/3}/\rho$



Example 4: Torsionally stressed shaft (Callister Chpt. 6)



- shaft must carry moment, M_t, with length L.

Mass plus Twisting Moment, M_t: $\tau = 2M_t/\pi R^3$

- Strength relation: $\frac{\tau_f}{S} = \frac{2M_t}{\pi R^3}$
- Mass of bar: $m = \rho \pi R^2 L$

- Eliminate the "free" design parameter, R:

$$m = \left(2\sqrt{\pi}\, S M_t\right)^{2/3} L \frac{\rho}{\tau_f^{2/3}}$$

specified by application — minimize for small M

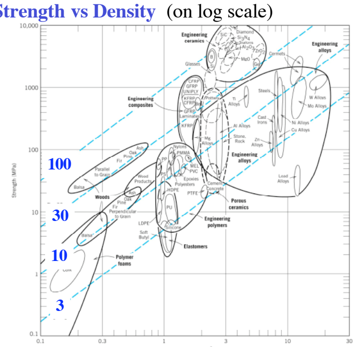
- Maximize the Material's Index: $M = \frac{\tau_f^{2/3}}{\rho}$ (strong, light torsion members)

Ashby Plot: Strength vs Density (on log scale)

M = 30 has 1/3 the mass of M =10 (mass ∝ 1/M ∝ ρ).

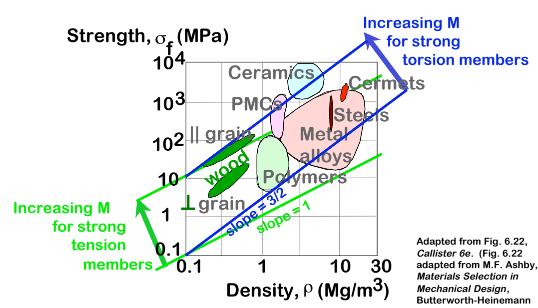
$M = \frac{\tau^{2/3}}{\rho} \Rightarrow$

$\log \tau = 3/2 \log \rho + 3/2 \log M$



* All materials that lie on these lines will perform equally for strength-per-mass basis. However, each line has a different Materials **M index**, or overall Performance **P index**.

Data Overview: Strong & Light Tension/Torsion Members

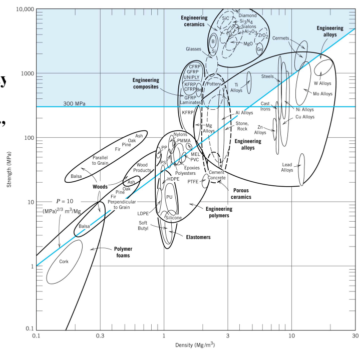


Adapted from Fig. 6.22, *Callister 6e*. (Fig. 6.22 adapted from M.F. Ashby, *Materials Selection in Mechanical Design*, Butterworth-Heinemann Ltd., 1992.)

Strength vs Density

• Additional constraints may be added, such as strength having minimum value, e.g., σ_f > 300 GPa.

• Seach area is then limited to the area in plot above all lines (if maximizing).



Other Material Indices: Cost factor

Considering mass

Maximize:
$M = \tau^{2/3}/\rho$

CRFP are best!

Table 23.1 Density (ρ), Strength (τ_f), the Performance Index (P) for Five Engineering Materials

Material	ρ (Mg/m^3)	τ_f (MPa)	$\tau_f^{2/3}/\rho = P$ [$(MPa)^{2/3}m^3/Mg$]
Carbon fiber-reinforced composite (0.65 fiber fraction)[a]	1.5	1140	72.8
Glass fiber-reinforced composite (0.65 fiber fraction)[a]	2.0	1060	52.0
Aluminum alloy (2024-T6)	2.8	300	16.0
Titanium alloy (Ti-6Al-4V)	4.4	525	14.8
4340 Steel (oil-quenched and tempered)	7.8	780	10.9

[a] The fibers in these composites are continuous, aligned, and wound in a helical fashion at a 45° angle relative to the shaft axis.

