Materials Selection in Design

- The Role of Materials Selection in Design
- Exploring relationships - Materials Property Charts
- The Materials Selection Process –Design Models
- Selecting materials –Materials Indices
- Case Studies of Materials Selection using CES

Demystifying Material Indices

Material properties --

the "Physicists" view of materials, e.g.

Cost,	C_m
Density,	ρ
Modulus,	E
Strength,	σ_y
Endurance limit,	σ_e
Thermal conductivity,	λ
T- expansion coefficient,	α

Material indices --

the "Engineers" view of materials

Objective: minimise mass

Function	Stiffness	Strength
Tension (tie)	ρ/E	ρ/σ_y
Bending (beam)	$\rho/E^{1/2}$	$\rho/\sigma_y^{2/3}$
Bending (panel)	$\rho/E^{1/3}$	$\rho/\sigma_y^{1/2}$

Minimise these!

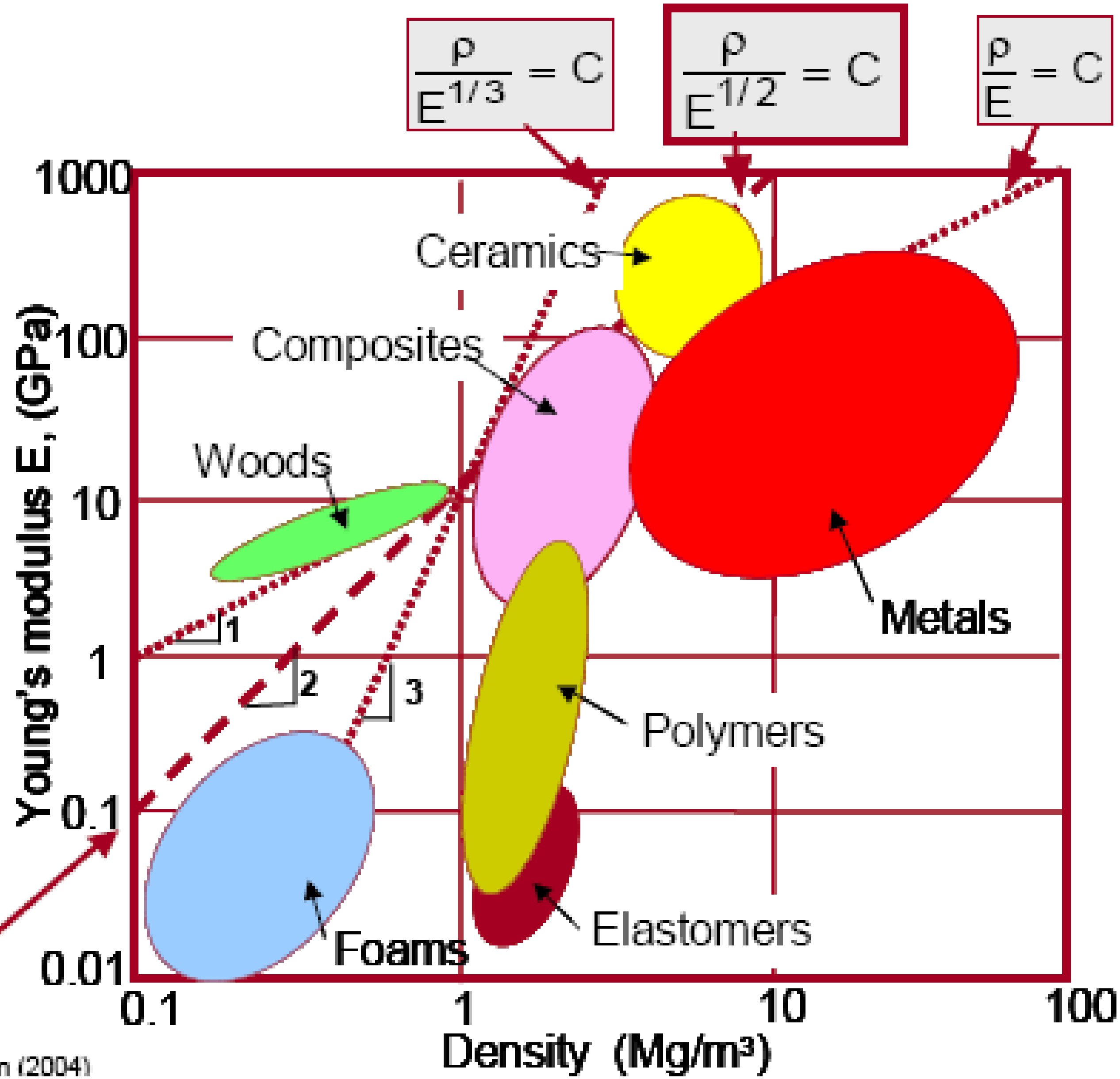
Ashby – Materials Selection in Mechanical Design (2004)

Using Materials Indices with Materials Selection Charts

Index $M = \dfrac{\rho}{E^{1/2}}$

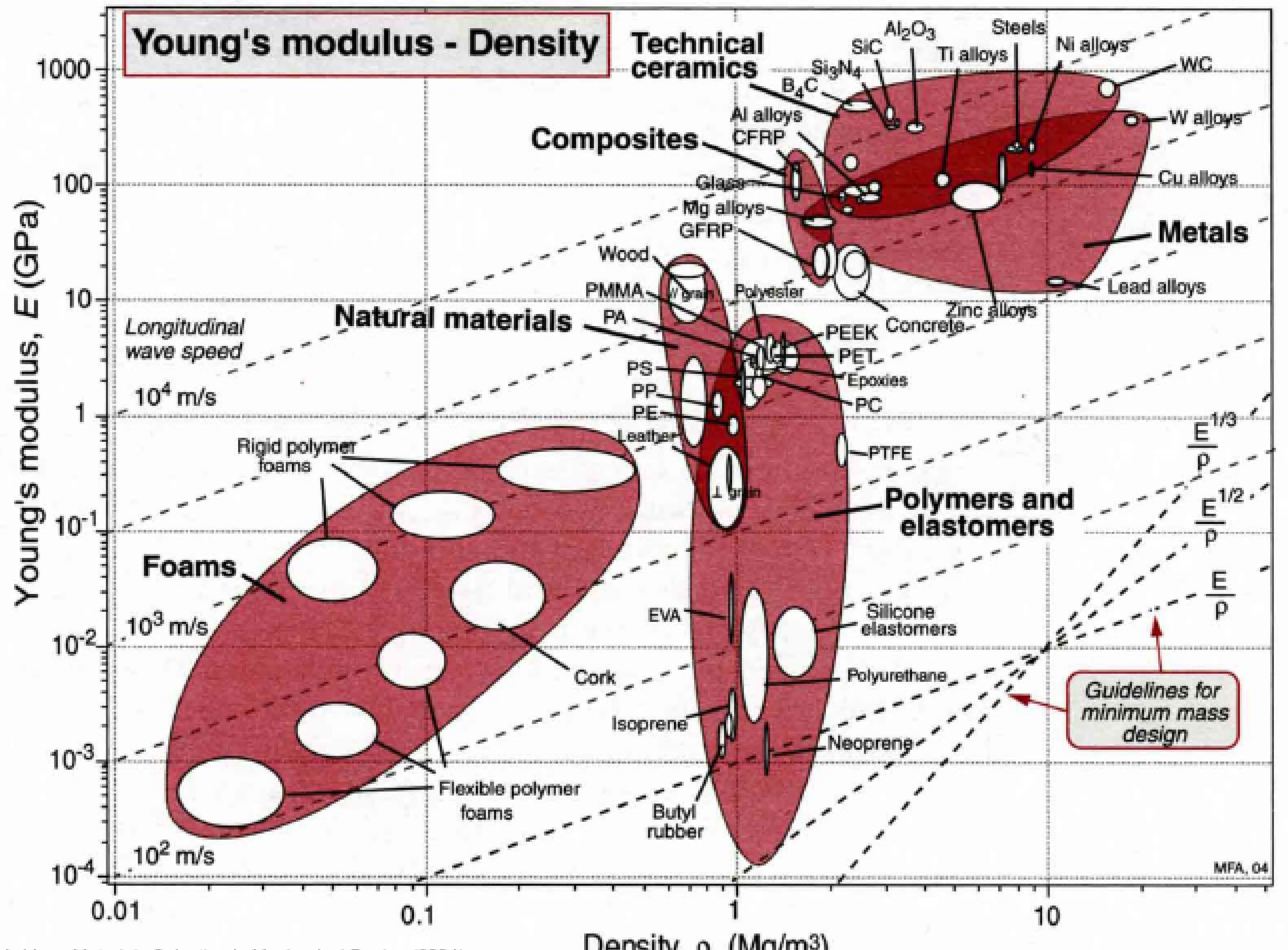
$\Rightarrow E = \rho^2 / M^2$

$\text{Log}(E) = 2\text{Log}(\rho) - 2\text{Log}(M)$

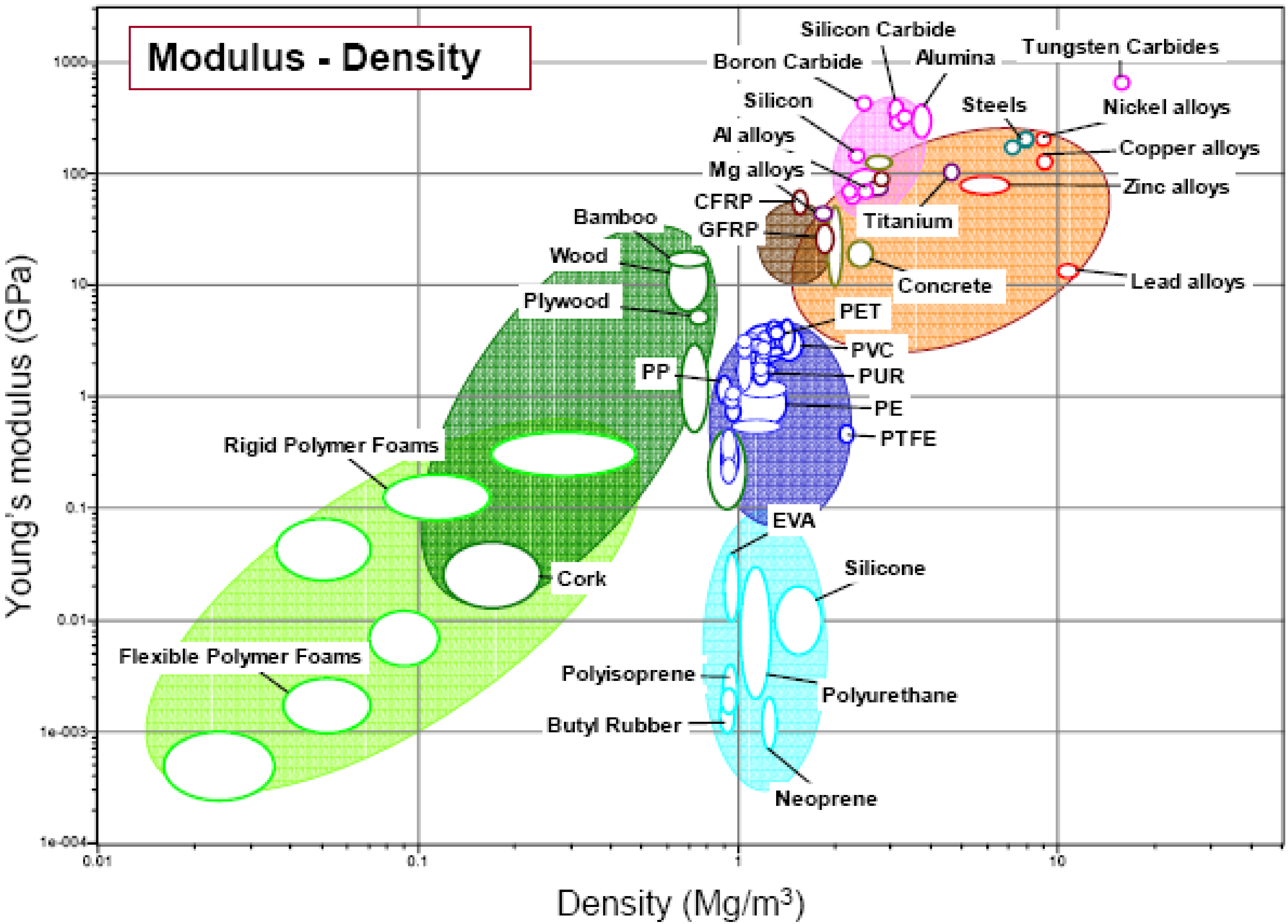


Contours of constant M are lines of slope 2 on an E-ρ chart

Ashby – Materials Selection in Mechanical Design (2004)



Ashby – Materials Selection in Mechanical Design (2004)


Modulus - Density
Young's modulus (GPa)
Density (Mg/m^3)
1000
100
10
1
0.1
0.01
1e-003
1e-004
0.01
0.1
1
10
Silicon Carbide
Boron Carbide
Alumina
Tungsten Carbides
Silicon
Steels
Nickel alloys
Al alloys
Copper alloys
Mg alloys
Zinc alloys
CFRP
Titanium
GFRP
Bamboo
Wood
Concrete
Lead alloys
Plywood
PET
PVC
PP
PUR
PE
PTFE
Rigid Polymer Foams
EVA
Silicone
Cork
Flexible Polymer Foams
Polyisoprene
Polyurethane
Butyl Rubber
Neoprene

Commonly used Materials Indices (MI's)

Function, objective, and constraints	Index
Tie, minimum weight, stiffness prescribed	$\frac{E}{\rho}$
Beam, minimum weight, stiffness prescribed	$\frac{E^{1/2}}{\rho}$
Beam, minimum weight, strength prescribed	$\frac{\sigma_y^{2/3}}{\rho}$
Beam, minimum cost, stiffness prescribed	$\frac{E^{1/2}}{C_m \rho}$
Beam, minimum cost, strength prescribed	$\frac{\sigma_y^{2/3}}{C_m \rho}$
Column, minimum cost, buckling load prescribed	$\frac{E^{1/2}}{C_m \rho}$
Spring, minimum weight for given energy storage	$\frac{\sigma_y^2}{E \rho}$
Thermal Insulation, minimum cost, heat flux prescribed	$\frac{1}{\lambda C_p \rho}$
Electromagnet, maximum field, temperature rise prescribed	$\frac{C_p \rho}{\rho_e}$

ρ = density; E = Young's modulus; σ_y = elastic limit; C_m = cost/kg λ = thermal conductivity; ρ_e = electrical resistivity; C_p = specific heat.

