TECHNISCHE UNIVERSITÄT DRESDEN

DRESDEN concept

Dr.-Ing. Sascha Heitkam,

Insitute for Process Engineering and Environmental Technology

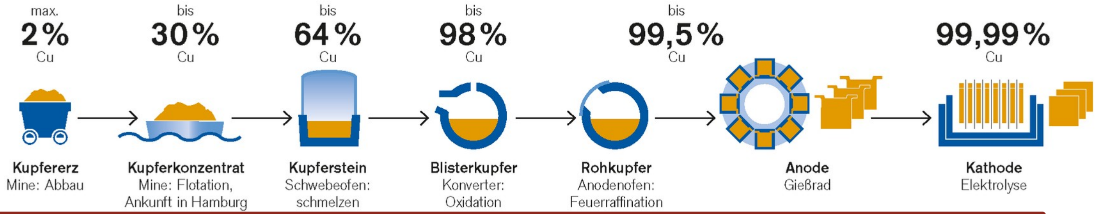
Lecture 12: Solid foam

Structure

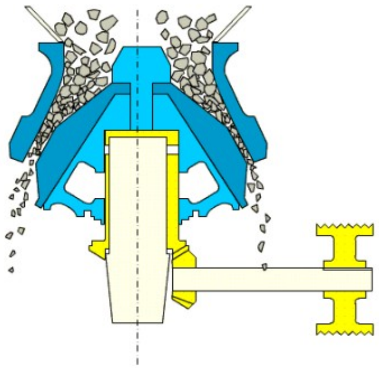
- Review lecture 11
- Solid foam production
- Solid foam mechanics
- Solid foam application

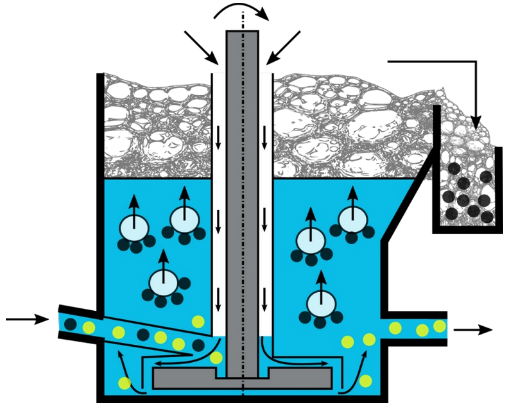
- Exam preparation
- Evaluation

From ore to copper

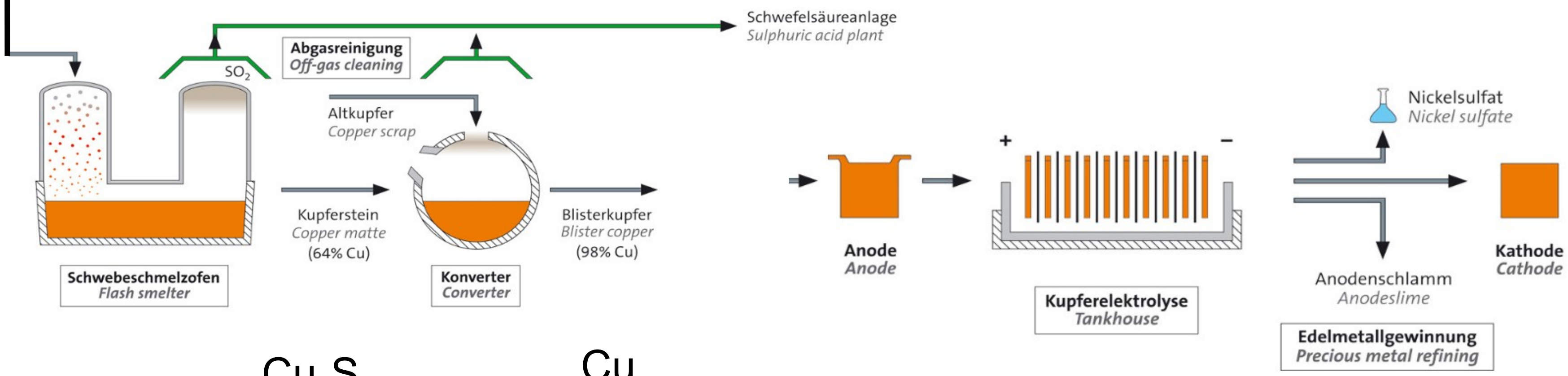


$CuFeS_2$





$CuFeS_2$

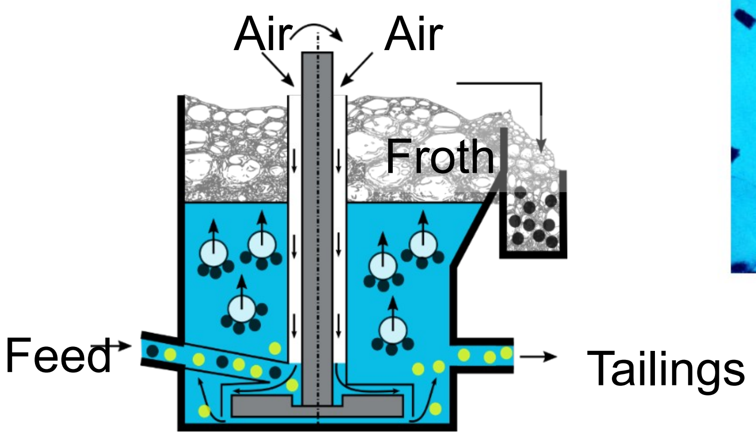


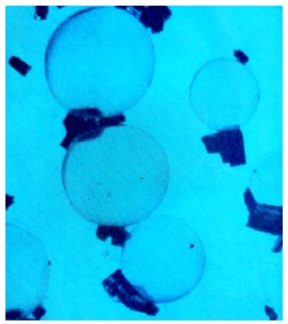
Cu_2S

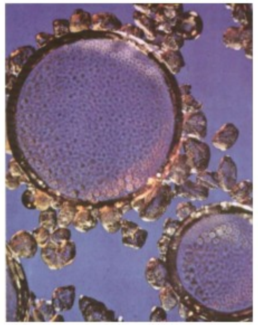
Cu

Froth flotation

- Grinded particles added to surfactant solution
- Collectors (surfactants) render mineral particles hydrophobic, suppressors render gangue hydrophilic
- Bubbles are introduced, pick up particles, transport to top
- Frothers (surfactants) cause generation of meta-stable froth zone
- Overflowing froth extracts particles

