Foams: Microstructural Design

- foams - behavior dominated by cell wall bending

· foam properties can be increased by increasing EI of cell walls

Hollow walls

thin walled tube $I_t = \pi r^3 t$

solid circular section $I_s = \dfrac{\pi R^4}{4}$

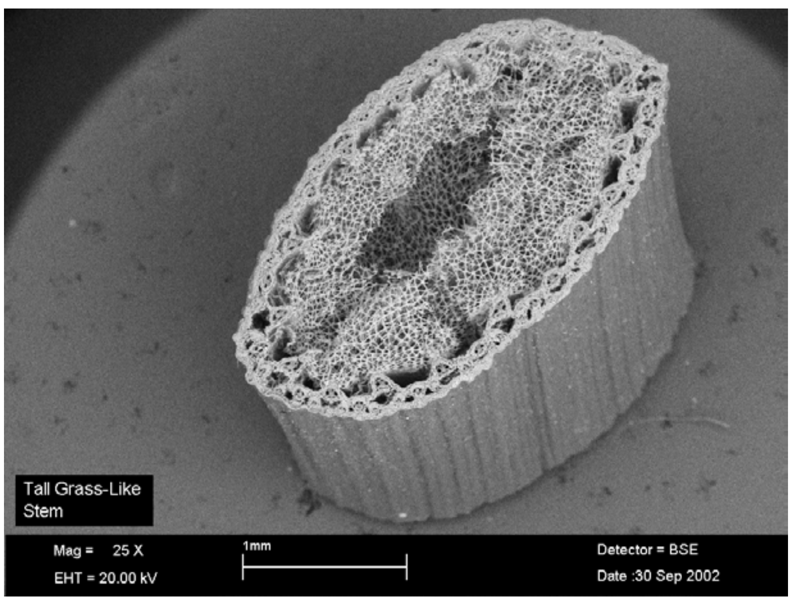
masses equal: $\pi R^2 = 2\pi r t$

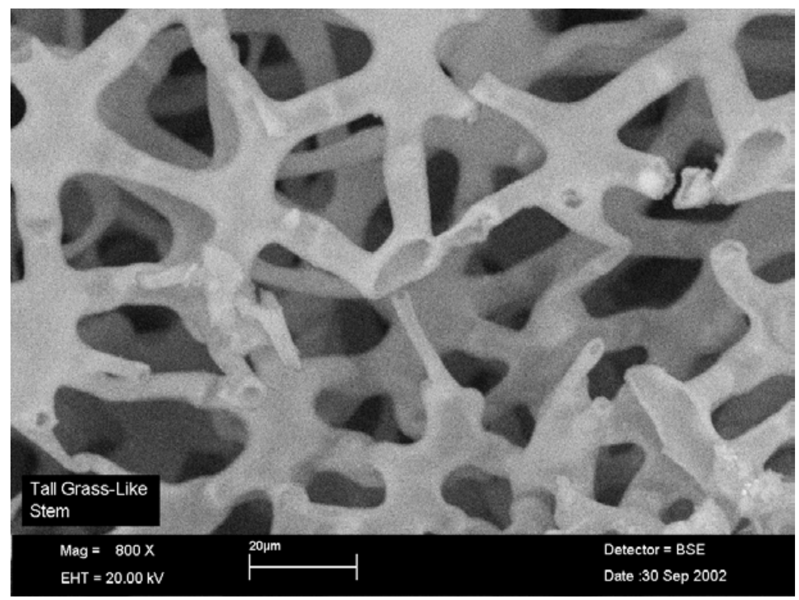
$R = \sqrt{2rt}$

$$\frac{I_t}{I_s} = \frac{4\pi r^3 t}{\pi R^4} = \frac{4 r^3 t}{4 r^2 t^2} = \frac{r}{t}$$

$$\therefore \quad \frac{E^*_{\text{tube wall}}}{E^*_{\text{solid wall}}} \propto \frac{r}{t}$$

· can do similar analysis for other properties


Tall Grass-Like
Stem
Mag = 25 X
1mm
EHT = 20.00 kV
Detector = BSE
Date :30 Sep 2002