The nature of material data

- **Numeric:** properties measured by numbers: density, modulus, cost …other properties

Can extrude?

Good or bad in sea water?

- **Non-numeric:** properties measured by yes - no (Boolean) or poor-average-good type (Rankings)

Design guide lines

Case studies

Failure analyses

Established applications

- **Supporting information, specific:** what is the experience with the material?

Supplier information

FE modules

Standards and codes (ISO 14000)

Sector-specific approval (FDA, MilSpec)

- **Supporting information, general:** what else do you need to know?

"Structured" and "Unstructured" data

Handbooks, data sheets

Reports, papers, the Web

Other Materials Selection Charts

- Modulus-Relative Cost
- **Strength-Relative Cost Modulus-Strength**
- **Specific Modulus-Specific Strength**
- **Fracture Toughness-Modulus**
- **Fracture Toughness-Strength**
- **Loss Coefficient-Modulus**

- Facture Toughness-Density
- **Conductivity-Diffusivity**
- **Expansion-Conductivity**
- **Expansion-Modulus**
- **Strength-Expansion**
- **Strength Temperature**
- Wear Rate-Hardness
- Environmental Attack Chart

Summary: Material Indices

- A method is necessary for translating design requirements into a prescription for a material
- Modulus-Density charts
  - Reveal a method of using lines of constant

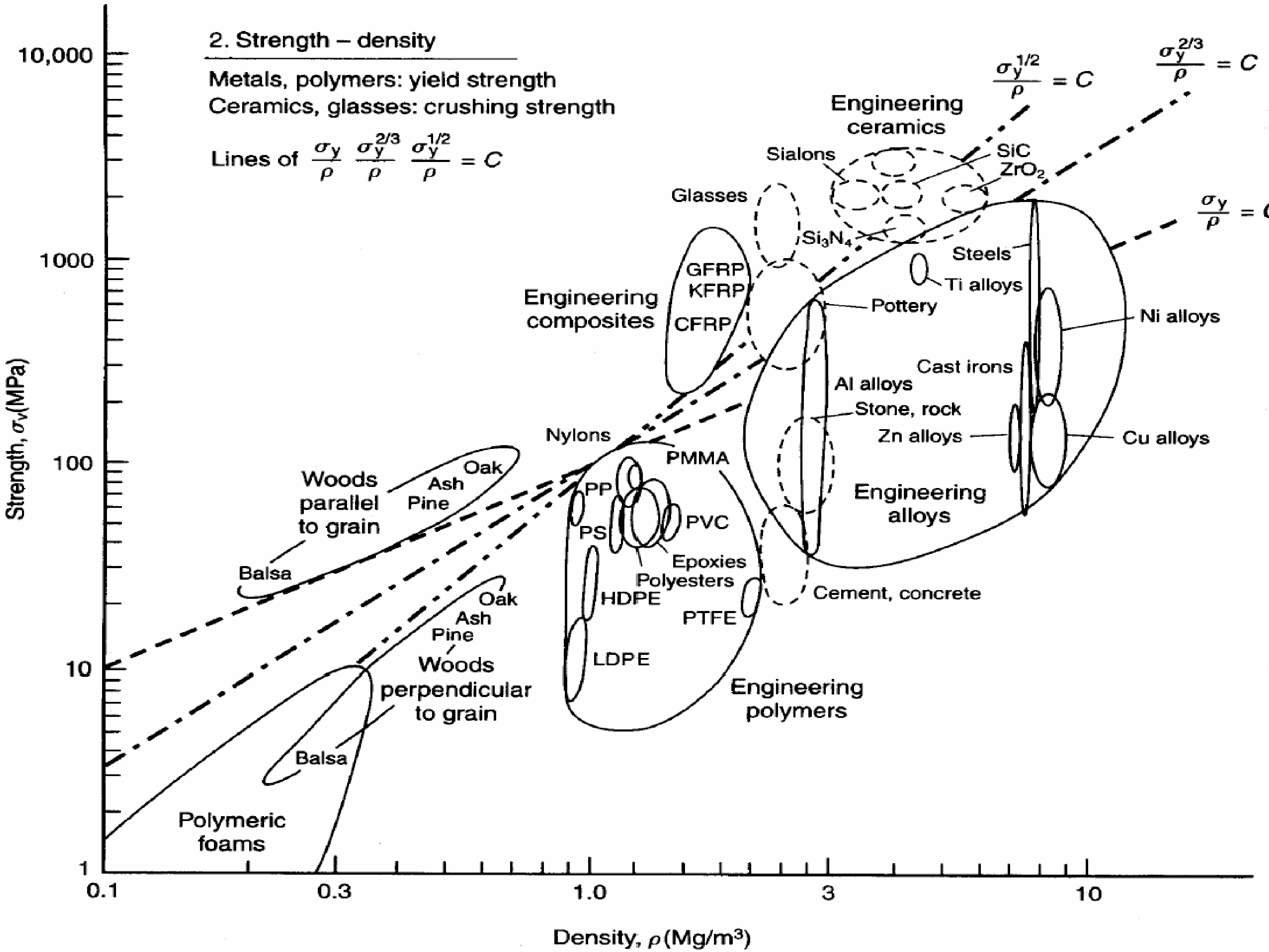
$$E^{1/n}/\rho \qquad n = 1,2,3$$

to allow selection of materials for minimum weight and deflection-limited design.

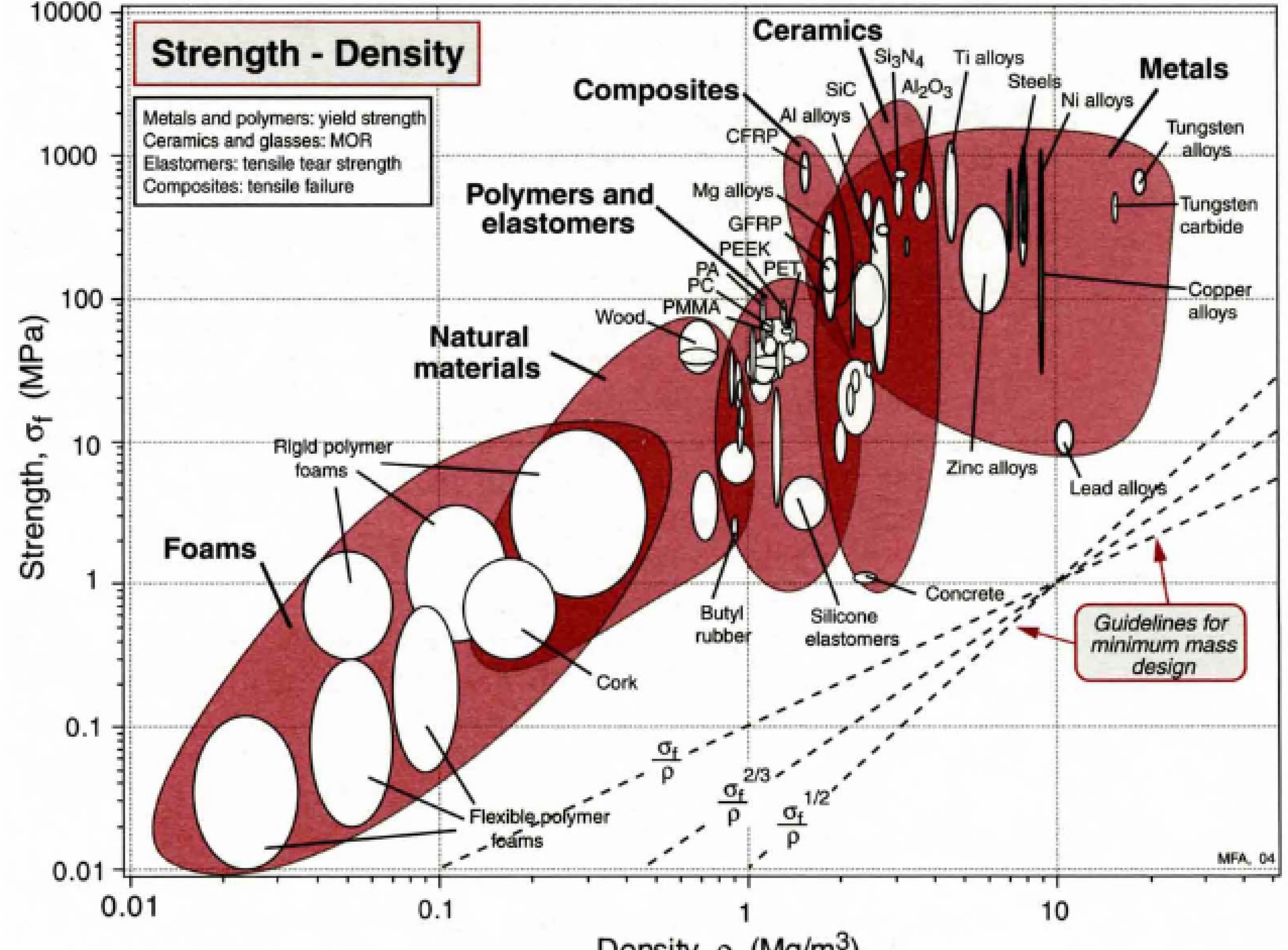
- Material Index
  - Combination of material properties which characterize performance in a given application.
- Performance of a material:

$$p = f\left[\begin{pmatrix} Functional \\ Needs,\ F \end{pmatrix}, \begin{pmatrix} Geometeric \\ Parameters,\ G \end{pmatrix}, \begin{pmatrix} Material \\ Characteristics,\ M \end{pmatrix}\right]$$