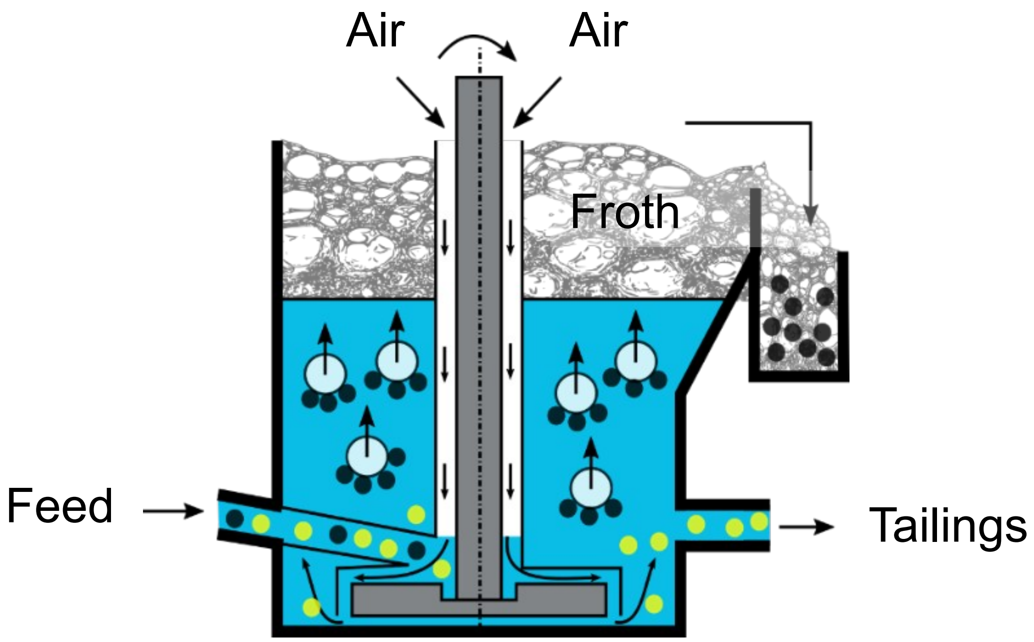


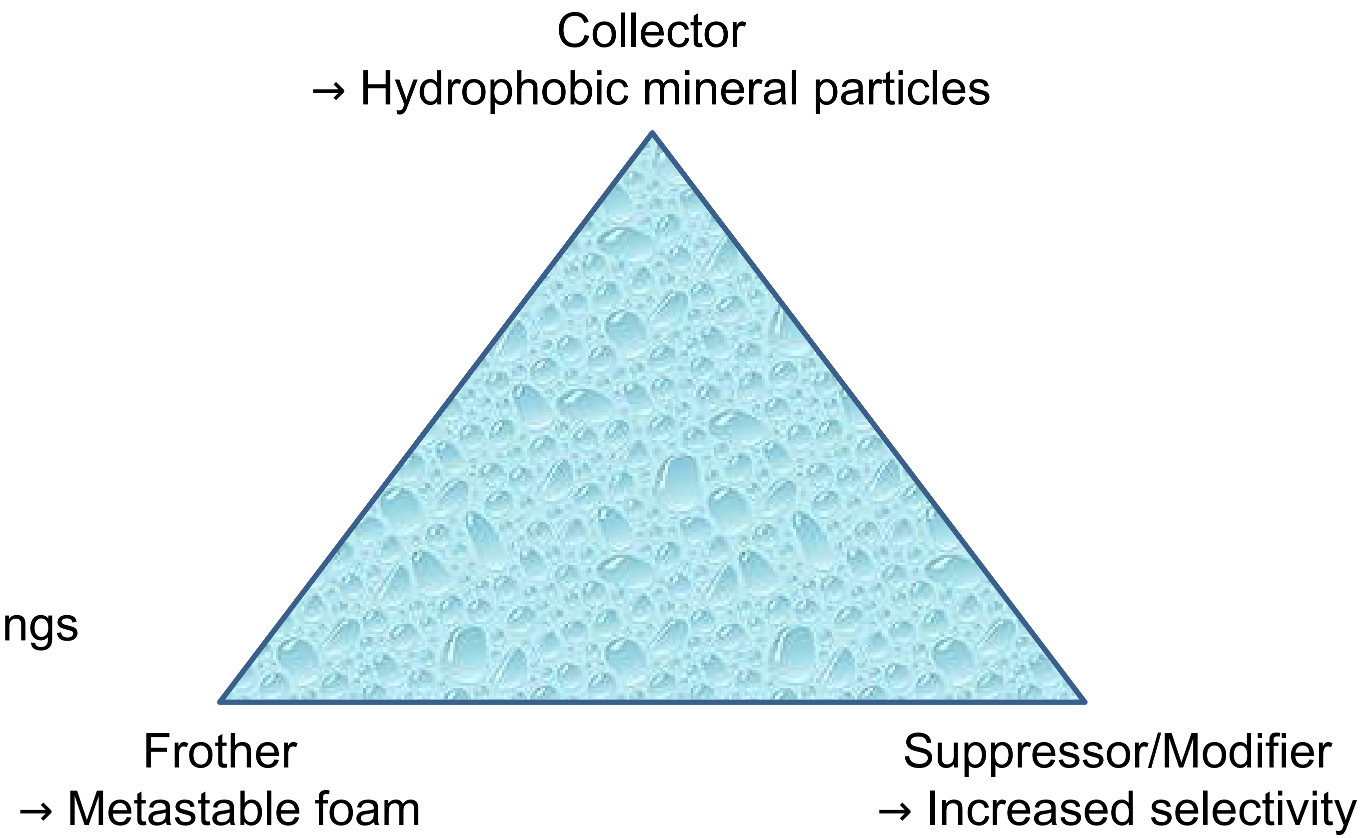




Types of surfactants

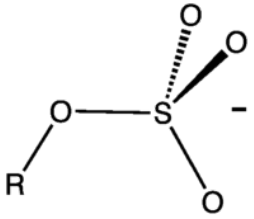
- Important branch of chemical industry
- Purposely designed molecules for different classes of ores/minerals



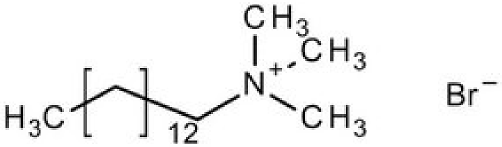


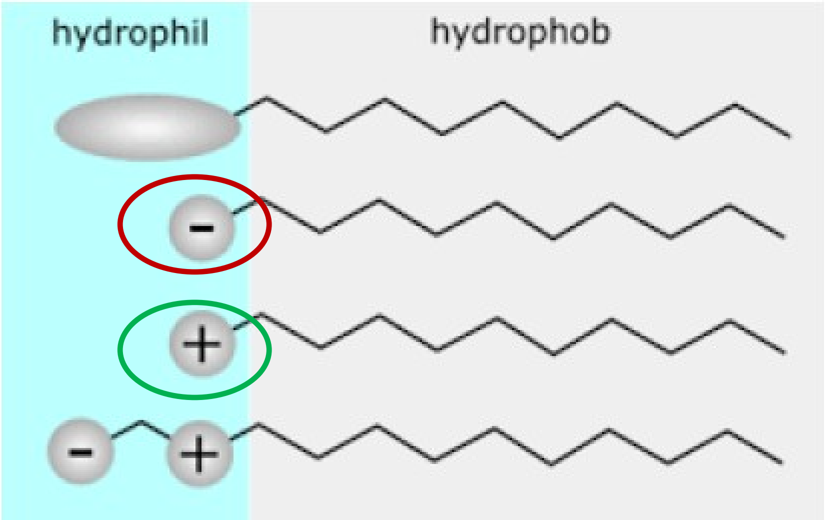
Collector

- Ionic surfactants
- Typical anionic surfactants: organosulfates (e.g. SDS)

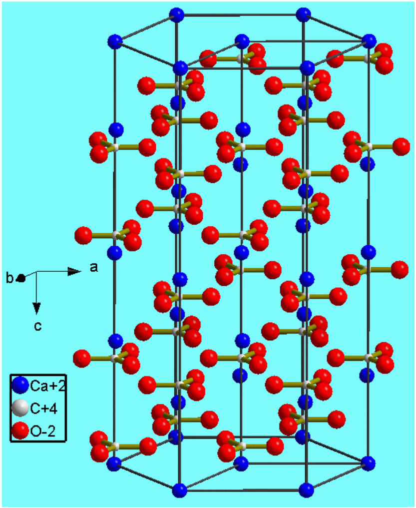


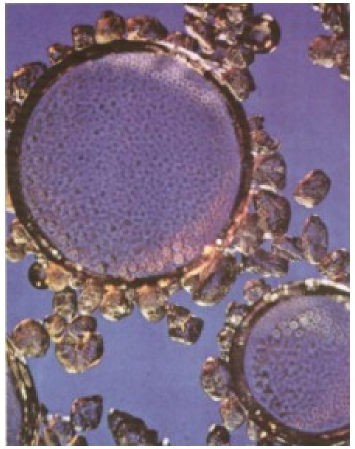
- Typical cationic surfactants: quaternary ammonium cations (e.g. TTAB)





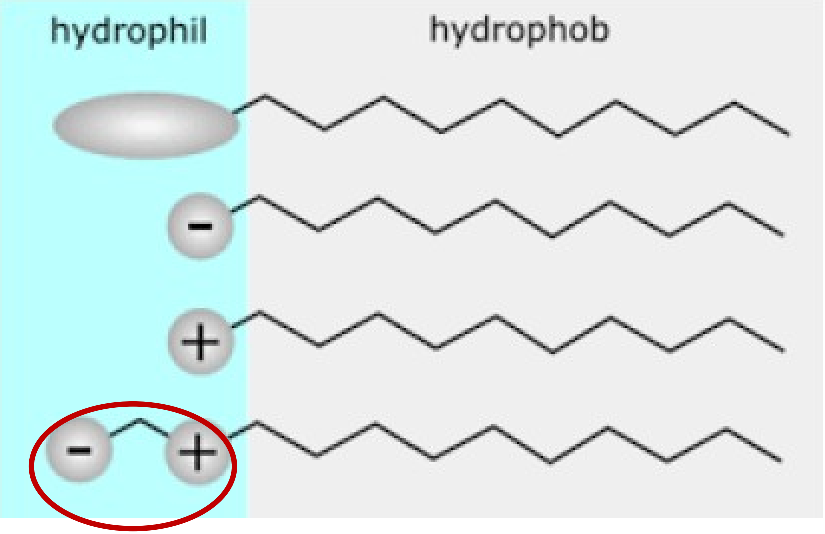
- Optimum at $C_{12}...C_{14}$
- Compromise between solubility (few C-atoms) and surface activity (many C-atoms)
- Particles are conditioned before entering the flotation cell

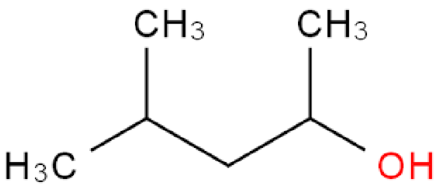


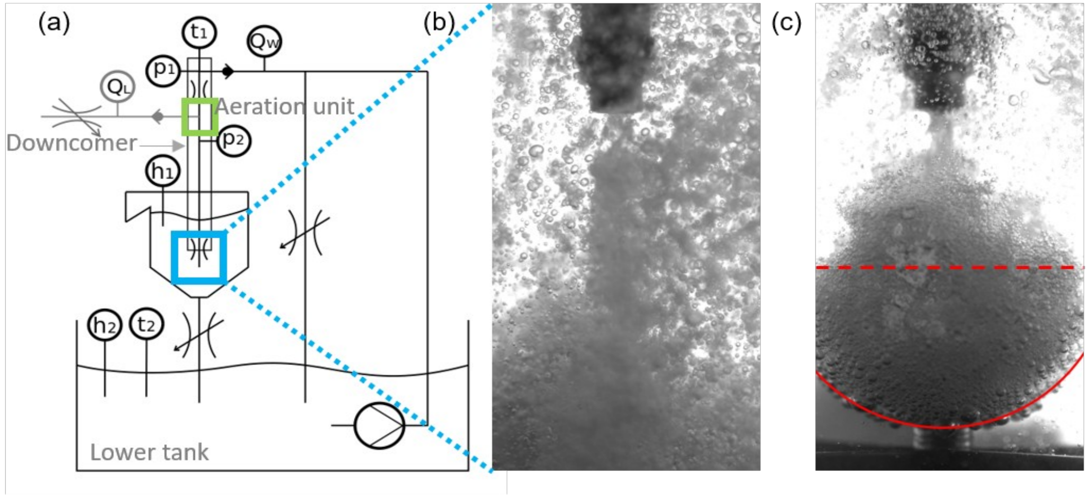


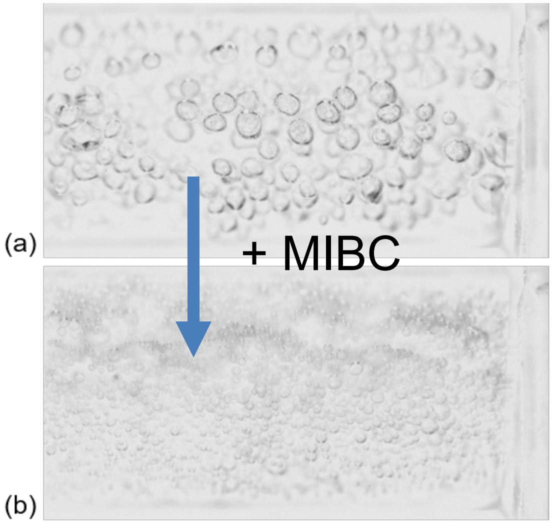
Frother

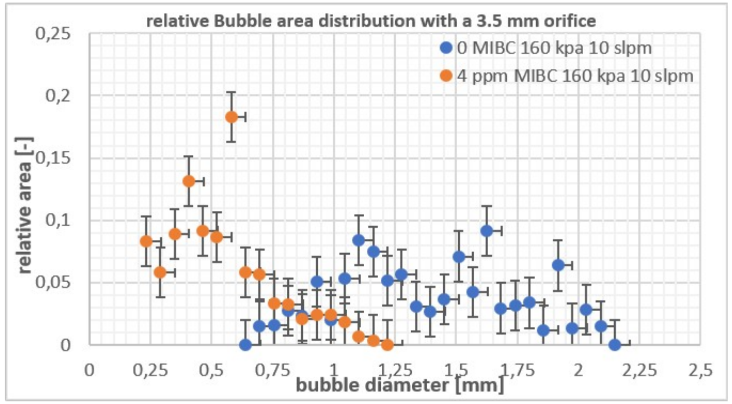
- Typical frother: methyl isobutyl carbinol - MIBC
- Hydroxy-group is polar, but not charged (=hydrophilic)
- Molecule is unpolar, otherwise (= hydrophobic)
- → generates small bubbles
- → generates meta-stable froth