Tall Grass-Like
Stem
Mag = 800 X
20µm
EHT = 20.00 kV
Detector = BSE
Date :30 Sep 2002

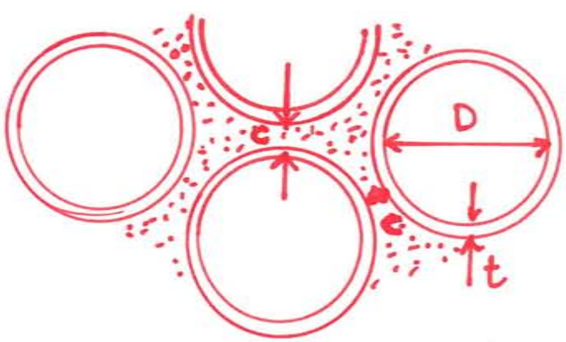
Sandwich cell walls

· sandwich beam - two stiff faces separated by a lightweight core
- core typically a honeycomb or foam (or balsa)

I-beam effect - increase in moment of inertia, with little increase in weight

faces - like flanges of I beam - resist bending
core - " web " " " - " shear

· microsandwich foam



d = foam cell size

microsandwich foam

· thin walled hollow spheres distributed in a foam

· have to get geometry right

· require:

Spheres: $t \ll D$

$E_{sphere} \gg E_{foam}$

$V_{f\,spheres} \approx 50-60\%$

foam: $d \ll c$

Foams: Microstructural design

- another alternative is to use microstructure that induces axial, rather than bending, deformations
- 3D lattice materials - triangulated trusses in 3D
  - forces in members all axial; bending negligible
- various processing methods + geometries possible - all triangulated
- can analyze truss as having pin joints - axial forces in members
- open-cell structures

$$E^* = \frac{\sigma}{\epsilon} \propto \frac{F}{l^2} \frac{l}{\delta} \qquad \delta \propto \frac{Fl}{AE_s} \propto \frac{Fl}{t^2 E_s}$$

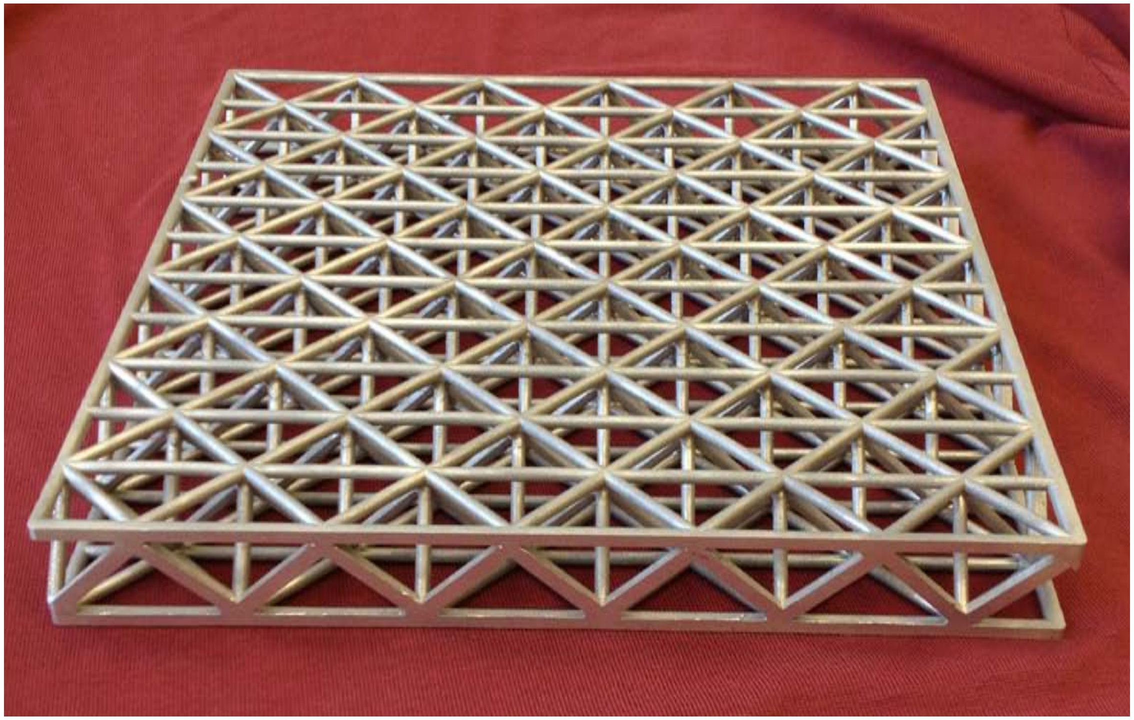
$$E^* \propto \frac{F}{l} \frac{E_s t^2}{Fl} \propto E_s \left(\frac{t}{l}\right)^2 \propto E_s\left(\frac{\rho^*}{\rho_s}\right)$$