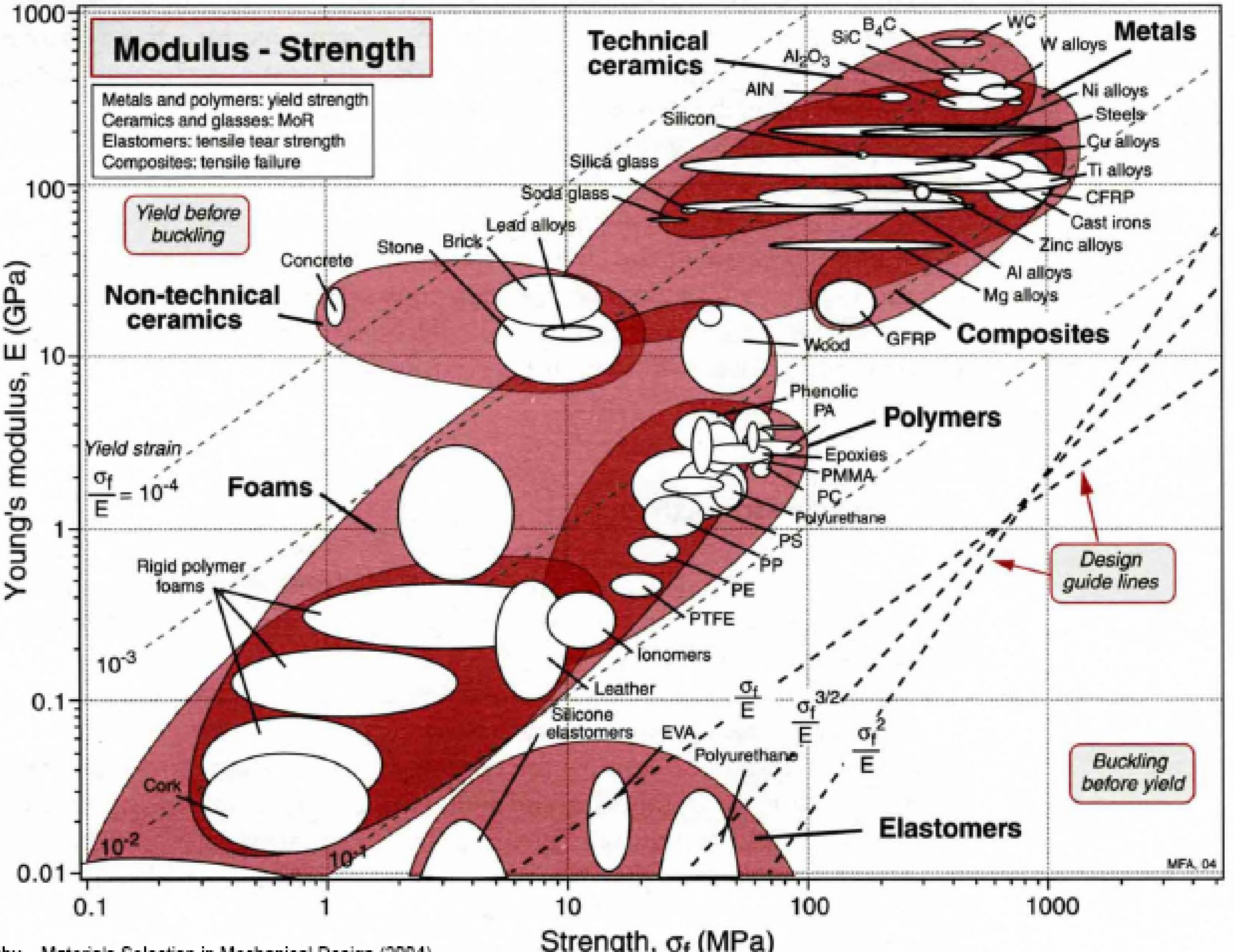
$$p = f_1(F)\, f_2(G)\, f_3(M)$$



2. Strength – density
Metals, polymers: yield strength
Ceramics, glasses: crushing strength
Lines of $\frac{\sigma_y}{\rho}$ $\frac{\sigma_y^{2/3}}{\rho}$ $\frac{\sigma_y^{1/2}}{\rho}$ = C
$\frac{\sigma_y^{1/2}}{\rho} = C$
$\frac{\sigma_y^{2/3}}{\rho} = C$
Engineering ceramics
Sialons
SiC
ZrO_2
Glasses
Si_3N_4
Steels
Ti alloys
GFRP
KFRP
CFRP
Engineering composites
Pottery
Ni alloys
Cast irons
Al alloys
Stone, rock
Zn alloys
Cu alloys
Nylons
PMMA
Woods parallel to grain
Oak
Ash
Pine
Balsa
PP
PS
PVC
Epoxies
Polyesters
HDPE
PTFE
LDPE
Engineering alloys
Cement, concrete
Woods perpendicular to grain
Engineering polymers
Polymeric foams
Strength, σ_y (MPa)
Density, ρ (Mg/m³)
10,000
1000
100
10
1
0.1
0.3
1.0
3
10



Ashby – Materials Selection in Mechanical Design (2004)



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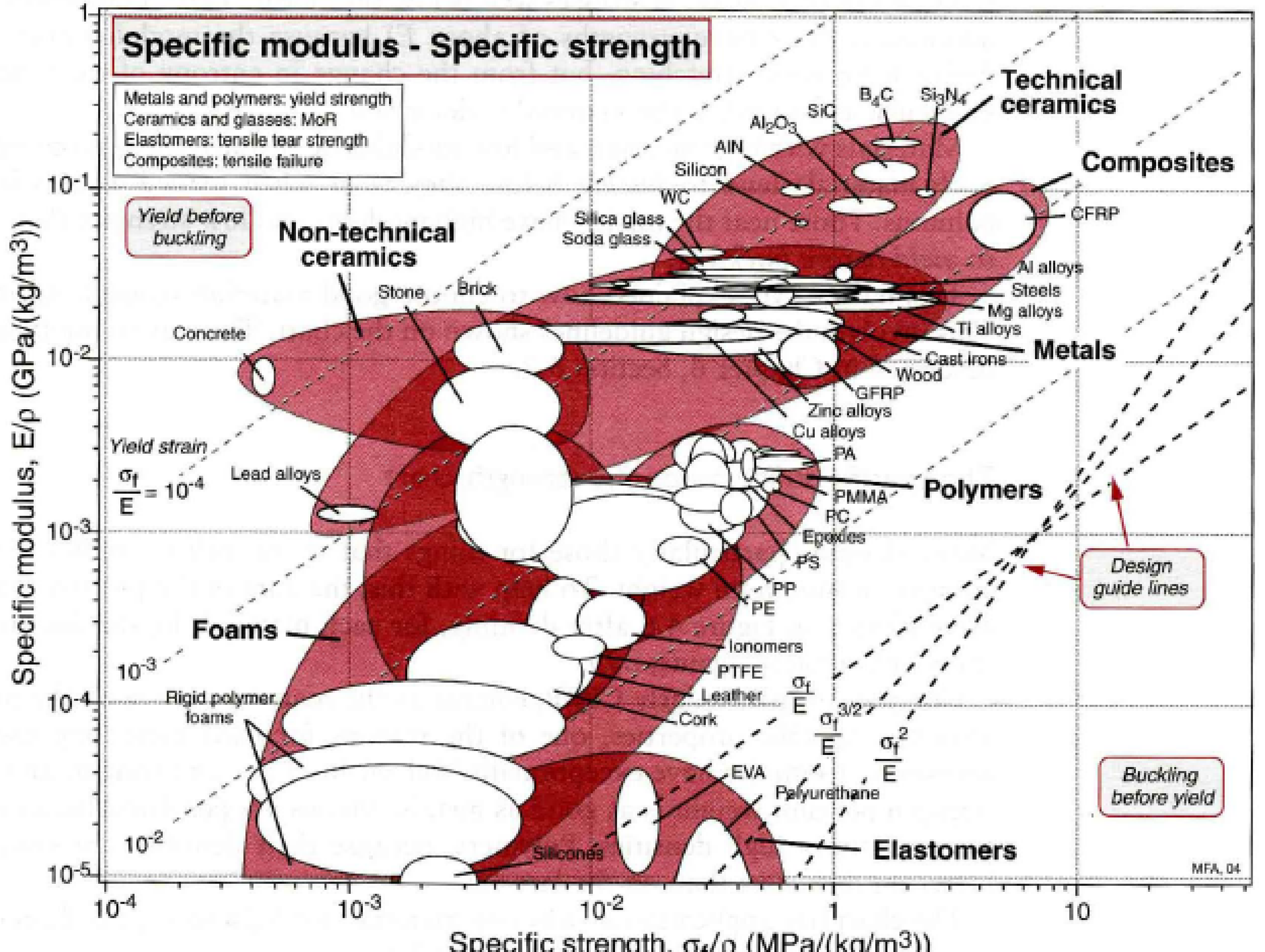

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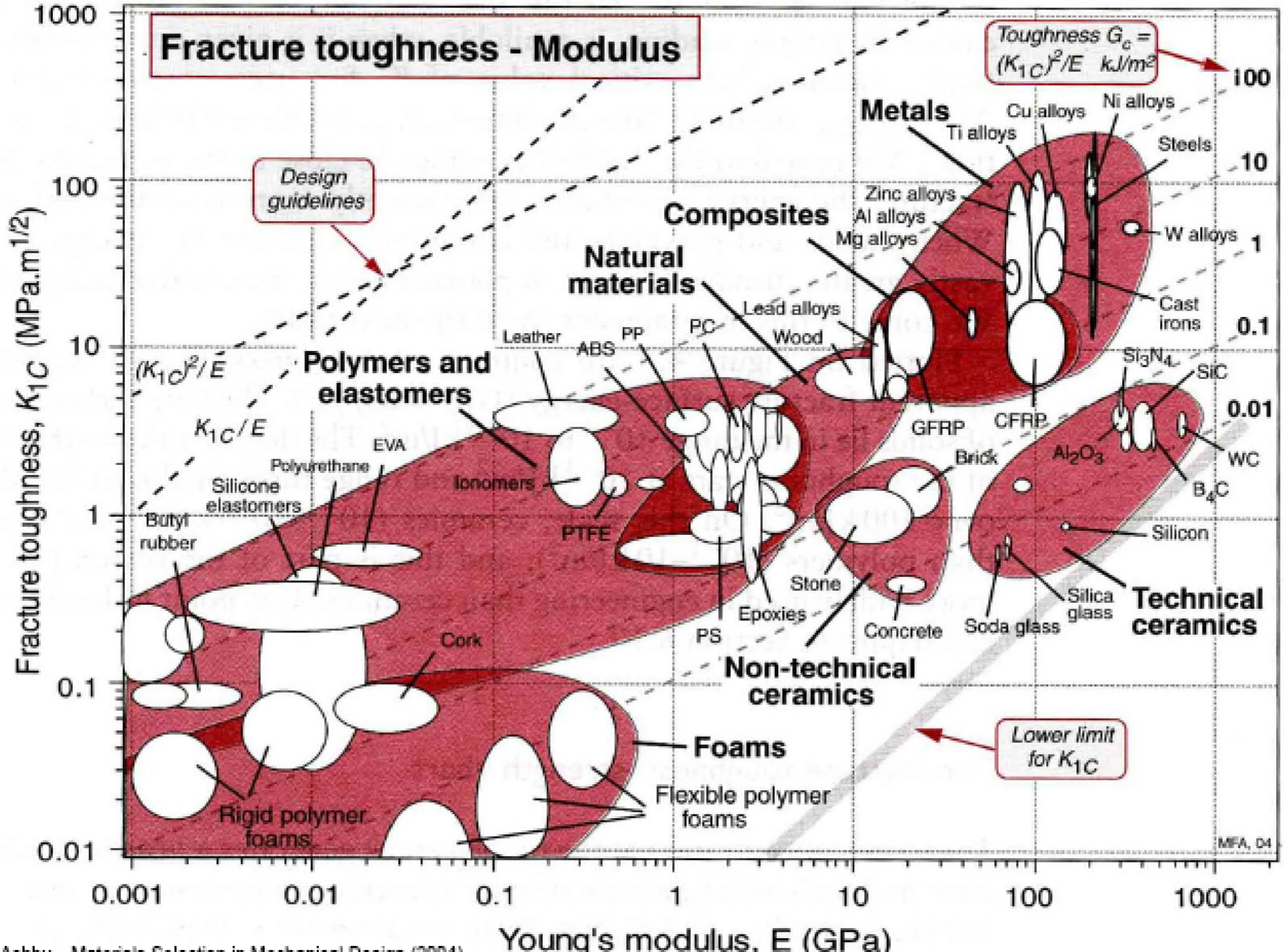

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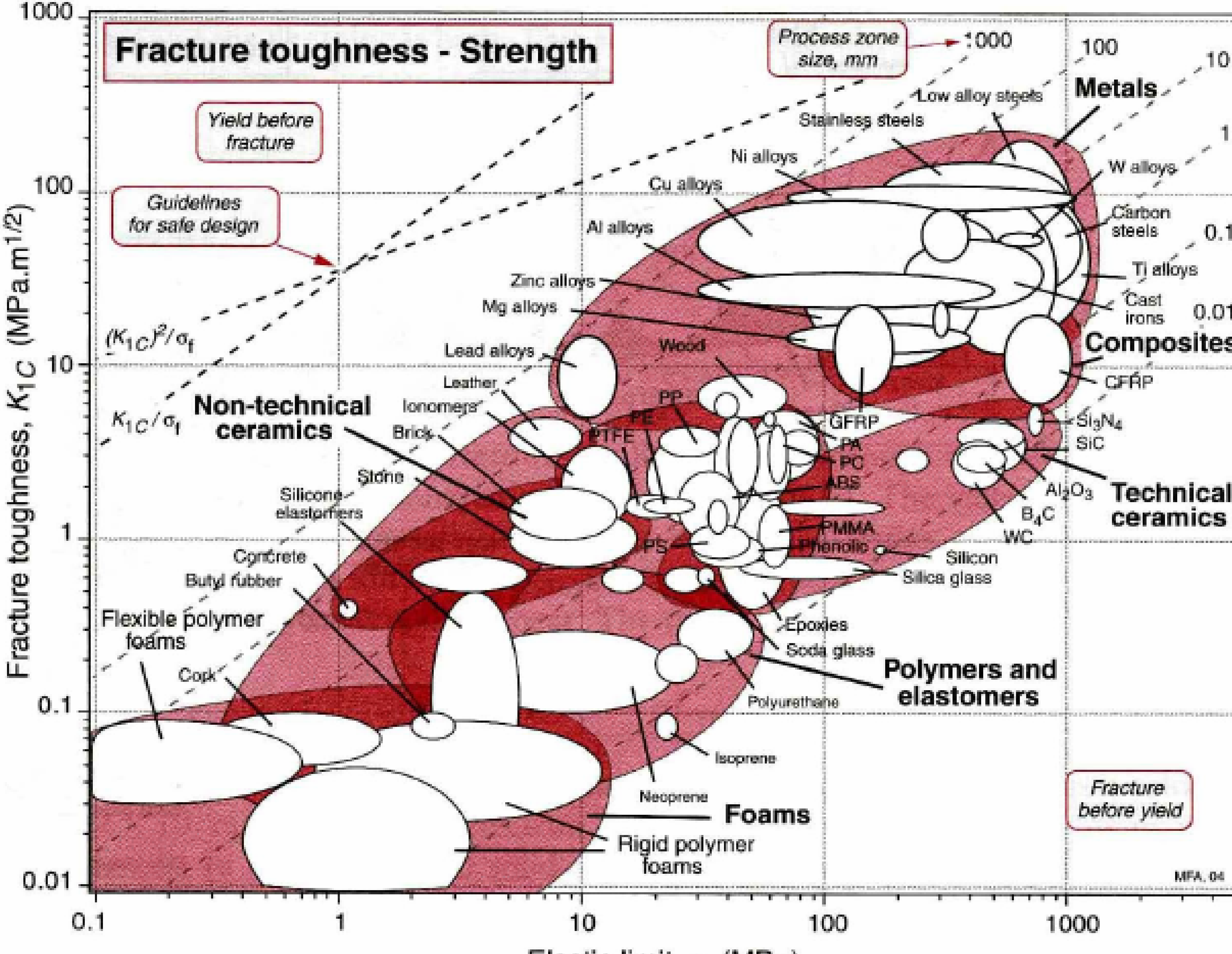