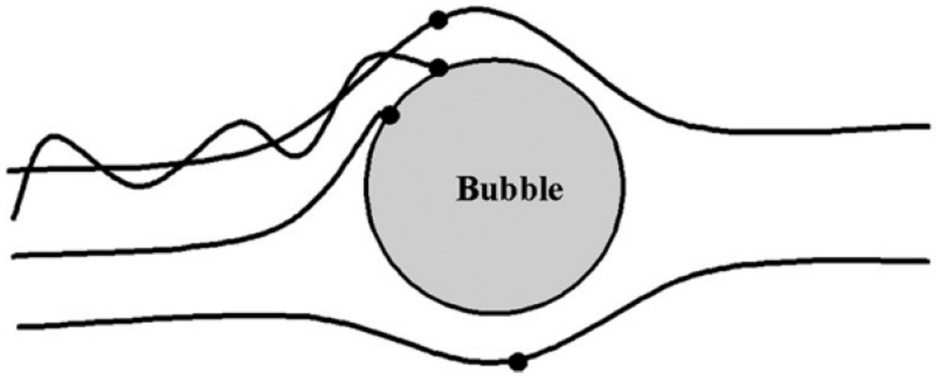


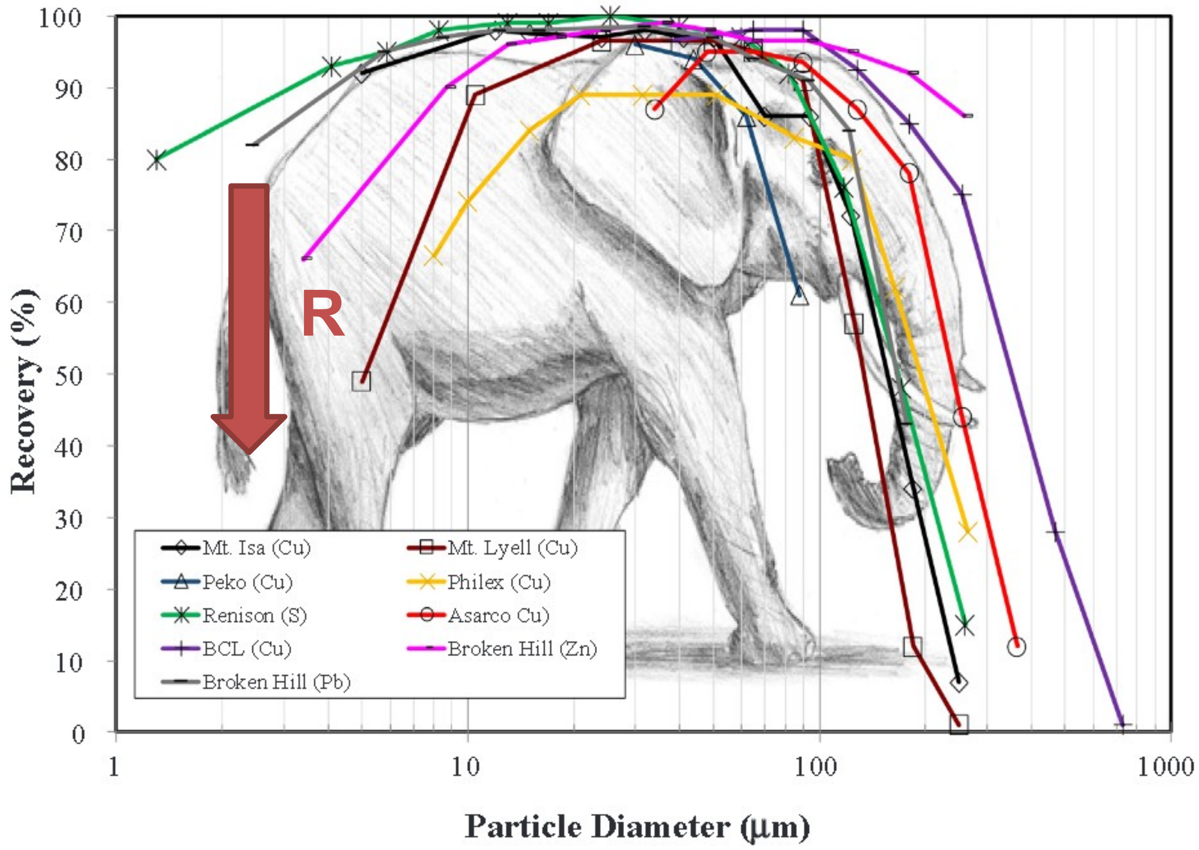


(c)

Fine particle flotation

- Fine particles: d < 20 μm
- nearly inertialess
- low Stokes number
- following of fluid streamlines
- low collision probability



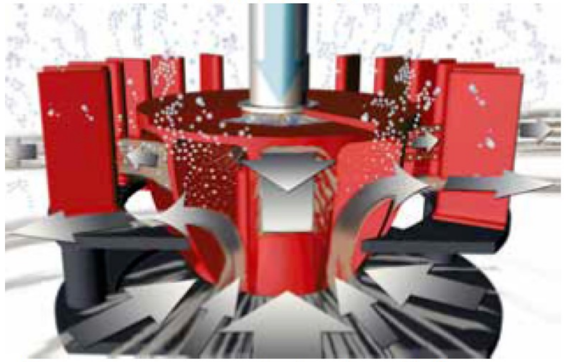


$$St = \frac{\tau_p}{\tau_f} \qquad \tau_p = \frac{4\rho_p d_p^2}{3\mu_f C_D Re_p}$$

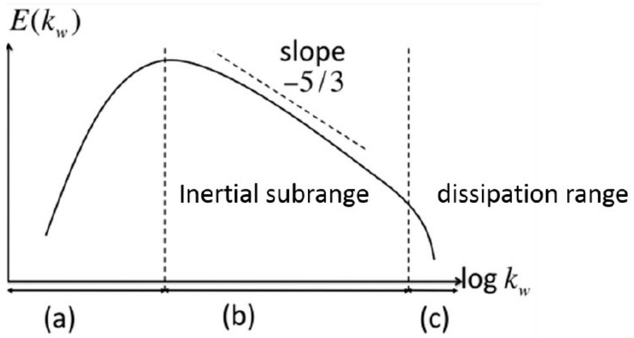
Long range hydrodynamics

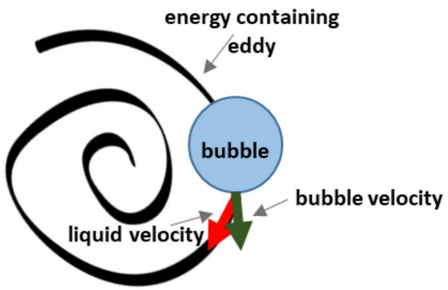
- Controlled by relative velocity between particle and bubble
- Depends on local turbulence
  - Turbulent kinetic energy, spectrum, dissipation

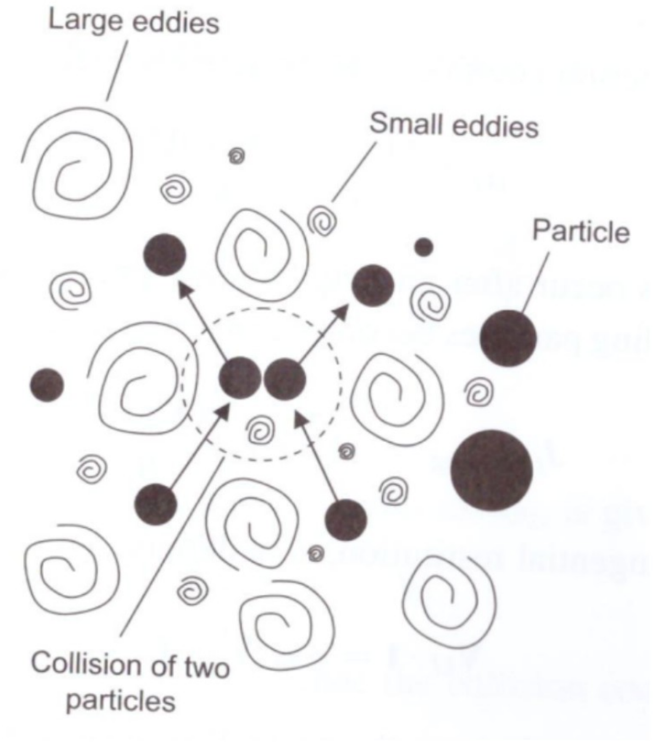
- Classification into two eddy sizes:
- I) Eddy > bubble
  - → influences bubble movement
- II) Eddy < bubble
  - → influences movement of particles near bubbl



Rotor stator unit in detail (Outotec Flotation technologies)







Yeoh et al.