$$\boxed{E^* = C\, E_s\, (\rho^*/\rho_s)}$$ C depends on cell geometry + loading direction

- strength: if struts fail by uniaxial yield

$$\sigma^*_{pl} = C\, \sigma_{ys}\, (\rho^*/\rho_s)$$

But some struts in compression - may buckle (generally do buckle)



Compressive strut buckling

- elastic buckling $\sigma^*_{el} = C\,E_s\,(\rho^*/\rho_s)^2$ (like an open-cell foam)
- if interaction between elastic buckling + yield - use a reduced modulus (tangent modulus)
- also: imperfections such as non-straight struts or misaligned struts reduce buckling resistance "knock-down" factor can be significant ~50%.

Material selection

- how to select the best material for some mechanical requirement?
- section on wood: derived performance index for minimizing mass of a beam of a given stiffness: $\boxed{E^{1/2}/\rho}$
- here, discuss materials selection more broadly
- another example: what material minimizes the mass of a beam of a given failure load, P_f?
  given P_f, span l, square cross-section t^2

$$\sigma_{max} = \frac{My}{I}$$

M = Maximum moment in beam $\propto Pl$

y = maximum distance from neutral axis $\propto t$

I = moment of inertia $\propto t^4$

σ_f = failure stress of beam material

$$\sigma_{max} \propto \frac{P_f l t}{t^4} \propto \sigma_f$$

$$t \propto \left(\frac{P_f l}{\sigma_f}\right)^{1/3}$$

$$\text{mass, } m = \rho t^2 l$$

$$m \propto \rho \left(\frac{P_f l}{\sigma_f}\right)^{2/3} l$$

Performance index: $\boxed{\sigma_f^{2/3}/\rho}$
to be maximized

Materials selection

Ashby book - Tables

- can obtain performance indices for various loading configurations + mechanical requirements
- if plot data for material properties on log-log scales, performance indices appear as straight lines
- shifting lines up + down identifies best material for that performance index

CMNM Fig 7.1

- example: modulus - density chart

  E/ρ: axially loaded tie of given stiffness

  $E^{1/2}/\rho$: beam of given stiffness

  $E^{1/3}/\rho$: plate " "

Property charts for foams

CS Fig 13.1 E^* vs ρ^* : range of E^* factor of 10^6, from 0.01 MPa to 10 GPa

Fig 13.2 σ^* vs ρ^* : range of σ^* from 10^{-3} to 30 MPa

$\Rightarrow$ scope for matching foam properties to design requirements

E^*/ρ vs σ^*/ρ : end grain balsa, metal foams high values

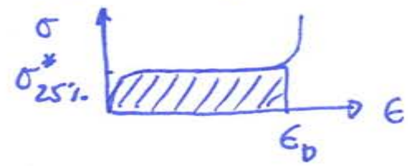
useful for sandwich panels - selection of core material