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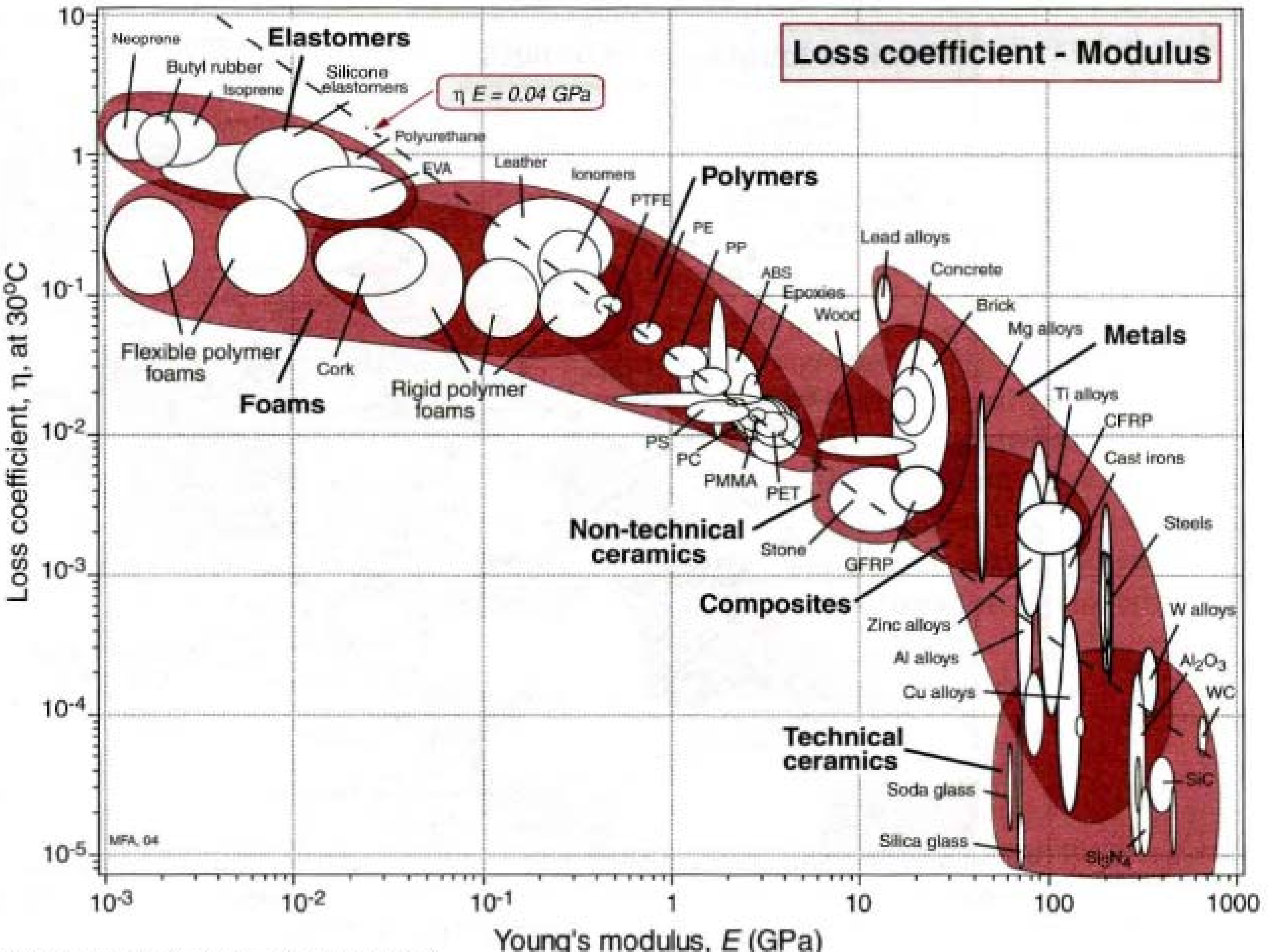

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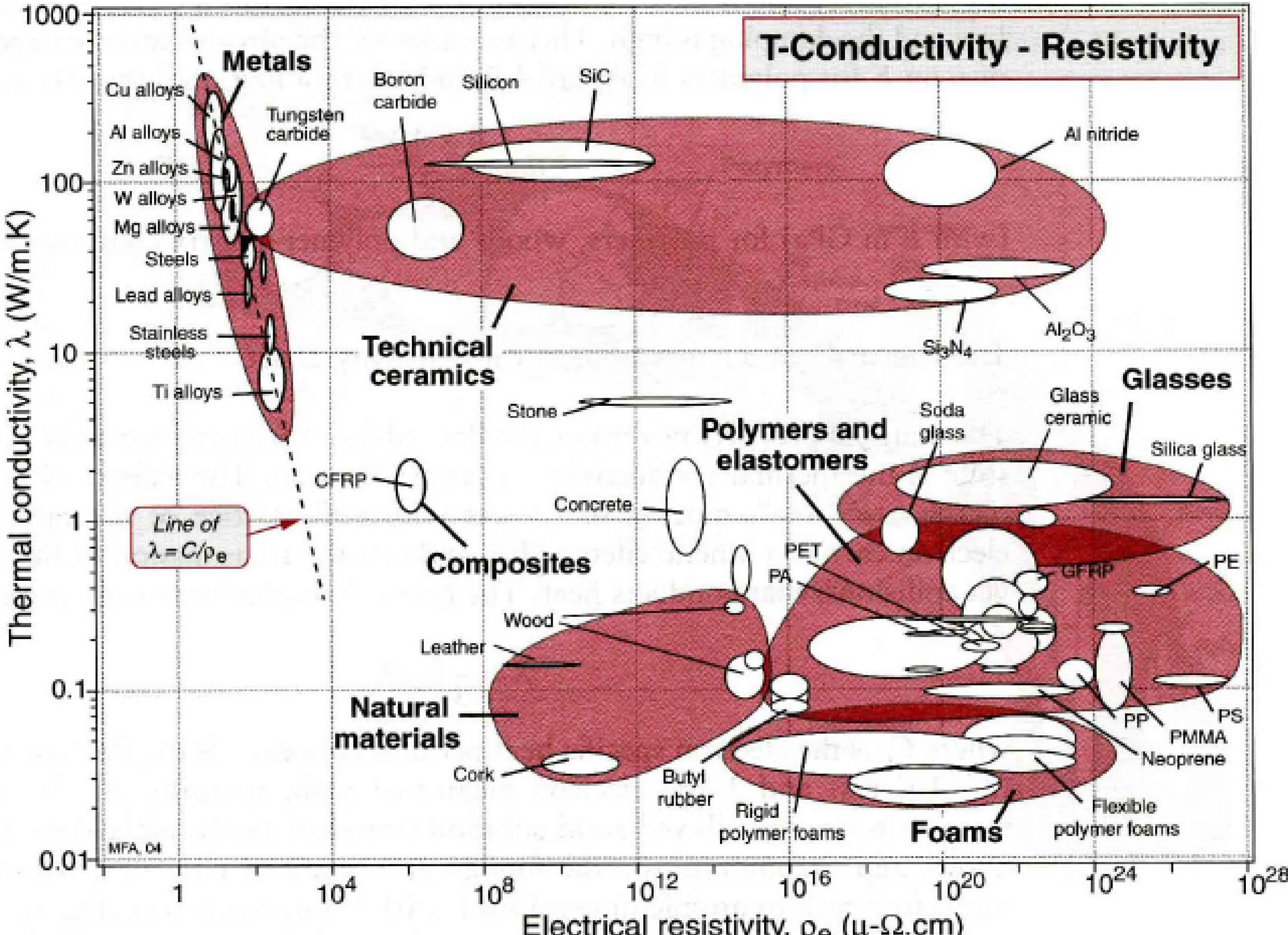