Processes in the froth

- Drainage, liquid fraction gradient
- Coalescence (film rupture) due to
  - hydrophobic particles
  - low frother concentrations
  - non-ionic frothers
- Froth life-times of seconds (gas diffusion negligible)
- Coalescence ⇒ particle clustering, particle drop-back

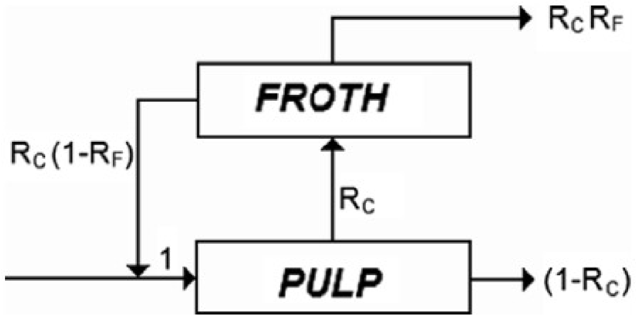
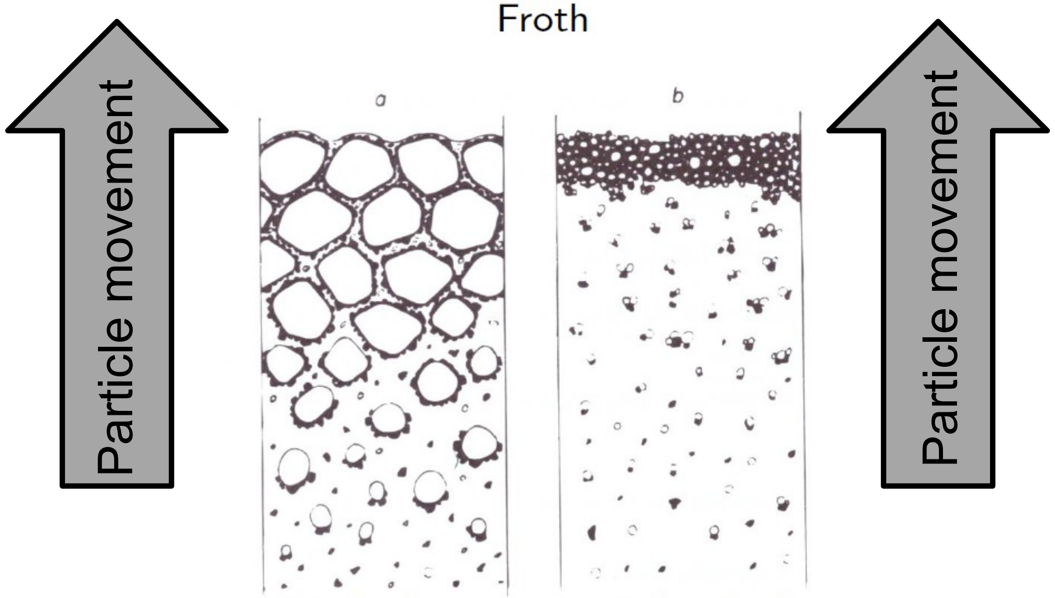


Fig. 2. Pulp and froth recovery model.


Froth



Typical structure of the froth

Different cell designs

- Mechanical flotation cell
  - Rotor-Stator configuration
  - Compressed air

- Pneumatic flotation cell
  - No moving parts
  - Compressed air or self-aspirating

Column flotation

Reactor-Separator flotation cells

Jameson cell

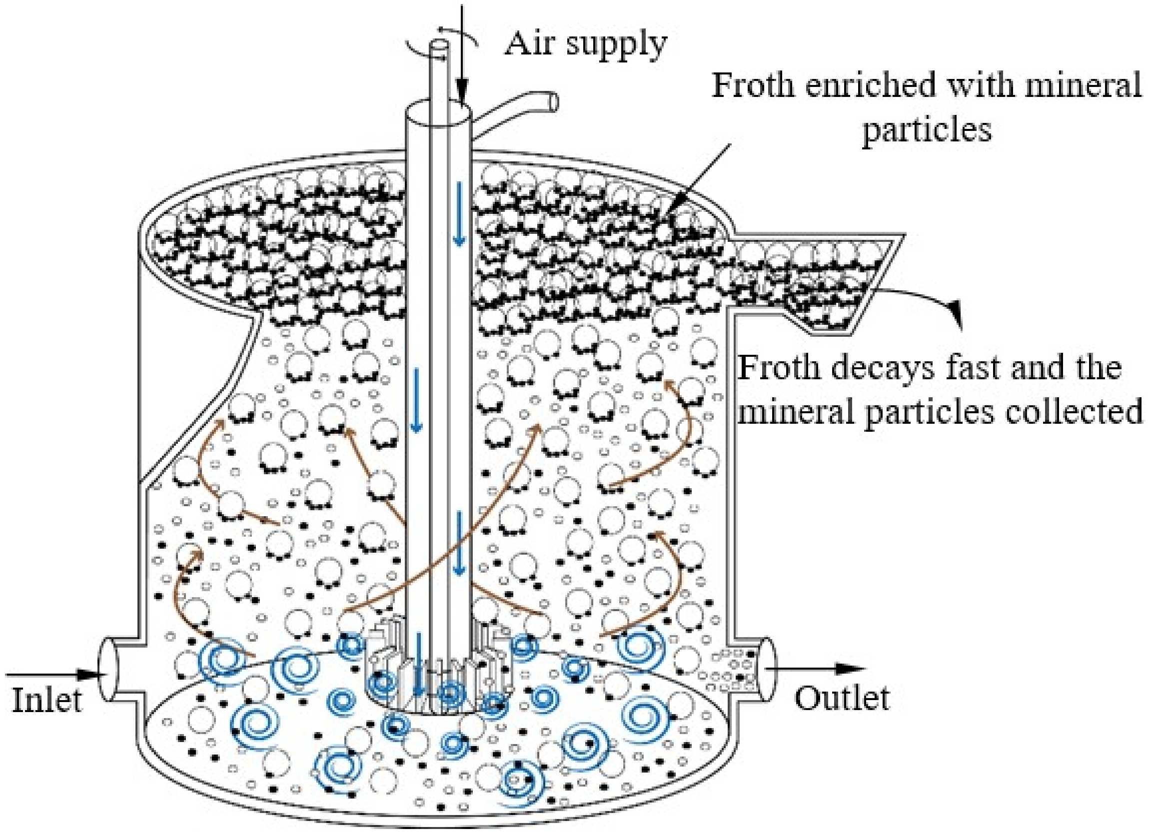
ImhoFlot

Tubular injector cells

→ Paper recycling

Mechanical flotation cell

- "Work horse" of froth flotation



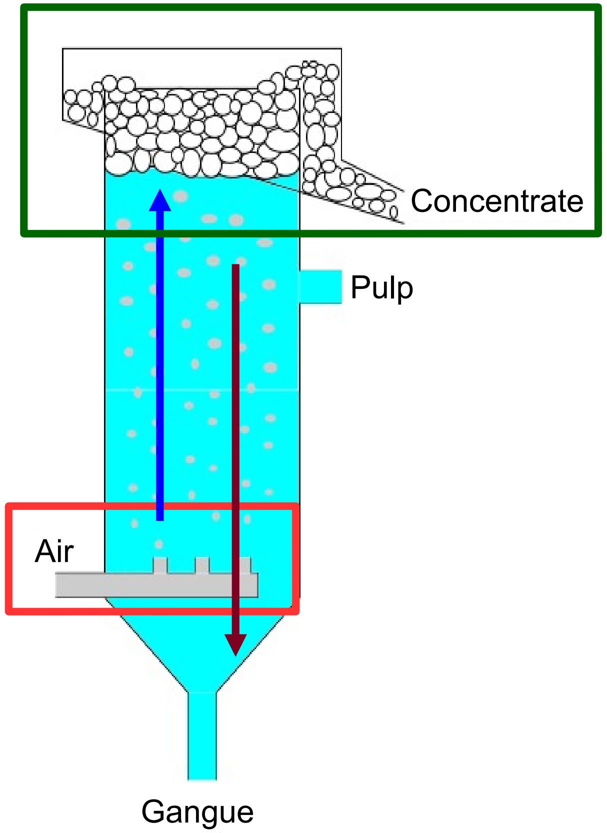
Froth zone

→ Concentrated mineral particles

Pulp zone

→ Bubble-particle clusters

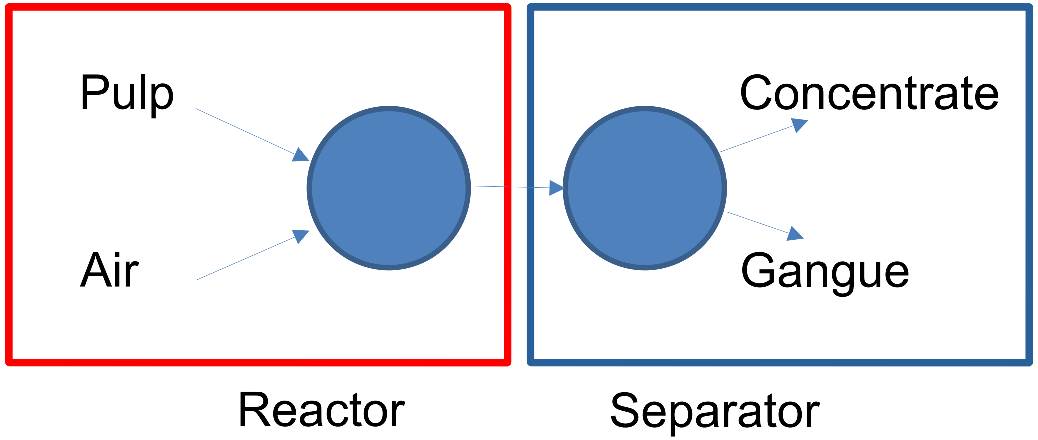
Column flotation



- Low turbulence
- → low recovery rate
- Bubble generator
  → gas flow and bubble size
- Air and pulp in counter-current
  → effective contact
- Deep froth
  → high grade of the extract
  → improved by wash water