Property charts - foams

ϵ_D vs. $\sigma^*_{25\%}$: contours show energy absorption/volume, u

$u \sim \sigma^*_{25\%}\, \epsilon_D$

$\epsilon_D = u / \sigma^*_{25\%}$



contours have slope of -1 on log-log scales

balsa, metal foams - high values of u

- can also produce selection charts for other properties - e.g. thermal
- λ vs $\sigma^*_{5\%}$ - thermal conductivity, λ
  - thermal insulation applications usually have constraint on strength, too.
- λ vs T_{max} - may have constraint on maximum service temperature, too.
- density plot - closed cell foams - buoyancy
- cell size - open cell foams - filtration + catalysis
  - surface area/volume increases as cell size decreases
    e.g. ceramic foams used in filtration of liquid metals

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Ashby MF (1999) Materials Selection in Mechanical Design.
Second Edition Butterworth Heinemann

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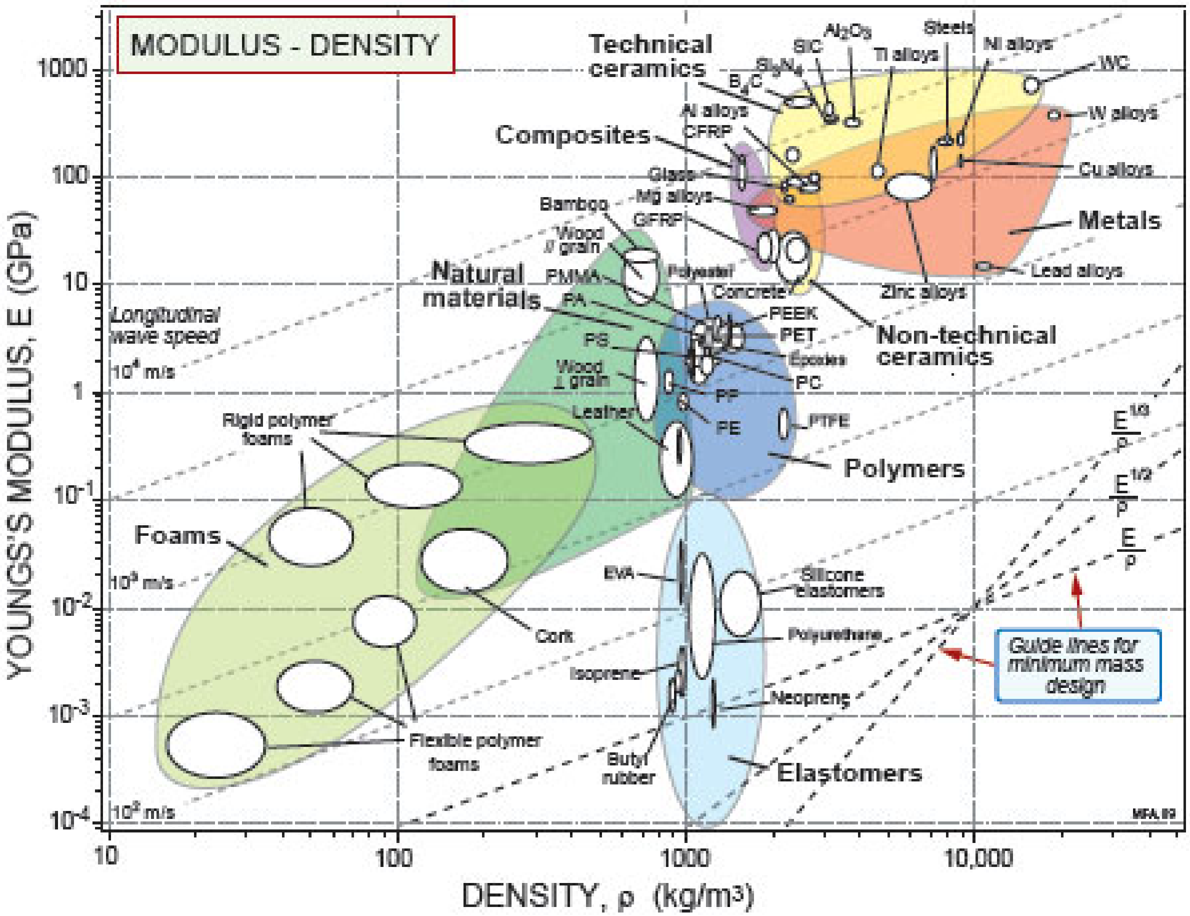
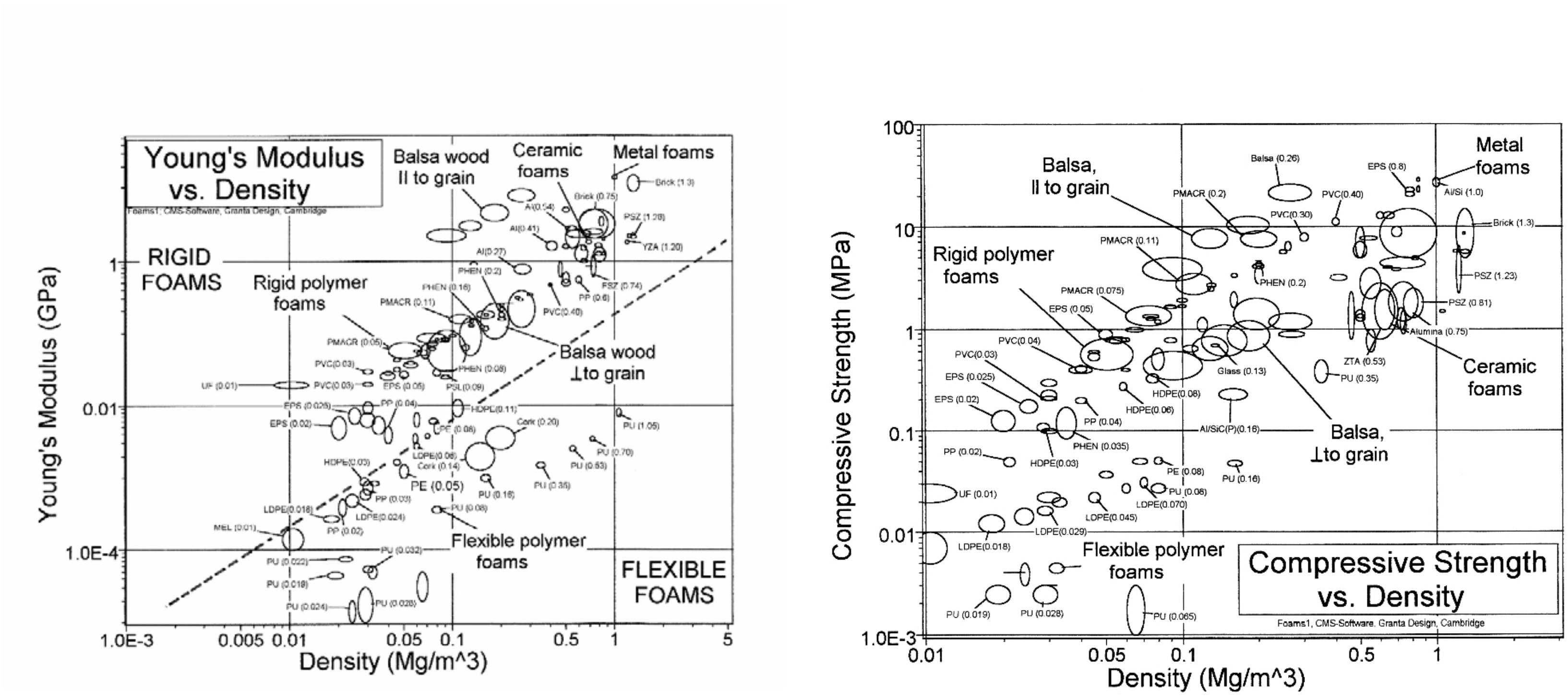