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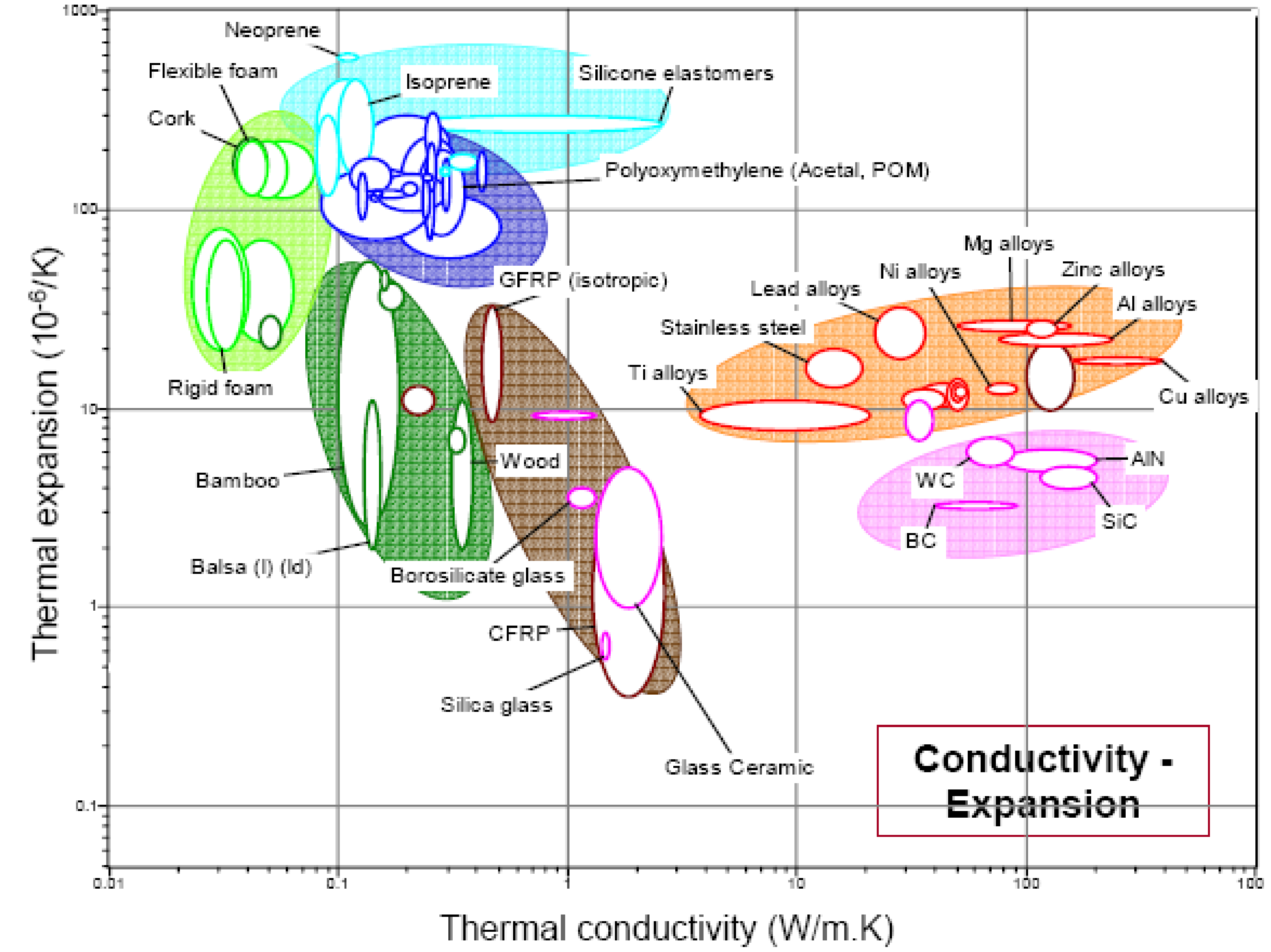
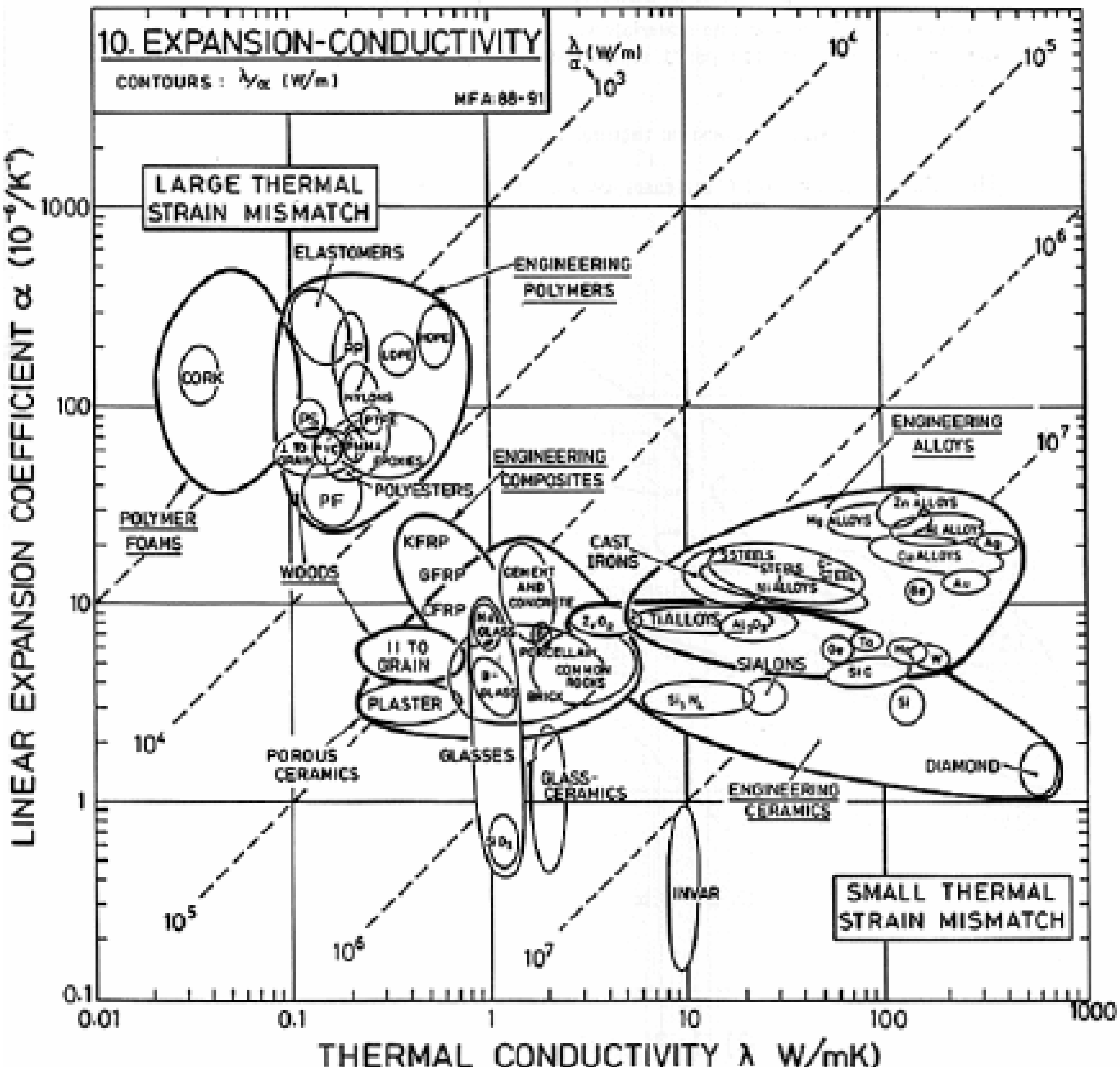
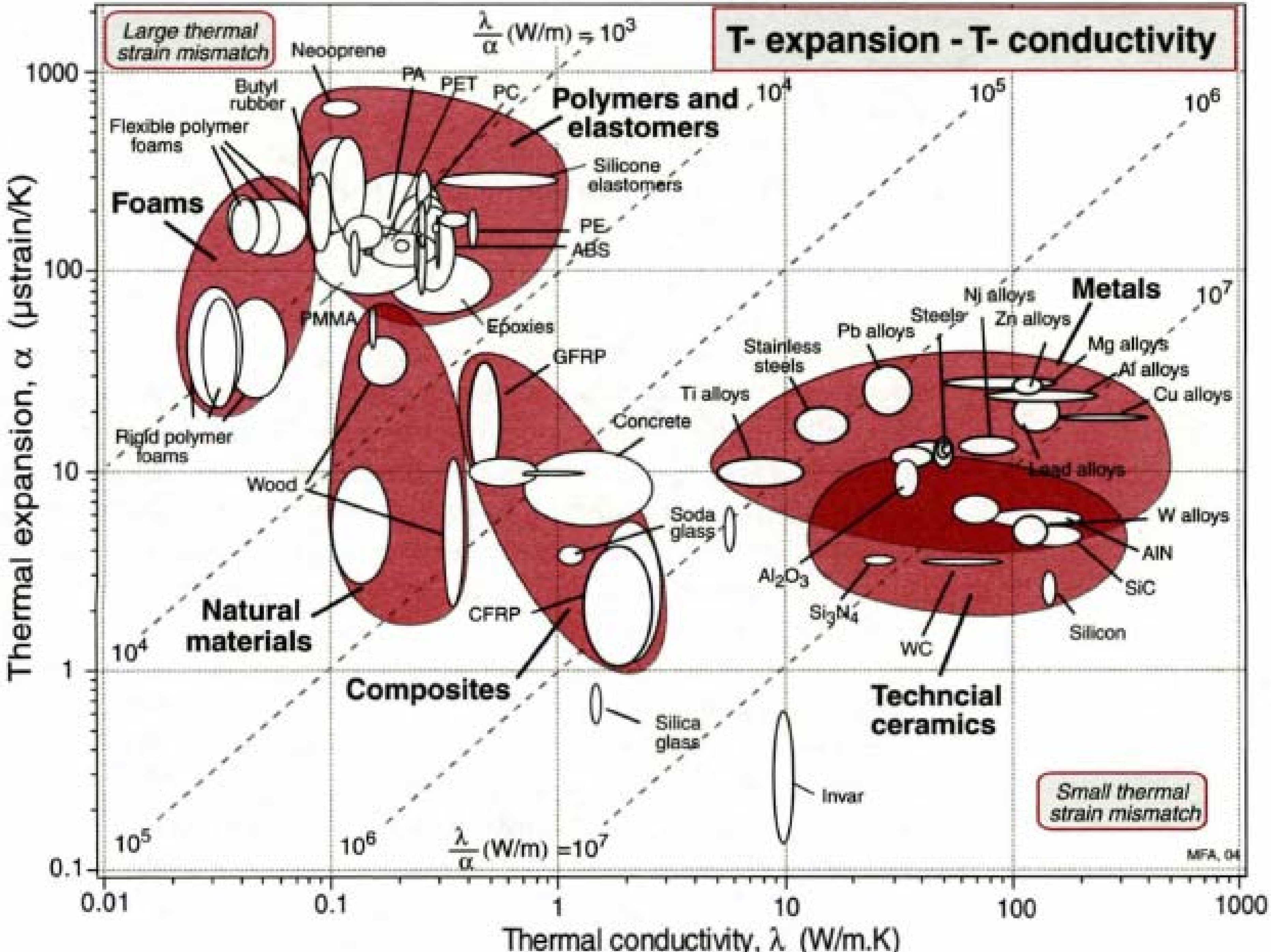


Neoprene
Flexible foam
Isoprene
Silicone elastomers
Cork
Polyoxymethylene (Acetal, POM)
GFRP (isotropic)
Rigid foam
Mg alloys
Ni alloys
Zinc alloys
Lead alloys
Al alloys
Stainless steel
Ti alloys
Cu alloys
Wood
Bamboo
AlN
WC
SiC
BC
Balsa (l) (ld)
Borosilicate glass
CFRP
Silica glass
Glass Ceramic
Conductivity - Expansion
Thermal expansion (10^{-6}/K)
Thermal conductivity (W/m.K)
1000
100
10
1
0.1
0.01
0.1
1
10
100
1000



10. EXPANSION-CONDUCTIVITY
CONTOURS : λ/α (W/m)
MFA:88-91
LARGE THERMAL STRAIN MISMATCH
SMALL THERMAL STRAIN MISMATCH
ELASTOMERS
ENGINEERING POLYMERS
ENGINEERING COMPOSITES
ENGINEERING ALLOYS
ENGINEERING CERAMICS
POLYMER FOAMS
CORK
PP
LDPE
HDPE
NYLONS
PS
PTFE
PVC
PMMA
EPOXIES
POLYESTERS
PF
WOODS
KFRP
GFRP
CFRP
CEMENT AND CONCRETE
PORCELAIN
COMMON ROCKS
BRICK
PLASTER
POROUS CERAMICS
GLASSES
GLASS-CERAMICS
CAST IRONS
STEELS
Ni ALLOYS
Ti ALLOYS
Mg ALLOYS
Zn ALLOYS
Cu ALLOYS
Al ALLOYS
SIALONS
SiC
Si
DIAMOND
INVAR
LINEAR EXPANSION COEFFICIENT α (10^{-6}/K)
THERMAL CONDUCTIVITY λ W/mK)
0.01
0.1
1
10
100
1000
10^3
10^4
10^5
10^6
10^7



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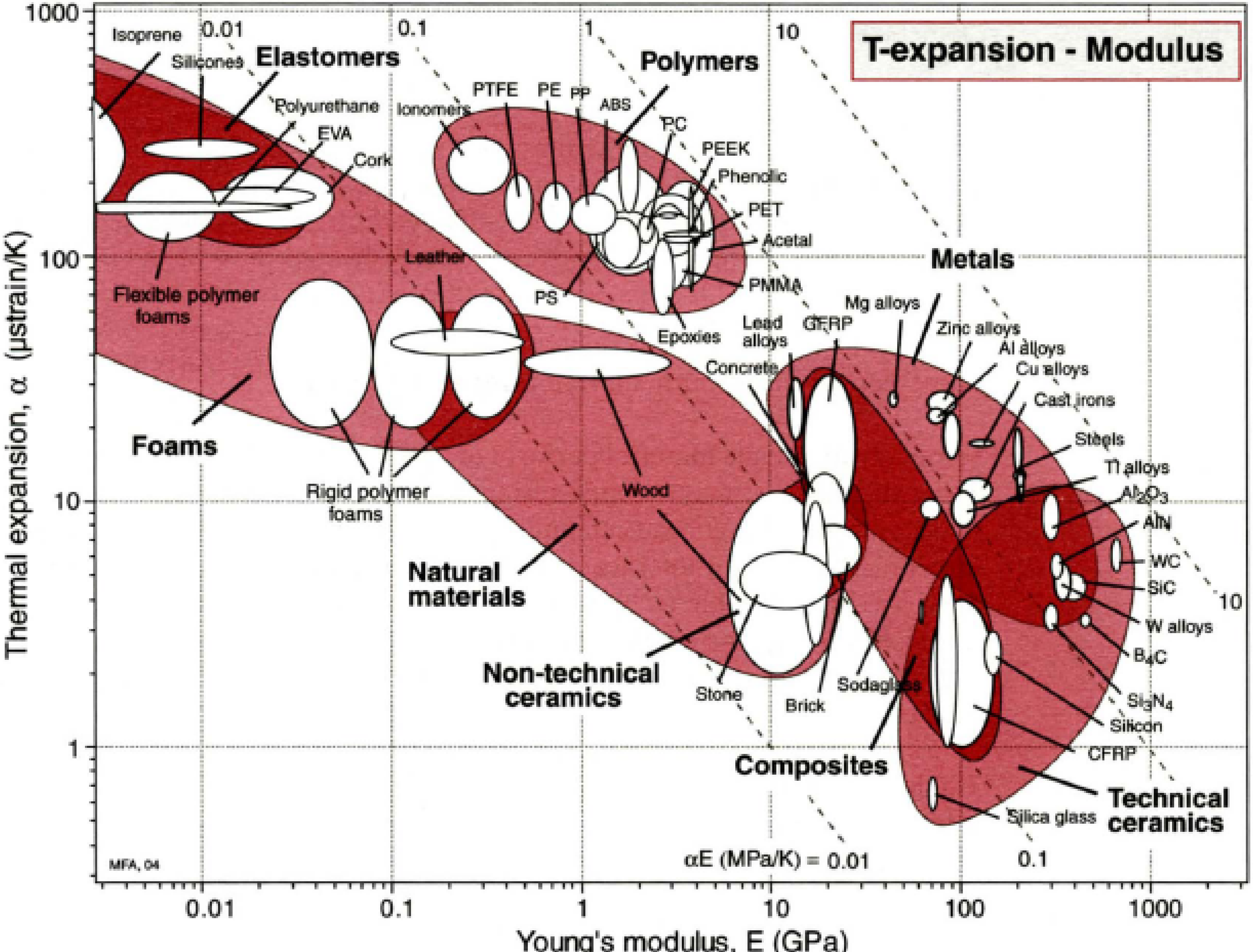