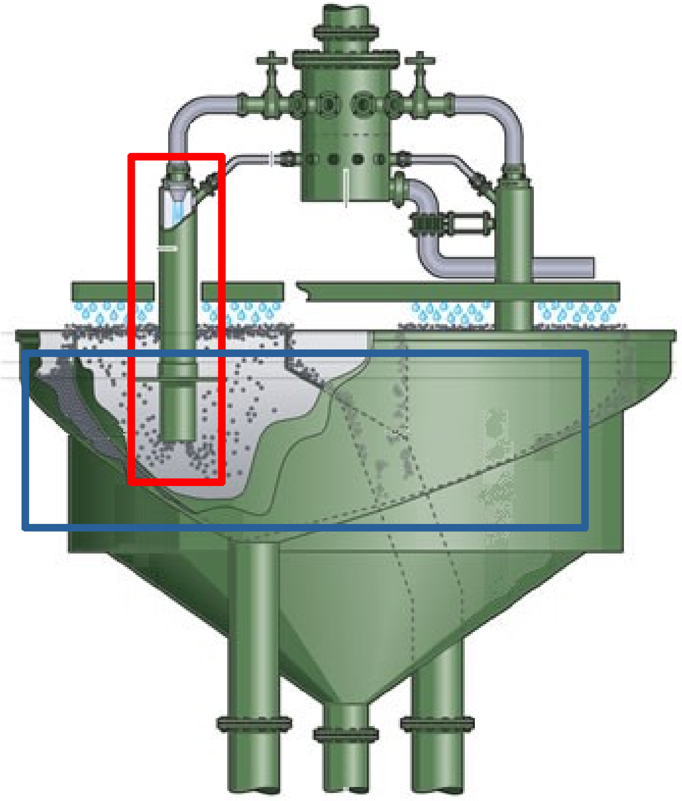
Reactor-separator approach

- Approach for fine particle flotation



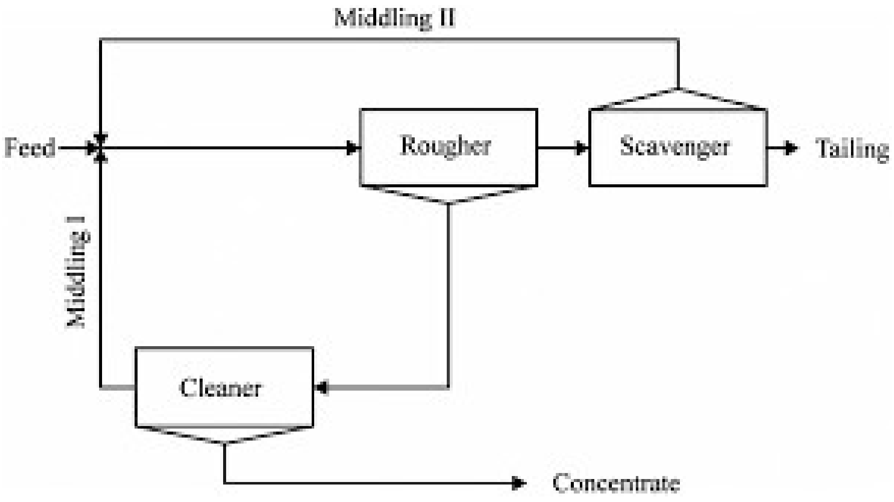
- Decoupled optimization of reactor and separator
- High turbulence, shear in reactor
- Quiescent flow in separator

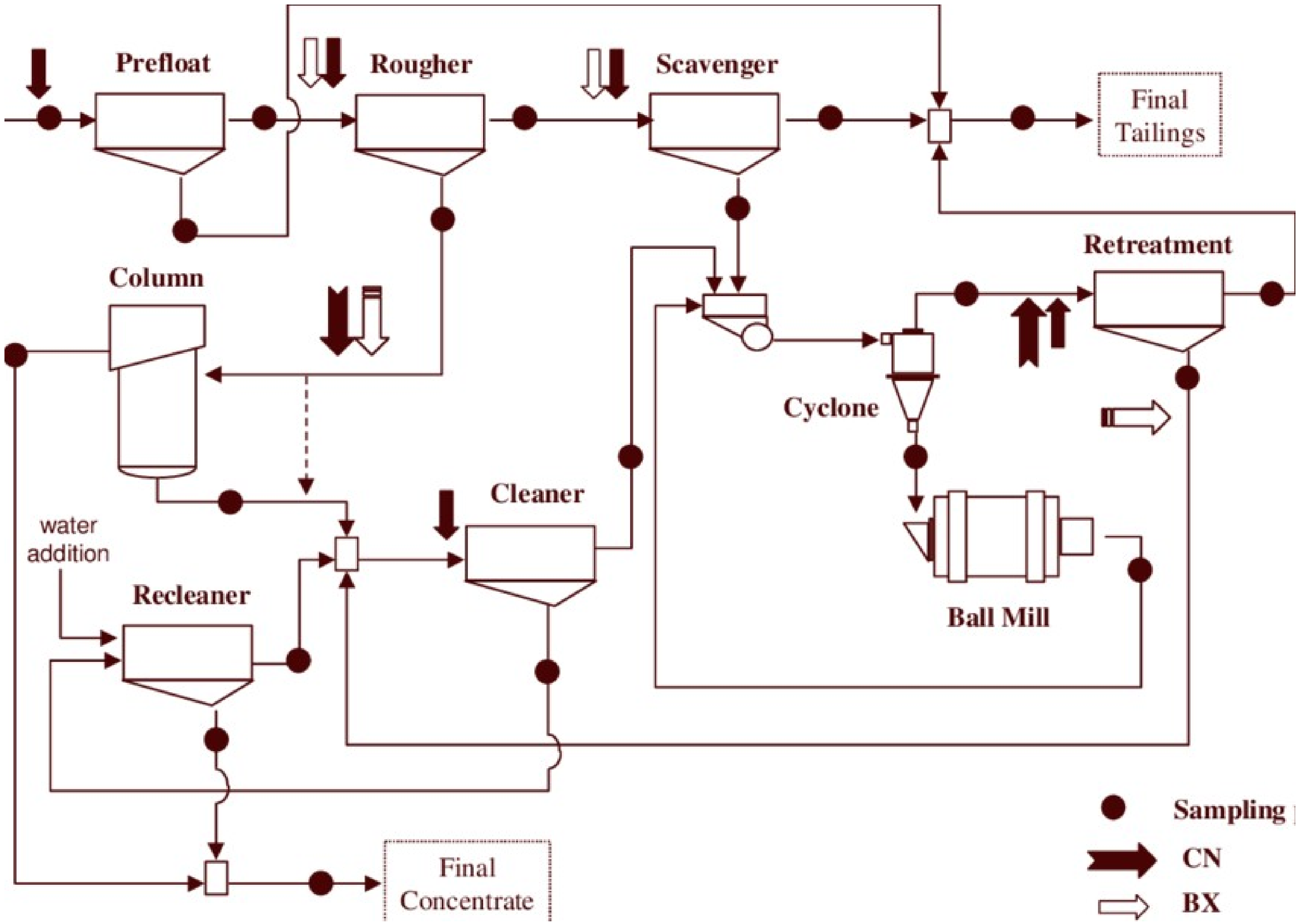
$$E_{coll} = P_c \times P_a \times (1 - P_d)$$