Considering (Cost/mass)*mass

Maximize:
$M = \tau^{2/3}/C_m\rho$

4340 Steel is best!

Table 23.2 Tabulation of the $\rho/\tau_f^{2/3}$ Ratio, Relative Cost ($\bar{c}$), and the Product of $\rho/\tau_f^{2/3}$ and $\bar{c}$ for Five Engineering Materials[a]

Material	$\rho/\tau_f^{2/3}$ [10^{-2} {$Mg/(MPa)^{2/3}m^3$}]	$\bar{c}$ ($/$)	$\bar{c}(\rho/\tau_f^{2/3})$ [10^{-2} ($/$){$Mg/(MPa)^{2/3}m^3$}]	$M = \tau^{2/3}/C_m\rho$
4340 Steel (oil-quenched and tempered)	9.2	5	46	22x10^{-3}
Glass fiber-reinforced composite (0.65 fiber fraction)[b]	1.9	40	76	13x10^{-3}
Aluminum alloy (2024-T6)	6.2	15	93	11x10^{-3}
Carbon fiber-reinforced composite (0.65 fiber fraction)[b]	1.4	80	112	9x10^{-3}
Titanium alloy (Ti-6Al-4V)	6.8	110	748	1x10^{-3}

Details: Strong, Light Torsion Members

• Maximize the Performance Index: $P = \frac{\tau_f^{2/3}}{\rho}$

• Other factors:
--require σ_f > 300MPa.
--Rule out ceramics and glasses: K_{Ic} too small.

• Numerical Data:

material	ρ (Mg/m^3)	τ_f (MPa)	P (MPa)$^{2/3}$m^3/Mg)
CFRE (vf=0.65)	1.5	1140	73
GFRE (vf=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.

Details: Strong, Low-Cost Torsion Members

• Minimize Cost: Cost Index ~ m$ ~ $/M (since m ~ 1/M)

• Numerical Data:

material	M (MPa)$^{2/3}$m^3/Mg)	$	($/M)x100
CFRE (vf=0.65)	73	80	112
GFRE (vf=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

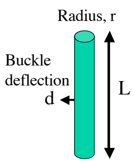
Data from Table 6.7, *Callister 6e*.

• Lowest cost: 4340 steel (oil quench & temper)

• Need to consider machining, joining costs also.

Example 5: Material Index for a Cheap, Stiff Support Column

(From Ashby 'Matierals Selection in Mechanical Design")



A slender column of fixed intial length L uses less material than a fat one; but must not be so slender than it buckles under load F.

- No buckling relation:

$$F \le F_{crit} = \frac{N\pi^2 EI}{L^2}$$

Load less than *Euler Load*.
N given by end constraint on column.

- Cost objective:

$$C = mC_m = AL\rho C_m$$

C_m is the cost/kg of (usually processed) material.

• **Eliminate the "free" design parameter, A:**

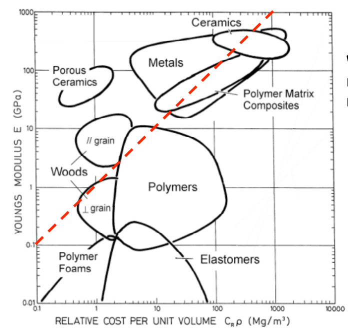
$$C \ge \left(\frac{4}{n\pi}\right)^{1/2}\left(\frac{F}{L^2}\right)^{1/2} L^3 \left(\frac{C_m\rho}{E^{1/2}}\right)$$

Maximize → $\left[\frac{E^{1/2}}{C_m\rho}\right]$ Cheap, Stiff Beam

specified by application

minimize for small m

Performance of Stiff but Cost Effective Beam



With cost considered, now polymers and metals area useful!

Example 6: Selecting a Slender but strong Table Leg

(Note this uses previous example from Ashby.)