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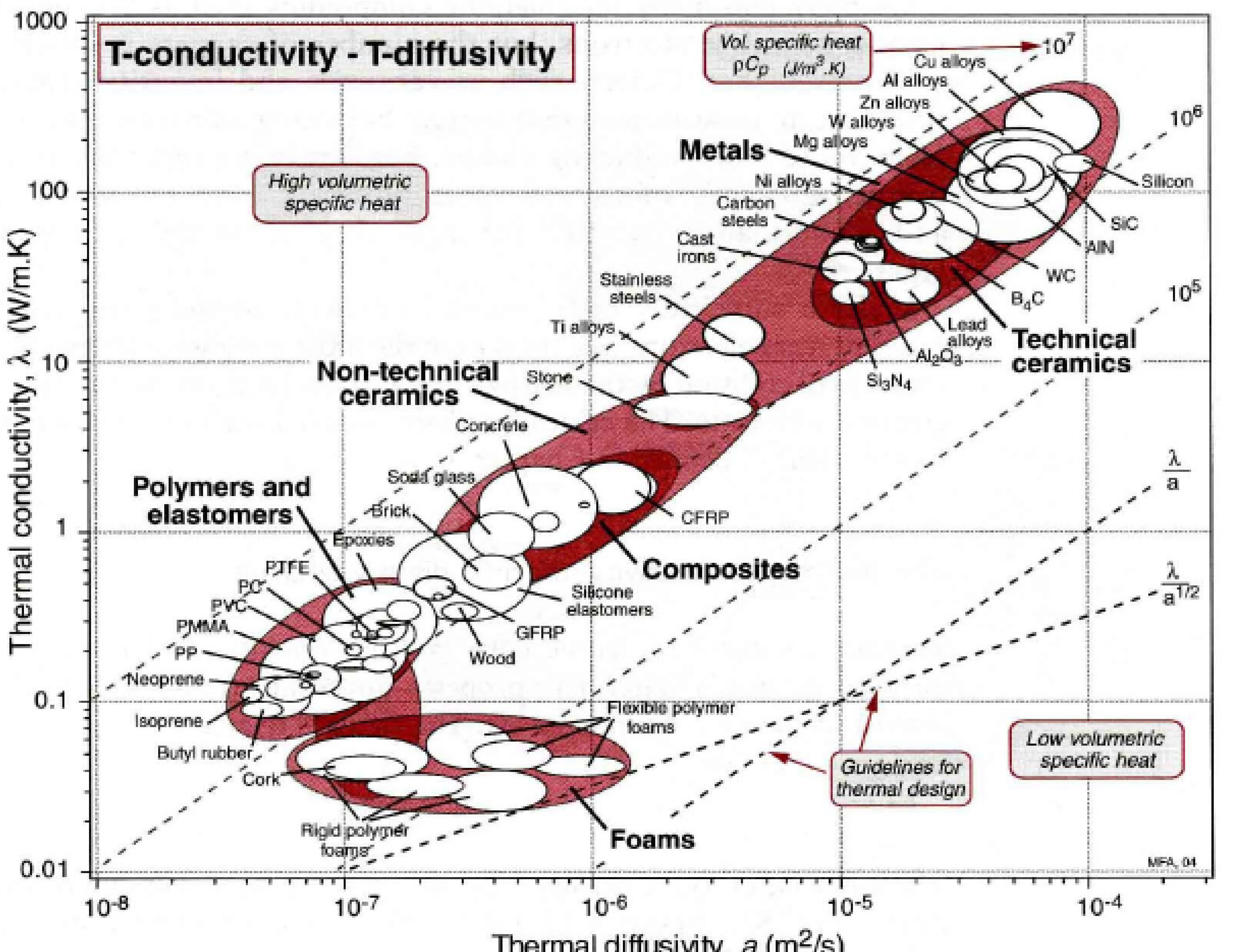

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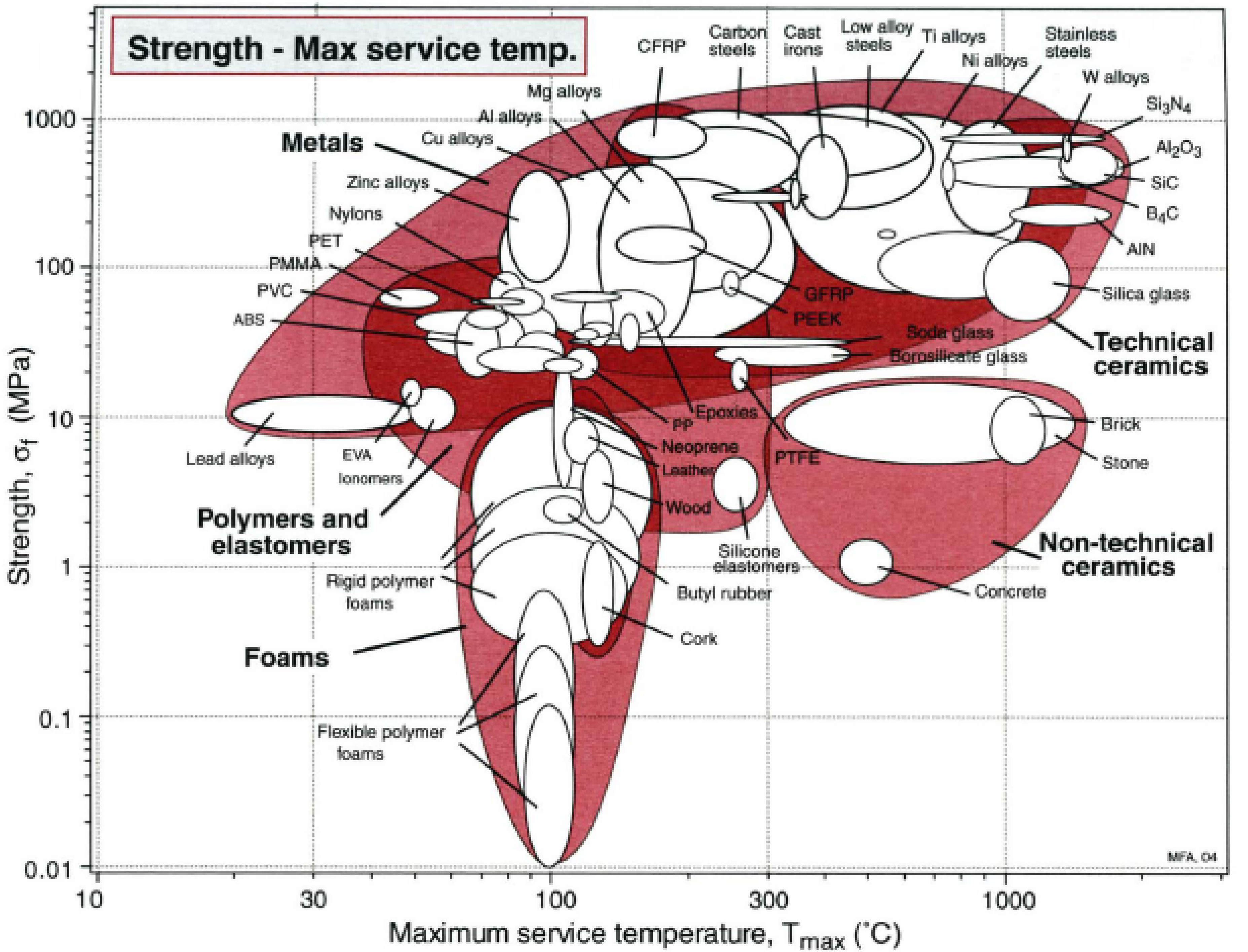

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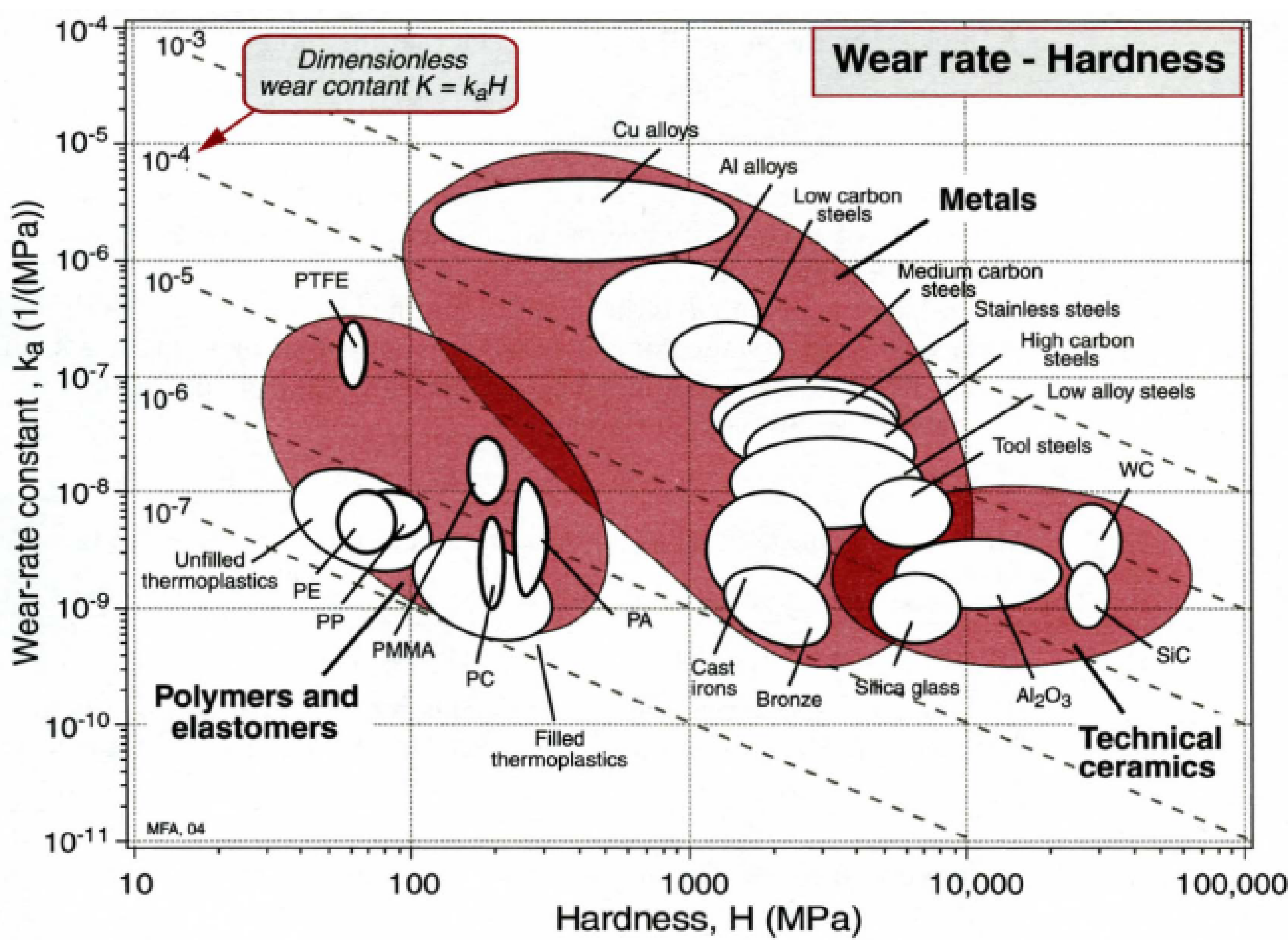

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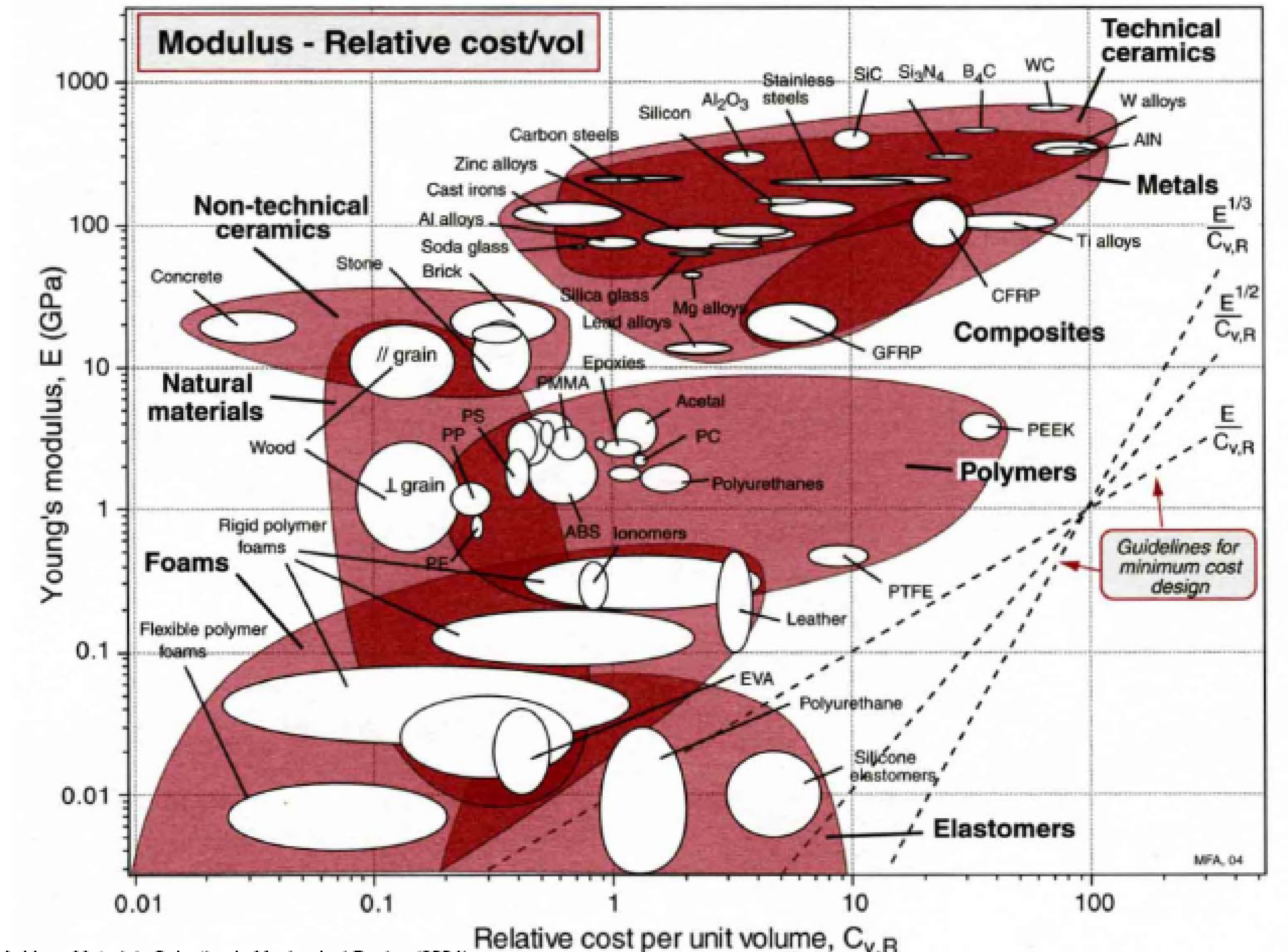