Quelle: Jameson, G. J,

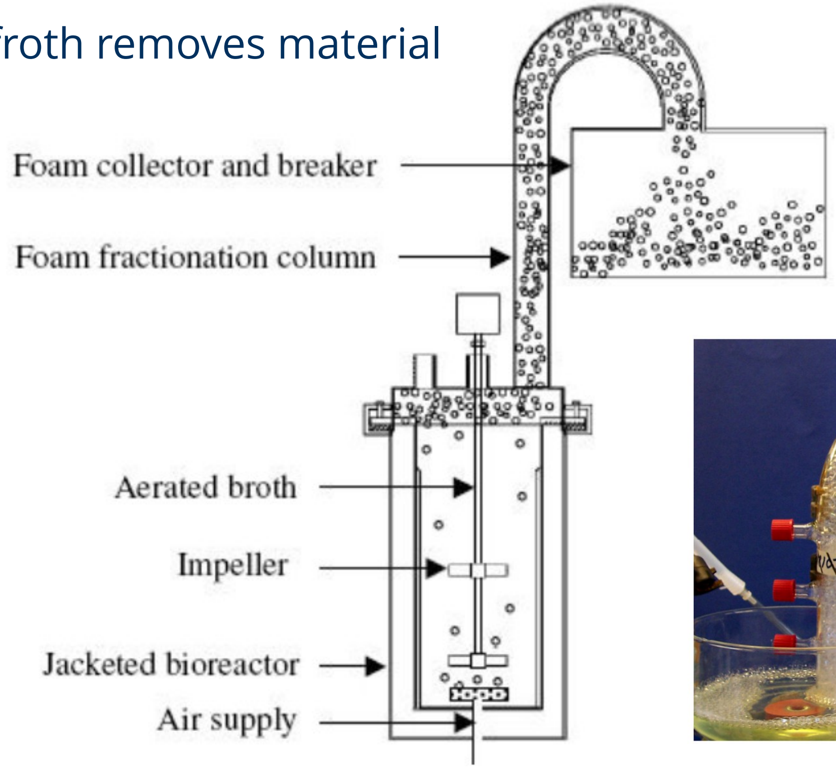
Flotation plant design

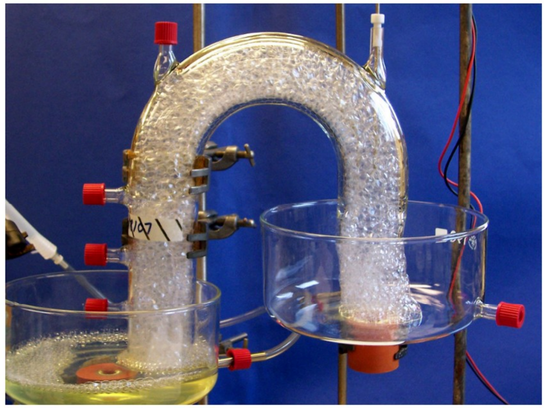




Foam fractionation / Adsorptive bubble separation

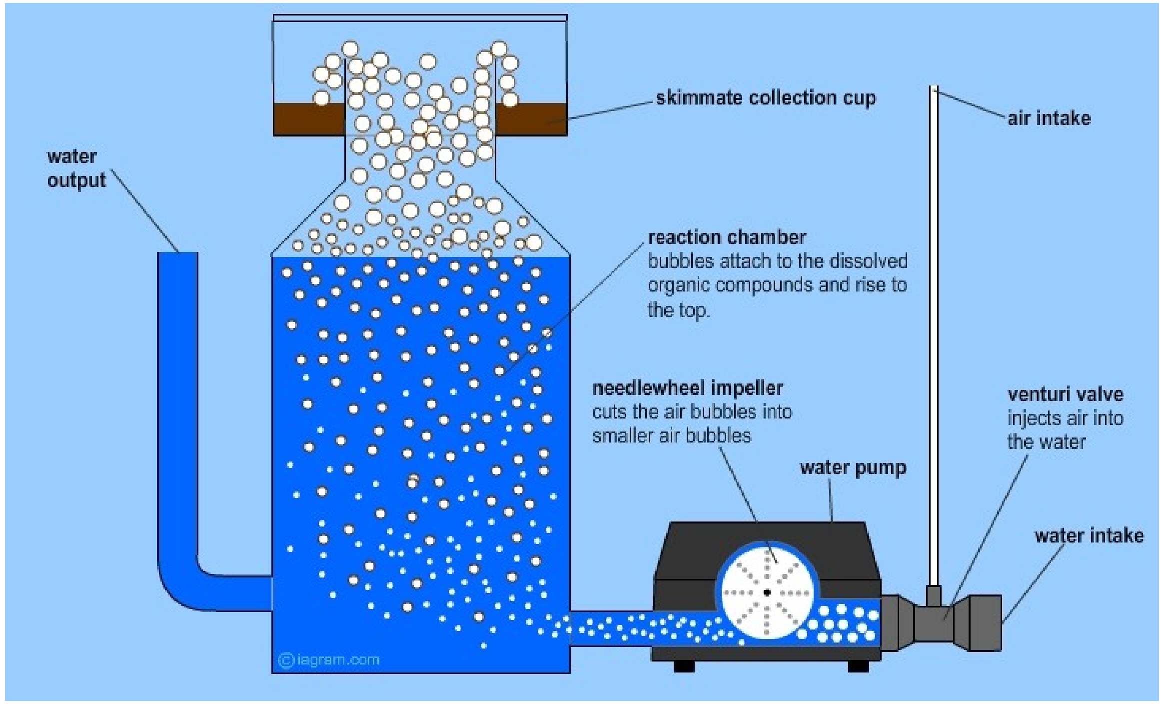
- Removal/recovery of hydrophobic material from solution
- Rising bubbles pick up material
- Froth generation at the surface
- Overflowing froth removes material





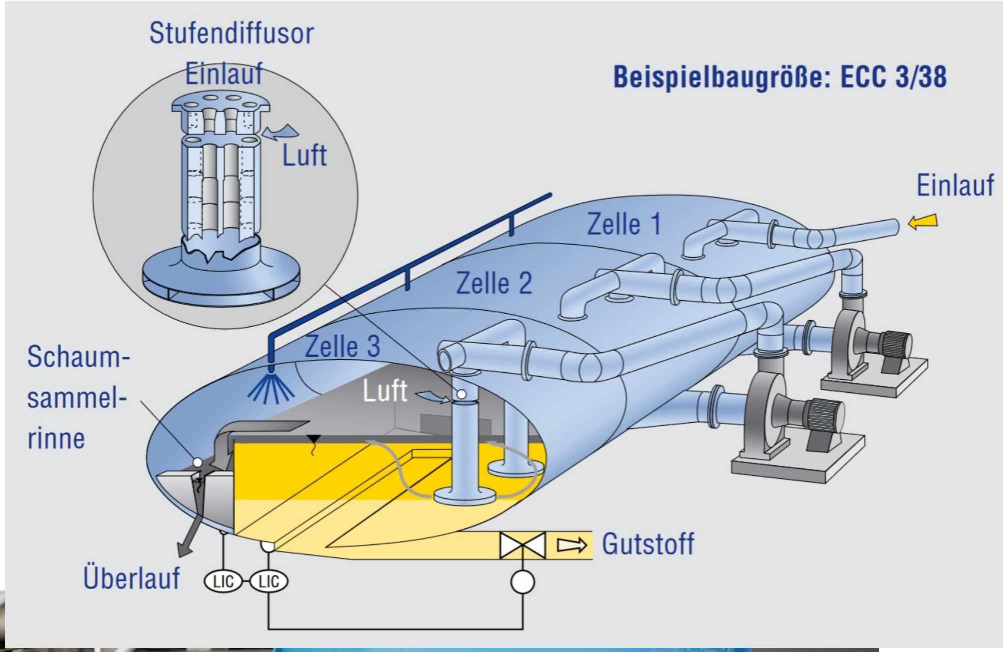
Protein skimmer

- Removal/recovery of hydrophobic bio-substances (proteins, bacteria, biosurfactants)
- Application in biochemical industry researched, but not yet full potential
- Application in fish tanks



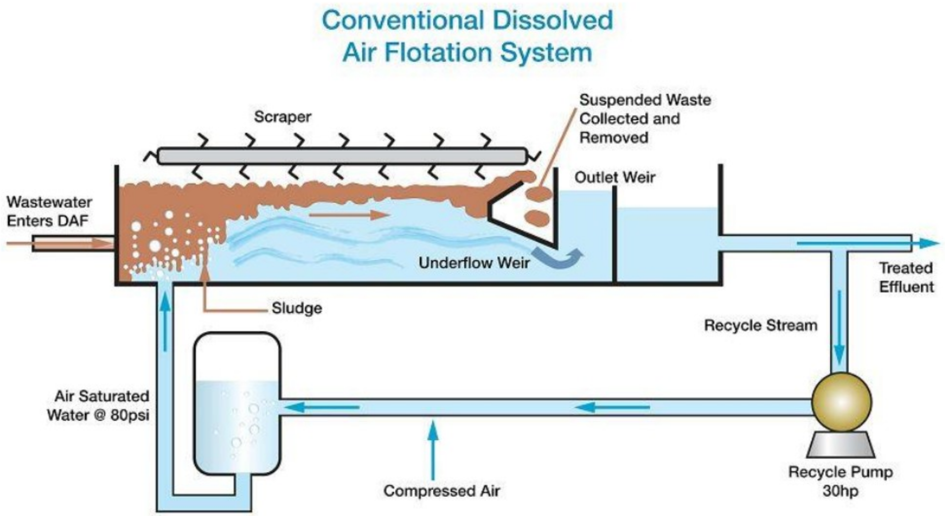
De-inking process

- Removal of old ink to produce recycled paper
- Sodium hydroxide (NaOH)
  → swelling of the fibres
  → ink-film breaks
- Surfactant (Fatty acid)
  → hydrophobizes ink droplets
- Sodium silicate
  → coagulation
- Hydrogen peroxide
  → bleaching



Dissolved air flotation (waste water treatment)

- Water, saturated with air at several bar
- Saturated air enters flotation cell,
- Microbubbles form on the surface of hydrophobic particles



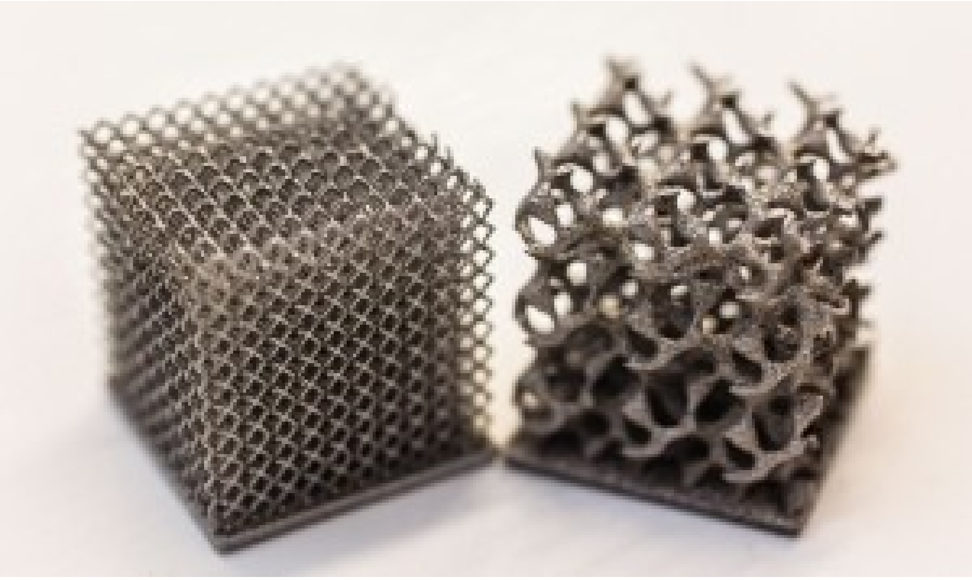
Structure

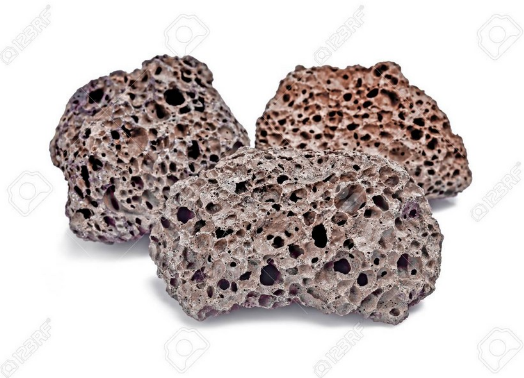
- Review lecture 10
- Solid foam production
- Solid foam mechanics
- Solid foam application