MODULUS - DENSITY
Technical ceramics
Composites
Natural materials
Foams
Polymers
Elastomers
Metals
Non-technical ceramics
Rigid polymer foams
Flexible polymer foams
Cork
Leather
Bamboo
Wood // grain
Wood ⊥ grain
PMMA
PA
PS
Polyester
Concrete
PEEK
PET
Epoxies
PC
PP
PE
PTFE
EVA
Silicone elastomers
Polyurethane
Isoprene
Neoprene
Butyl rubber
Al alloys
CFRP
Glass
Mg alloys
GFRP
B_4C
Si_3N_4
SiC
Al_2O_3
Ti alloys
Steels
Ni alloys
WC
W alloys
Cu alloys
Zinc alloys
Lead alloys
Longitudinal wave speed
10^4 m/s
10^3 m/s
10^2 m/s
$\frac{E^{1/3}}{\rho}$
$\frac{E^{1/2}}{\rho}$
$\frac{E}{\rho}$
Guide lines for minimum mass design
MFA 09
YOUNG'S MODULUS, E (GPa)
DENSITY, ρ (kg/m³)



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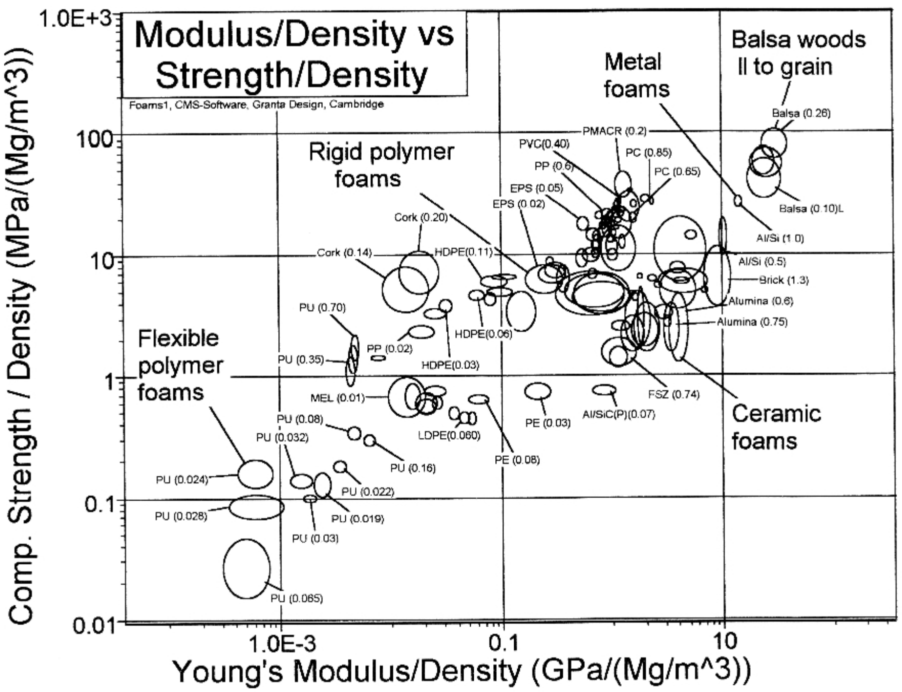