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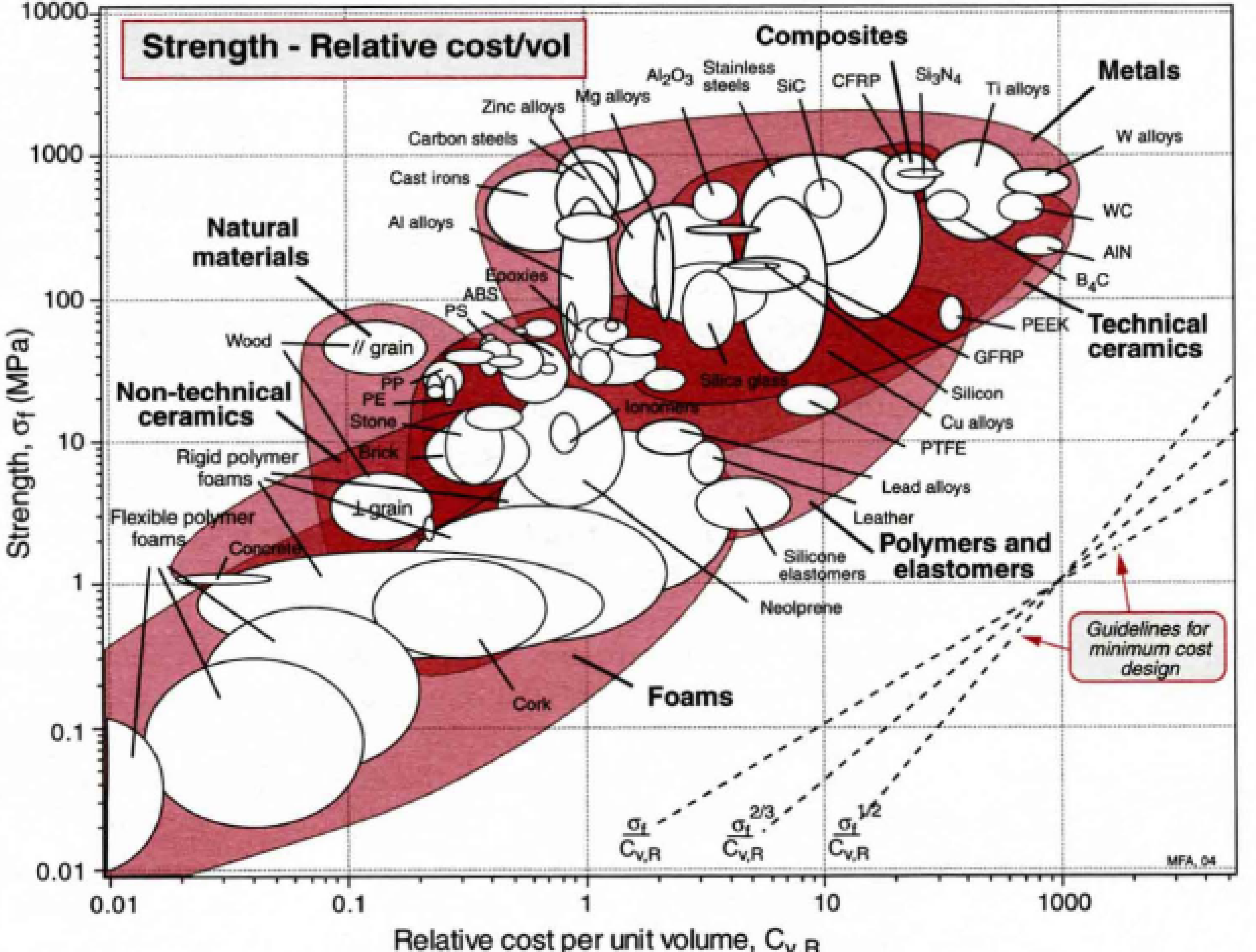
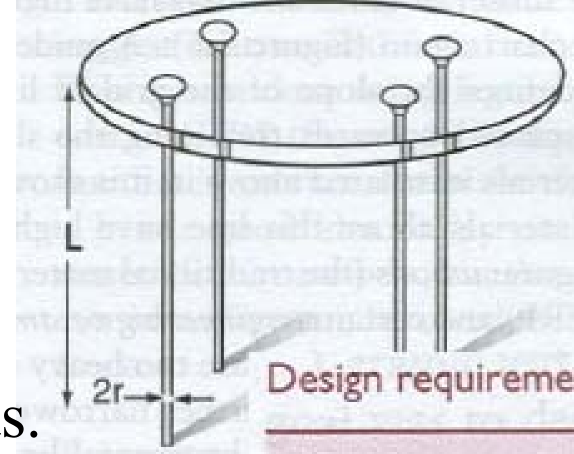


Ashby – Materials Selection in Mechanical Design (2004)

Case 1: Materials for Table legs



Design a slender, light table legs that will support the applied design load and will not fracture if struck.

Function Column, supporting compressive loads.

Objective Minimize mass and maximize slenderness

Constraints Specified length, Must not buckle Must not fracture if struck

Free Variables Diameter of the legs Choice of materials

mass: $$m = \pi r^2 L \rho \qquad (1)$$

Maximum elastic buckling load:

$$F_{crit} = \frac{\pi^2 E I}{L^2} = \frac{\pi^3 E r^4}{4L^2} \quad where \quad I = \frac{\pi r^4}{4} \qquad (2)$$

Solving for ***r***

$$m \geq \left(\frac{4F}{\pi}\right)^{1/2} L^2 \left(\frac{\rho}{E^{1/2}}\right) \qquad (3)$$

The weight is minimized by selecting materials with the greatest value of the materials index:

$$M_1 = \left(\frac{E^{1/2}}{\rho}\right) \qquad (4)$$

Inverting equation (2) gives and equation for the thinnest legs which will not buckle:

$$r \geq \left(\frac{4F}{\pi^3}\right)^{1/4} L^{1/2} \left(\frac{1}{E}\right)^{1/4} \quad (5)$$

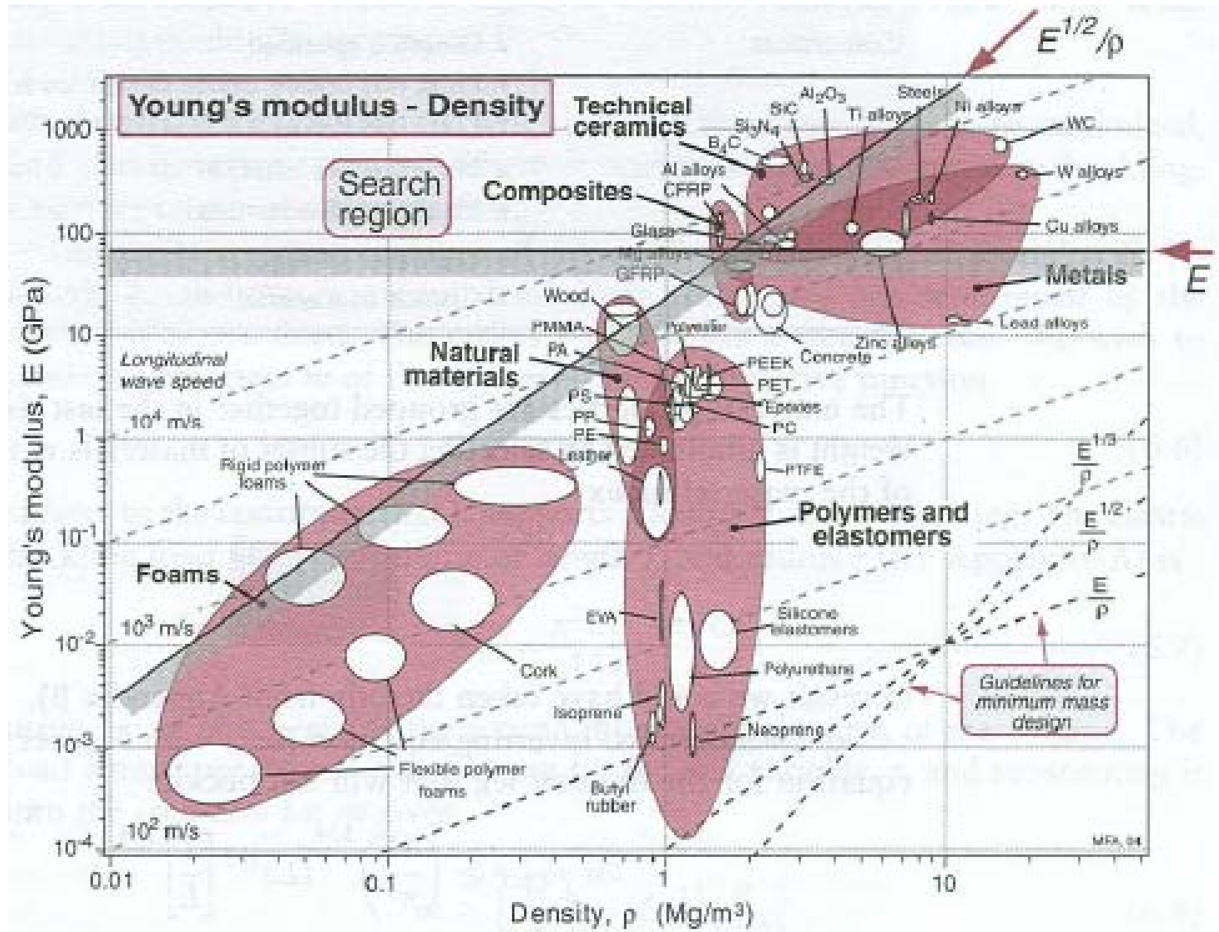
to yield the second materials index (maximize): $M_2 = E$ (6)

Set M_1 to be minimum of 5 and M_2 to be greater than 100 (an arbitrary choice –it can be modified later if a wider choice of materials to be screened is desired). Candidate materials include some ceramics, CFRP

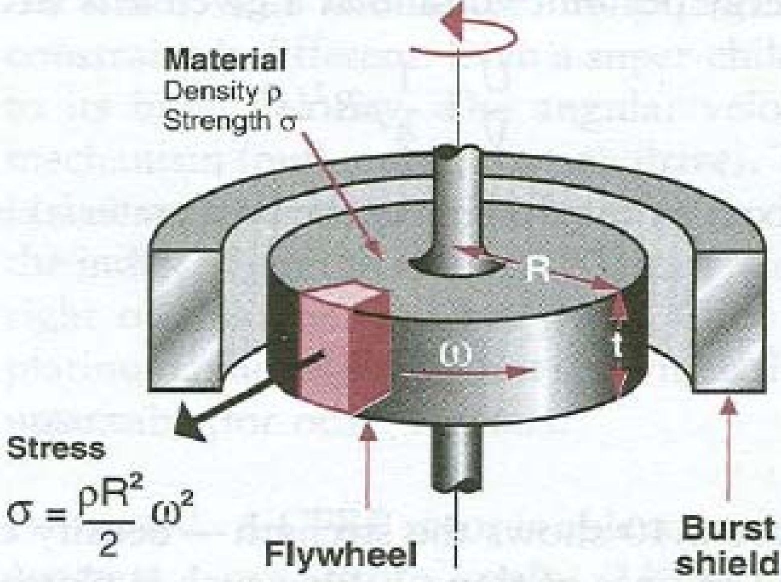
•engineering ceramics are not tough –legs are subjected to abuse and this makes them a bad selection for this application

Selection = CFRP

must consult designer wrt cost -expensive



Case 2: Materials for Flywheels



Flywheels are rotating devices that store rotational energy in applications such as automotive transmissions. An efficient flywheel stores maximum energy per unit volume/mass at a specified angular velocity.