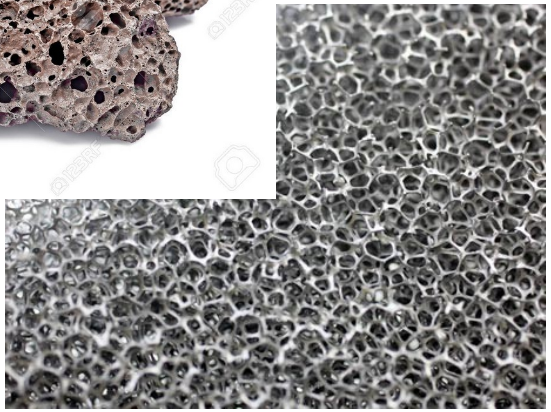
- Exam preparation

Foam generation

- All solid foams are generated from an initially liquid(-like) state
- (exception: 3D printing)
- Solidification during/after foam generation
- □ Polymerization (polymer foam)
- □ Freezing (metal, pumice)

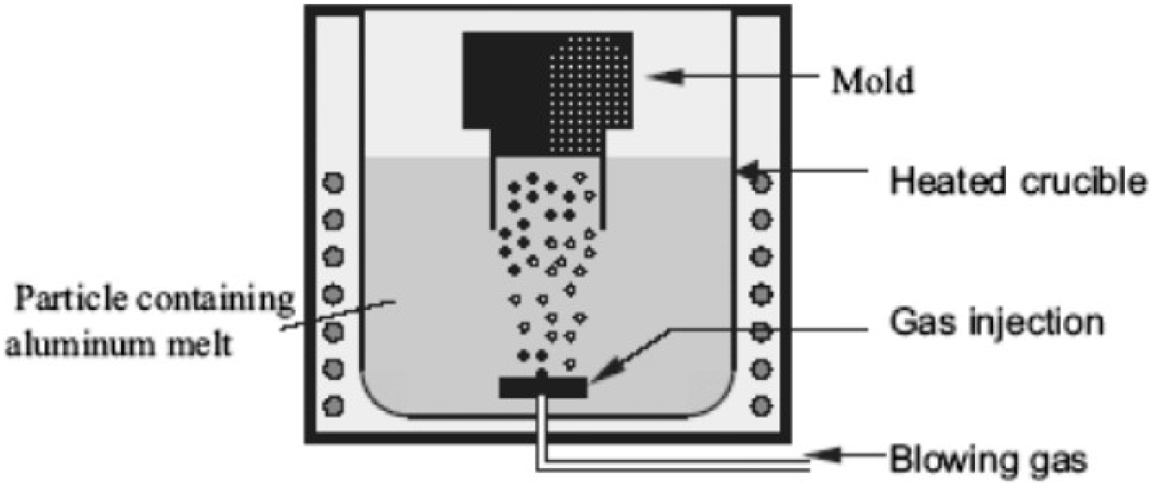






Mechanical bubble generation

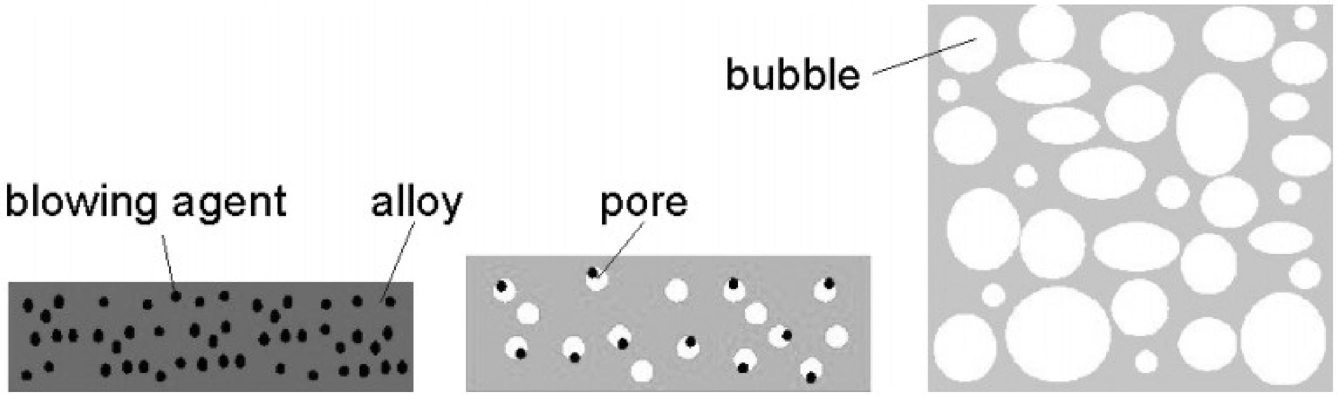
- Was state-of-the-art in 2006
- Difficult to control stability
- Less flexible in shaping



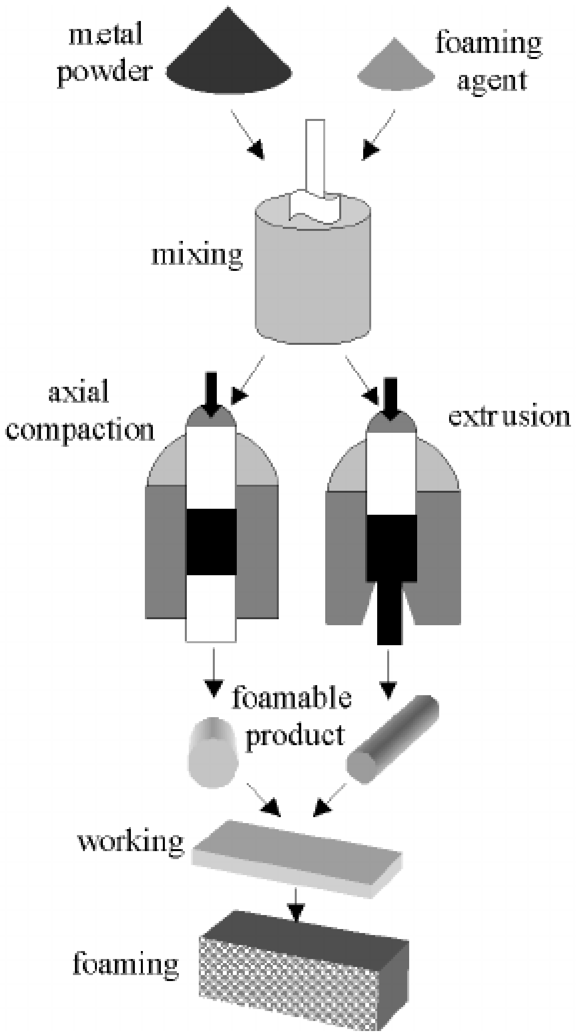
[Banhart 2006]

Physicochemical bubble generation

- Addition of blowing agents (TiH_2)
- Sintering / hot pressing / extrusion of Al-powder + TiH_2 + particles → precursor
- Heating/baking of precursor → Metal foam element

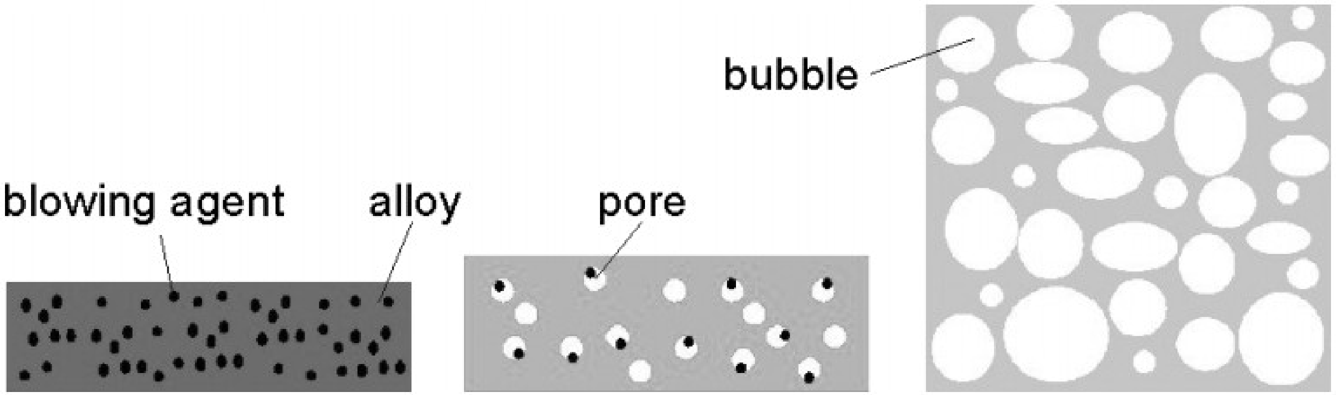


- 1kg Al + 1kg TiH2 → Solid fraction???
- Al: 26 g/mol, 2.7 kg/L Ti: 243 g/mol, 4.5 kg/L H2: 2 g/mol, 0.1 g/L