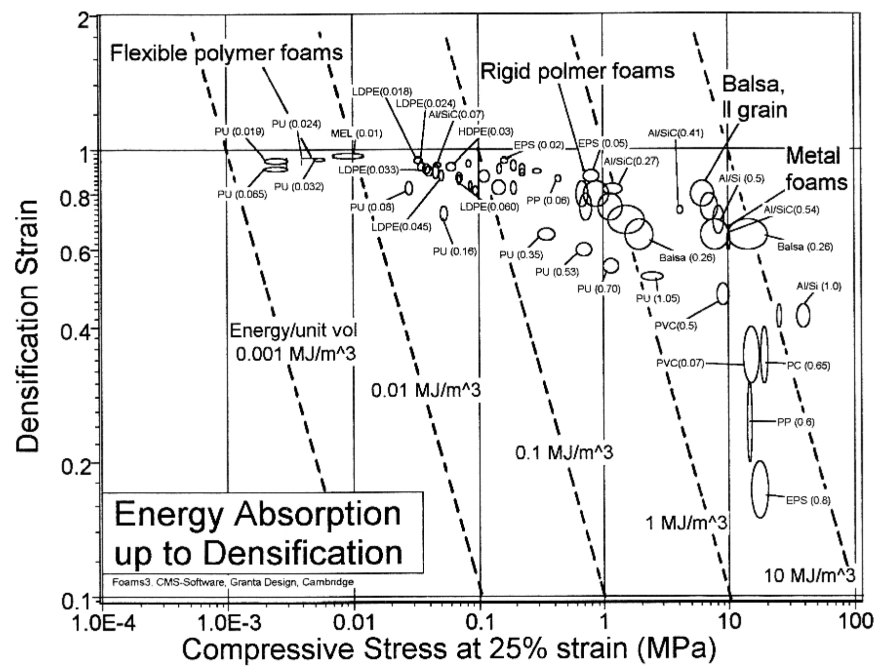

End grain balsa; metal foams
Useful for sandwich panels

Contours show energy absorption per unit volume

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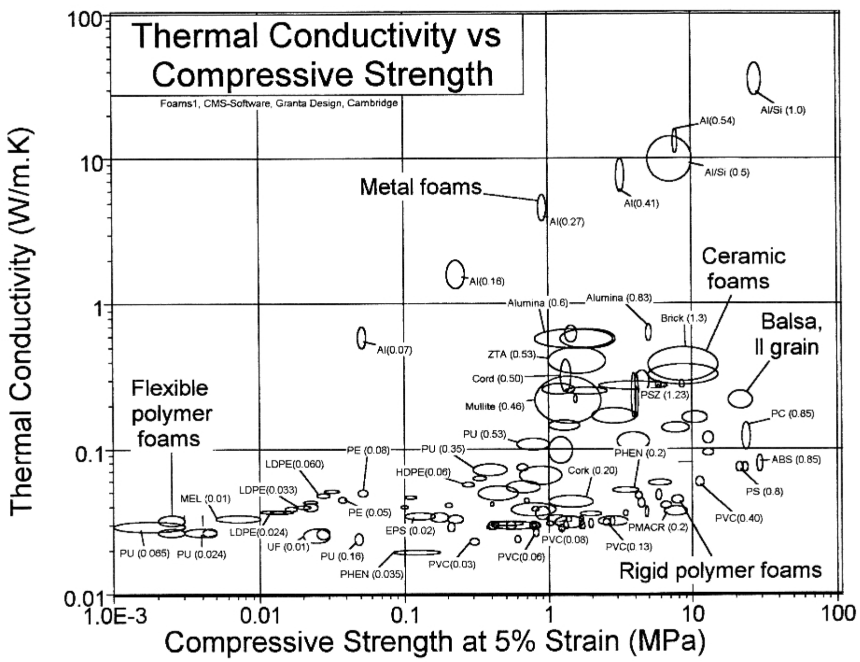