The kinetic energy the device can ~~the device can store is limited~~ store is limited by the material by the material strength.

Function	Flywheel for energy storage.
Objective	Maximize kinetic energy per unit mass.

Mass of the disc $m = \pi R^2 t \rho$

Kinetic energy (***J*** is the mass moment of inertia) $KE = \frac{1}{2} J w^2$

For a solid round disc ***J*** around its rotation axis $J = \frac{1}{2} m R^2$ $KE = \frac{1}{4} m R^2 w^2$

The quantity to be maximized is the energy per unit mass

$$\frac{KE}{m} = \frac{1}{4} R^2 w^2$$

Constraints

The outer radius is fixed.
It must not burst.
It must have adequate toughness (crack tolerance)

Free Variables

Choice of materials

The maximum radial stress (principal stress) is given by the equation:

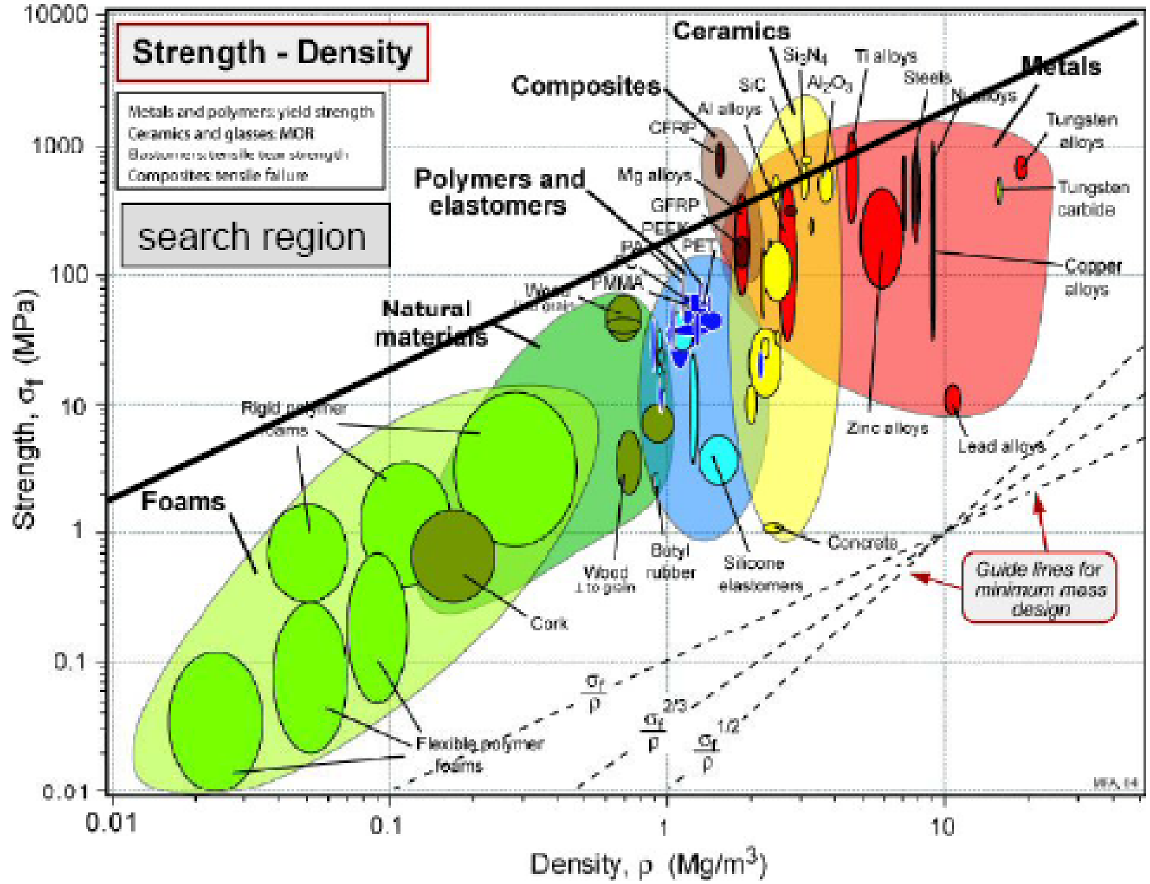
$$\sigma_{r,Max} = \frac{3+\upsilon}{8} \rho \omega^2 R^2 \cong \frac{\rho \omega^2 R^2}{2}$$

The stress must not exceed the yield stress:

$$\frac{KE}{m} = \frac{1}{2}\left(\frac{\sigma_y}{\rho}\right)$$

Hence, the material index to maximize is:

$$M = \frac{\sigma_y}{\rho}$$



$$M = \frac{\sigma_f}{\rho}$$

Ashby – Materials Selection in Mechanical Design (2004)

The choices are some composites (CFRP), some engineering ceramics and high strength Ti and Al alloys

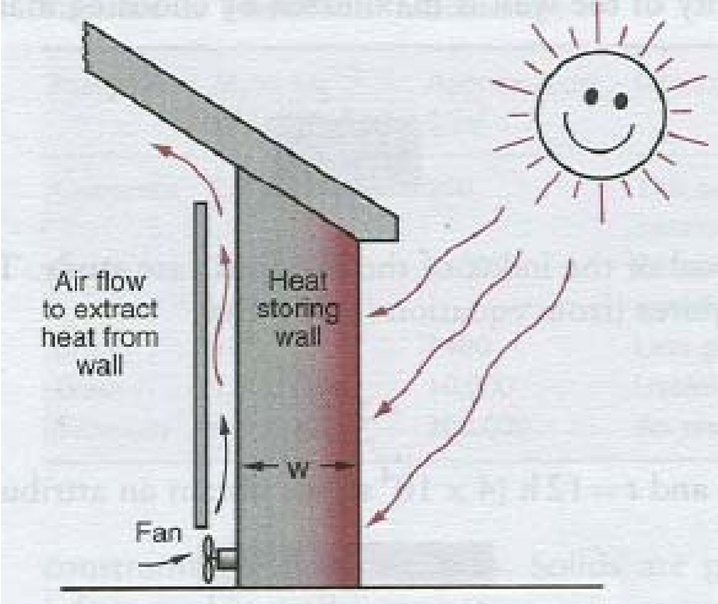
•engineering ceramics eliminated due to lack of toughness

•further selection must be made on the basis of cost and energy storage capacity for specific materials

–e.g. CFRP can store 400kJ/kg

Case 3: Materials for Passive Solar Heating

A simple way of storing solar energy for residential heating is by heating the walls during the day and transferring heat to the interior via forced convection at night. Need to diffuse heat from the outer to inner surface in 12h. For architectural reasons, the wall thickness (W) cannot exceed 0.5m



Function	Heat storage medium
Objective	Maximize thermal energy storage per unit material cost.
Constraints	Heat diffusion time through wall time (t) ~12h Wall thickness w<0.5m Working temperature $T_{Max} \sim 100^oC$
Free Variables	Wall thickness w. Choice of materials

What material will maximize the thermal energy captured by the wall while retaining the required heat diffusion time of up to 12h?

For a wall of thickness ***w***, the heat (***Q***) per unit area of wall heated through ***ΔT*** is given by:

$$Q = w\rho c_p \Delta T$$

For the heat diffusion distance in time ***t***:

$$w = \sqrt{2Dt}$$

where ***D*** is the thermal diffusivity, ***λ*** is the thermal conductivity and ***ρ*** is the density

$$D = \frac{\lambda}{\rho c_p}$$

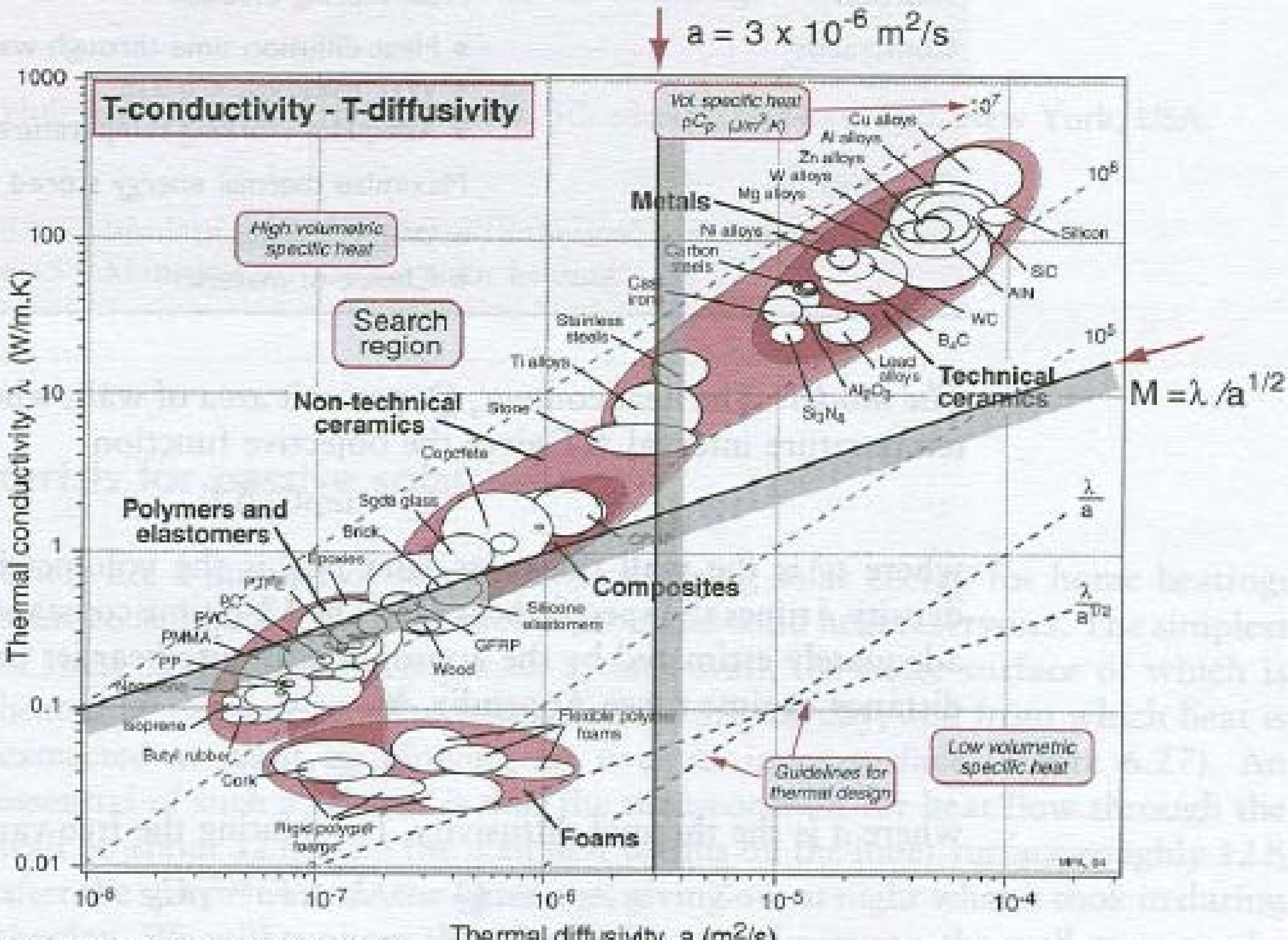
$$Q = \sqrt{2t}\,\rho c_p D^{1/2} \Delta T = \sqrt{2t}\,\Delta T \left(\frac{\lambda}{\sqrt{D}} \right)$$

The heat capacity of the wall is maximized by choosing a material with a high value of:

$$\frac{\lambda}{\sqrt{D}}$$

The restriction on the wall thickness (w) and diffusion time (t) yield the constraint:

$$D \leq \frac{w^2}{2t} \leq 3 \times 10^{-6}\, m^2/s$$



ls Selection in Mechanical Design (2004)

Materials for passive solar heat-storage

Ashby – Materials Selection in Mechanical Design (2004)

Material	$M_1 = \lambda/a^{1/2}$ $(W.s^{1/2}/m^2.K)$	Approx. cost $\$/m^3$	Comment
Concrete	2.2×10^3	200	The best choice—good performance at minimum cost
Stone	3.5×10^3	1400	Better performance than concrete because specific heat is greater, but more expensive
Brick	10^3	1400	Less good than concrete
Glass	1.6×10^3	10,000	Useful—part of the wall could be glass
Titanium	4.6×10^3	200,000	An unexpected, but valid, selection. Expensive

Cost must be a significant consideration in this selection because the application is for housing, where cost is always a significant factor. Taking cost into consideration, the most likely choice is concrete, with stone and brick as alternatives.

Literature Resources

M.F. Ashby, “Materials Selection in Mechanical Design, 2ndEd.”

- multiple sources listed in appendices of the book
- materials selection charts in lecture Appendix

Other references :

- ASM Metals Handbook
- Perry’s Chemical Engineering Handbook
- CRC Handbook of Mathematics and Physics
- ASM Handbook of Ceramics and Composites