Luigi Tavolina, furniture designer, conceives of a lightweight table of simplicity, with a flat toughened glass top on slender, unbraced, cylindrical legs.
For attractiveness, legs must be solid (to be thin) and light as possible (to make table easy to move). Legs must support table top and load without buckling.

• **What material would you recommend to Luigi?**

- Critical Elastic Load:

$$F \le \pi^2 \frac{EI}{L^2} = \pi^3 \frac{ER^4}{4L^2}$$

- Mass of leg:

$$m = \rho\pi R^2 L$$

• **Eliminate the "free" design parameter, R:**

$$m \ge \left(\frac{4P}{\pi}\right)^{1/2}\left(L^2\right)\left[\frac{\rho}{E^{1/2}}\right]$$

Maximize → $M_1 = \left[\frac{E^{1/2}}{\rho}\right]$

• **For slenderness, get R for *Critical Load Eq.*:**

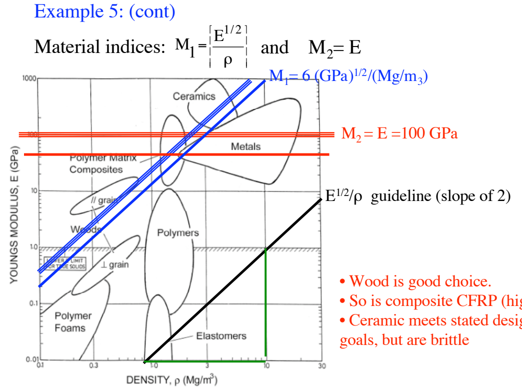
$$r = \left(\frac{4P_{crit}}{\pi^3}\right)^{1/4}\left(L^{1/2}\right)\left[\frac{1}{E}\right]^{1/4}$$

$M_2 = E$

2 indices to meet

Example 5: (cont)

Material indices: $M_1 = \left[\frac{E^{1/2}}{\rho}\right]$ and $M_2 = E$



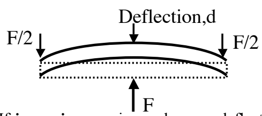
- Wood is good choice.
- So is composite CFRP (higher E).
- Ceramic meets stated design goals, but are brittle

Example 7: Elastic Recovery of Springs

Recall from Hooke's Law and Resilience, $U^{el} = \sigma^2/2E$.

We wish to maximize this, but the spring willl be damage if $\sigma > \sigma_{ys}$. $U^{el} = \sigma_{ys}{}^2/2E$

(Torsion bars and lead spring are less efficient than axial springs because some of the material is not fully loaded, for instance, the neutral axis it is not loaded at all!)



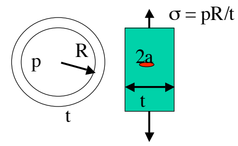
Can show that $U^{el} = (\sigma_{ys}{}^2/E)/18$

Addition constraint can be added.

- If ***in-service***, a spring under goes deflection of d under force F, then $\sigma_{ys}{}^2/E$ has to be high enough to avoid permanent set (a high resilience!).
- For this reason spring materials are heavily *SS-strengthening* and *work-hardening* (e.g, cold-rolled single-phase brass or bronze), SS plus precipitation strengthening (spring steel).
- *Annealing* any spring material removes work-hardening, or cause precipitation to coarsen, reducing YS and making materials useless as a spring!

Example 8: Safe Pressure Vessel

Uses info from leak-before-fail example.



Design requirements
Function: contain pressure, p
Objective: maximum safety
Constraints: (a) must yield before break
(b) must leak before break
(c) t small: reduces mass and cost

- Choose **t** so that at working pressure, **p**, the stress is less than σ_{ys}.
- Check (by x-ray, ultrasonics, etc.) that no cracks greater than $2a_c$ are present;

then the stress required to active crack propagation is $\sigma = \frac{K_{Ic}}{Y\sqrt{\pi a_c}}$