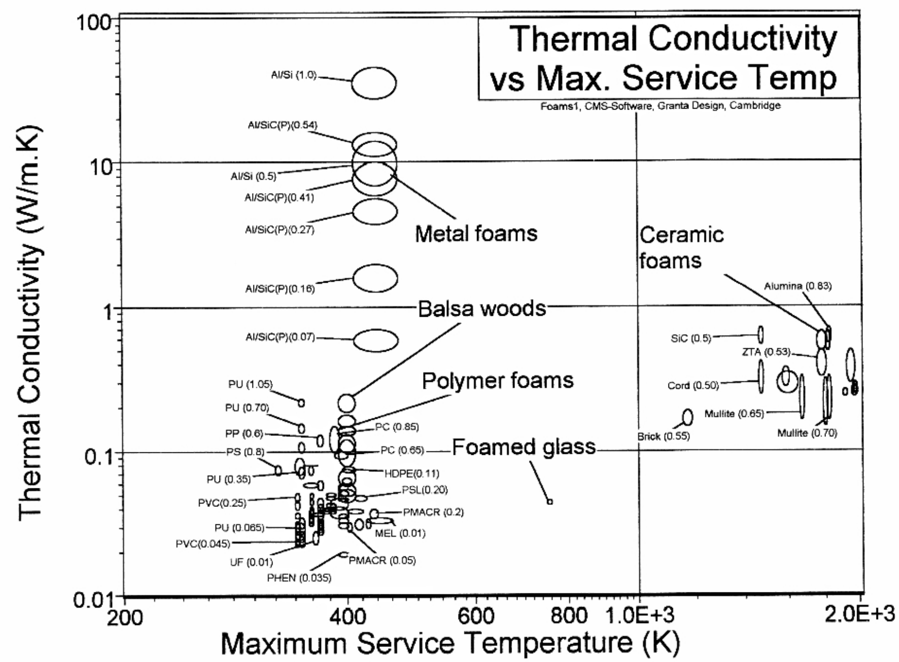

Thermal insulation applications;
Usually a constraint on strength, too

May also have a constraint on
maximum service temperature

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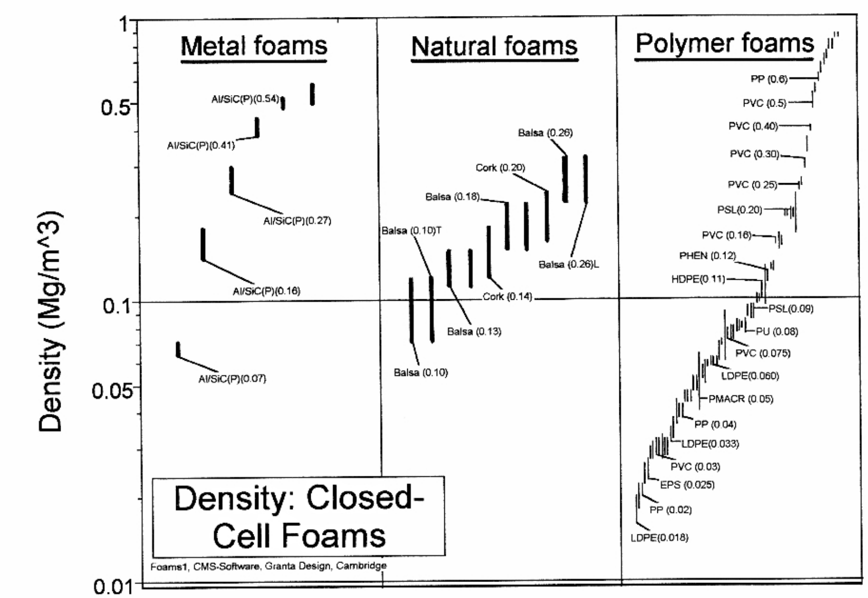

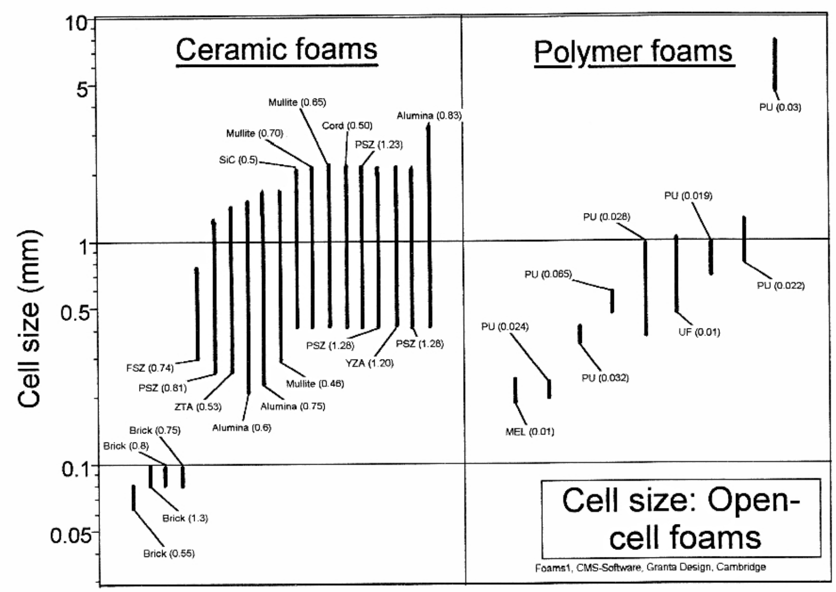

Buoyancy

Filtration and catalysis