- Safety (should have safety factor, S) achieved for stress less than this, but greater safety obtained requiring no cracks proposgate even if $\sigma = \sigma_{ys}$ (stably deform).
- This condition ($\sigma = \sigma_{ys}$) yields $\pi a_C \le \frac{1}{Y^2}\left[\frac{K_{Ic}}{\sigma_{ys}}\right]^2$

$M_1 = K_{Ic}/\sigma_{ys}$

Example 8: Safe Pressure Vessel (cont)

- Tolerable crack size is maximized by choosing largest **$M_1 = K_{Ic}/\sigma_{ys}$**
- Large pressure vessels cannot always be tested for cracks and stress testing is impractical. Cracks grow over time by corrosion or cyclic loading (cannot be determined by one measurement at start of service).
- Leak-before-fail criterion (leaks can be detected over lifetime) $\sigma = \frac{K_{Ic}}{Y\sqrt{\pi t}}$
- Wall thickness was designed to contain pressure w/o yielding, so $t \ge \frac{pR}{\sigma_{ys}}$
- Two equations solved for maximum pressure gives **$M_2 = (K_{Ic})^2/\sigma_{ys}$**
- Largest M_1 and M_2 for smallest σ_{ys}. FOOLISH for pressure vessel.
- Wall thickness must be thin for lightness and economy.
- Thinnest wall has largest yield stress, so **$M_3 = \sigma_{ys}$**

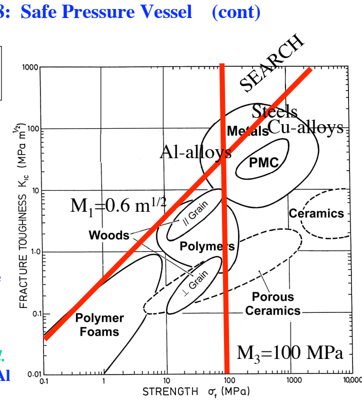
Example 8: Safe Pressure Vessel (cont)

Yield-before-break
$M_1 = K_{Ic}/\sigma_{ys}$

Leak-before-break
$M_2 = (K_{Ic})^2/\sigma_{ys}$

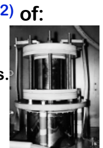
Thin wall, strong
$M_3 = \sigma_{ys}$

- ***Large pressure vessels*** **are always made of steel.**
- ***Models*** **are made of Cu, for resistance to corrosion.**
- ***Check that M_2 favors steel.***
- ***M_3=100 MPa*** **eliminates Al**



Optimal Magnet Coil Material (see CDROM)

- High magnetic fields permit study[2] of:
  - electron energy levels,
  - conditions for superconductivity
  - conversion of insulators into conductors.
- Largest Example:
  - short pulse of 800,000 gauss (Earth's magnetic field: ~ 0.5 Gauss)
- Technical Challenges:
  - Intense resistive heating can melt the coil.
  - Lorentz stress can exceed the material strength.
- Goal: Select an optimal coil material.



Pulsed magnetic capable of 600,000 gauss field during 20ms period.

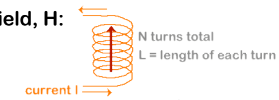
Fractured magnet coil. (Photos from NHMFL, Los Alamos National Labs, NM (Apr. 2002) by P.M. Anderson)

(1) Based on discussions with Greg Boebinger, Dwight Rickel, and James Sims, National High Magnetic Field Lab (NHMFL), Los Alamos National Labs, NM (April, 2002).
(2) See G. Boebinger, Al Passner, and Joze Bevk, "Building World Record Magnets", Scientific American, pp. 58-66, June 1995, for more information.

Lorentz Stress & Heating

- Applied magnetic field, H:

$H = N\,I/L$



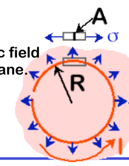
- Lorentz "hoop" stress:

$$\sigma = \frac{I\mu_o HR}{A} \quad \left(\le \frac{\sigma_f}{S}\right)$$

- Resistive heating: (adiabatic)

$$\Delta T = \frac{I^2\rho_e}{A^2 c_v}\Delta t \quad (< \Delta T_{max})$$

elect. resistivity; specific heat; temp increase during current pulse of Δt



$$\frac{\text{Force}}{\text{length}} = I\mu_o H$$

Magnet Coil: Performance Index

- Mass of coil: $m = \rho_d AL$
- Applied magnetic field: $H = N\,I/L$
- Eliminate "free" design parameters A, I from the stress & heating equations (previous slide):

--Stress requirement

$$\frac{H^2}{m} \le \frac{1}{2\pi R^2 L\mu_o N}\,\frac{\sigma_f}{\rho_d}$$

--Heating requirement

$$\frac{H\sqrt{\Delta t}}{m} \le \frac{\sqrt{\Delta T_{max}}}{\sqrt{2\pi}\,RL}\,\frac{1}{\rho_d}\sqrt{\frac{c_v}{\rho_e}}$$

specified by application

Performance Index P_1: maximize for large H^2/M

specified by application

Performance Index P_2: maximize for large $Ht^{1/2}/M$

Magnet Coil: Cost Index

- Relative cost of coil: $\$ = \$M$
- Applied magnetic field: $H = N\,I/L$
- Eliminate M from the stress & heating equations:

--Stress requirement

$$\frac{H^2}{\$} \le \frac{1}{2\pi R^2 L\mu_o N}\,\frac{\sigma_f}{\rho_d \$}$$

--Heating requirement

$$\frac{H\sqrt{\Delta t}}{\$} \le \frac{\sqrt{\Delta T_{max}}}{\sqrt{2\pi}\,RL}\,\frac{1}{\rho_d \$}\sqrt{\frac{c_v}{\rho_e}}$$

specified by application

Cost Index C_1: maximize for large $H^2/\$$

specified by application

Cost Index C_2: maximize for large $Ht^{1/2}/\$$

Indices For A Coil Material

- From Appendices B and C, *Callister 6e*:

Material	σ_f	ρ_d	$	c_v	ρ_e	P_1	P_2	C_1	C_2
1020 steel (an)	395	7.85	0.8	486	1.60	50	2	63	2.5
1100 Al (an)	90	2.71	12.3	904	0.29	33	21	3	1.7
7075 Al (T6)	572	2.80	13.4	960	0.52	204	15	15	1.1
11000 Cu (an)	220	8.89	7.9	385	0.17	25	5	3	0.6
17200 Be-Cu (st)	475	8.25	51.4	420	0.57	58	3	1	<0.1
71500 Cu-Ni (hr)	380	8.94	12.9	380	3.75	43	1	3	<0.1
Pt	145	21.5	1.8e4	132	1.06	7	19	<1	<0.1
Ag (an)	170	10.5	271	235	0.15	16	<1	<1	<0.1
Ni 200	462	8.89	31.4	456	0.95	52	2	2	<0.1
units	MPa	g/cm^3	--	J/kg-K	Ω-m^3	σ_f/ρ_d	$\frac{(c_v/\rho_e)^{0.5}}{\rho_d}$	P_1/$	P_2/$

Avg. values used. an = annealed; T6 = heat treated & aged;
st = solution heat treated; hr = hot rolled

- Lightest for a given H: 7075 Al (T6) ← P_1
- Lightest for a given $H(\Delta t)^{0.5}$: 1100 Al (an) ← P_2
- Lowest cost for a given H: 1020 steel (an) ← C_1
- Lowest cost for a given $H(\Delta t)^{0.5}$: 1020 steel (an) ← C_2

SUMMARY

- Material costs fluctuate but rise over long term as:
  - rich deposits are depleted,
  - energy costs increase.
- Recycled materials reduce energy use significantly.
- Materials are selected based on:
  - performance or cost indices.
- Examples:
  - design of minimum mass, maximum strength of:
    - shafts under torsion,
    - bars under tension,
    - plates under bending,
  - selection to optimize more than one property:
    - leg slenderness and mass.
    - pressure vessel safety.
    - material for a magnet coil (see CD-ROM).