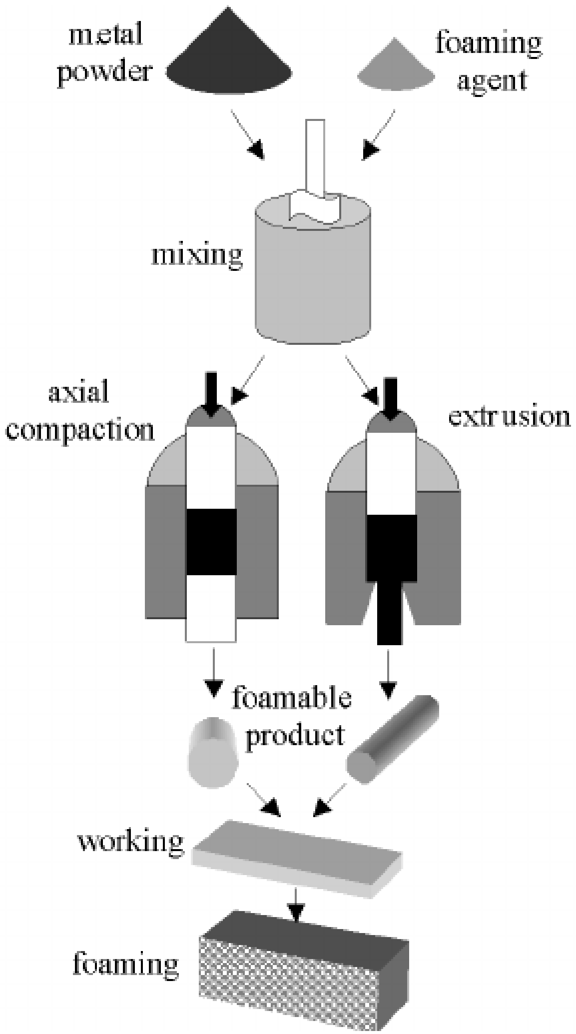


Physicochemical bubble generation

- Addition of blowing agents (TiH_2)
- Sintering / hot pressing / extrusion of Al-powder + TiH_2 + particles → precursor
- Heating/baking of precursor → Metal foam element

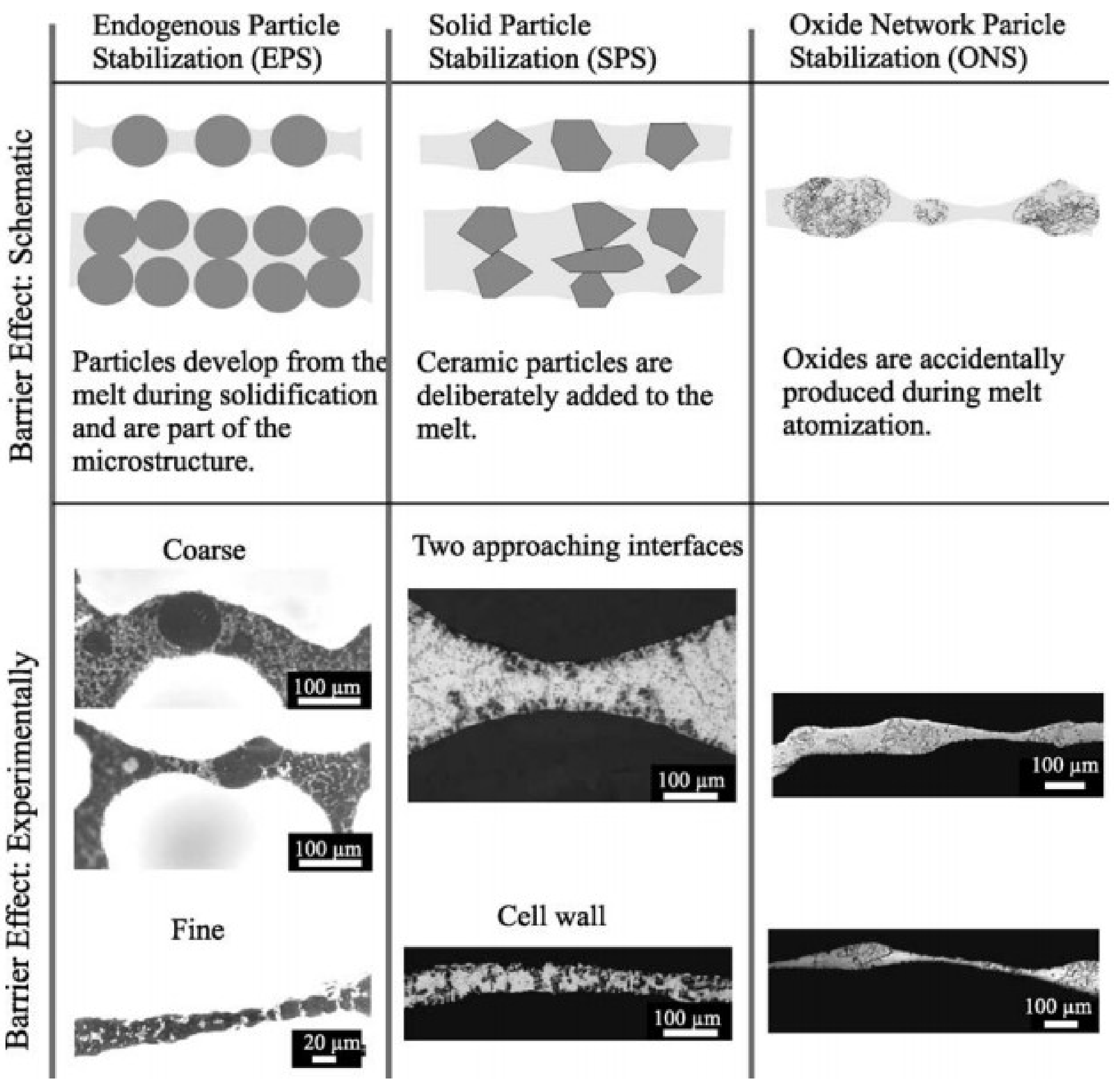


- 1kg Al + 1kg TiH2 → 0.7% solid fraction



Foam stabilization by particles

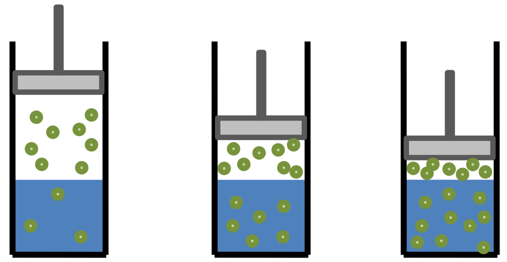
- Added to aluminium melt or to powder
- - Non-metallic particles (ceramic)
- - Oxide films
- - Non-equilibrium alloys

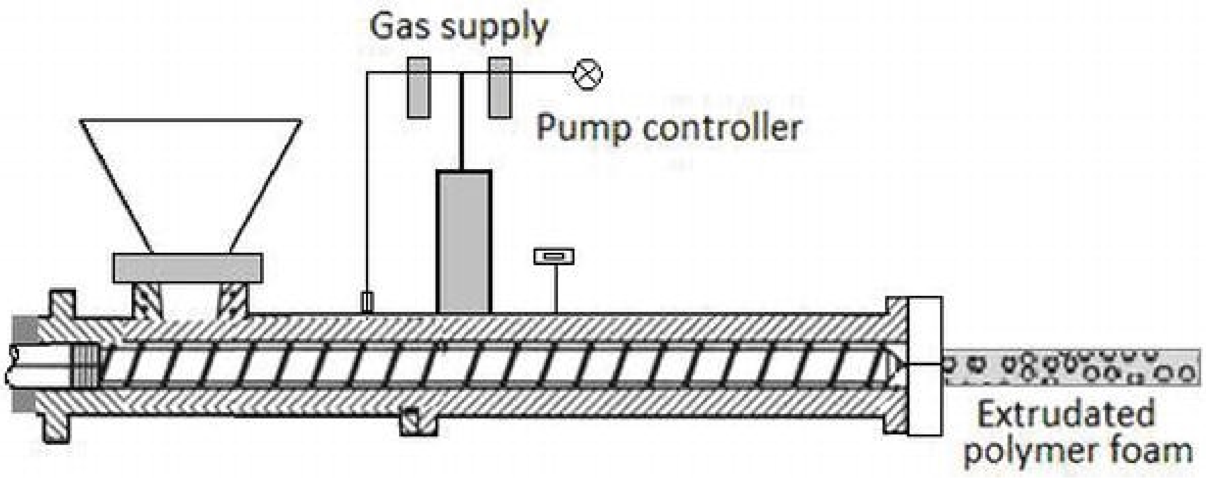


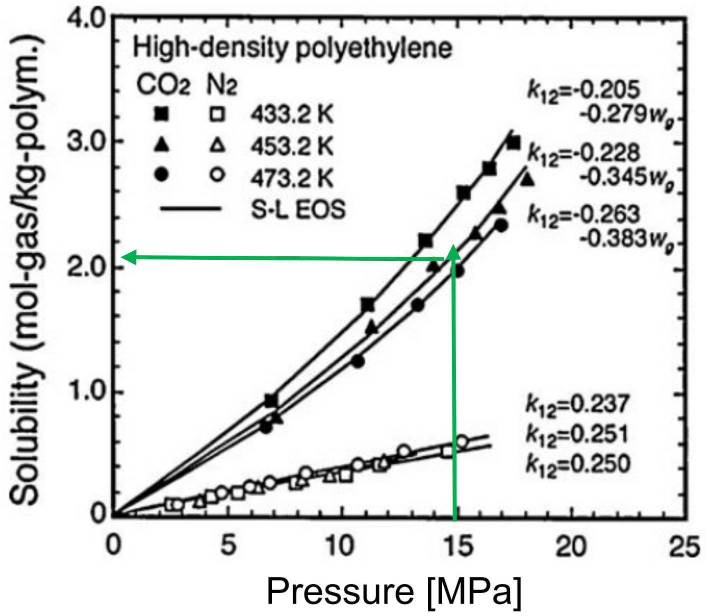
Physicochemical gas production

- Bubbles from phase transition
- Melted polymere saturated with pentane or CO_2 under high pressure
- Extrusion, expansion

$$c = k_H\, p$$



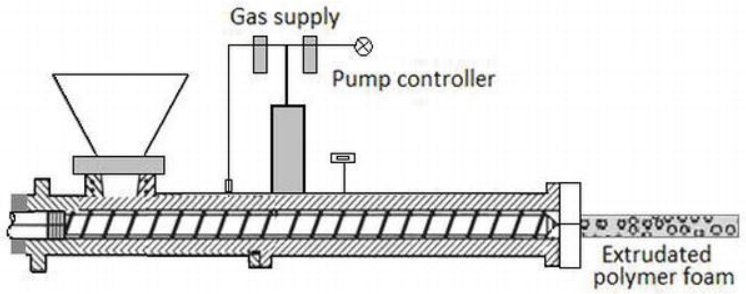




2 mol ≙ 44 Liter ≙ 44/45 gas fraction

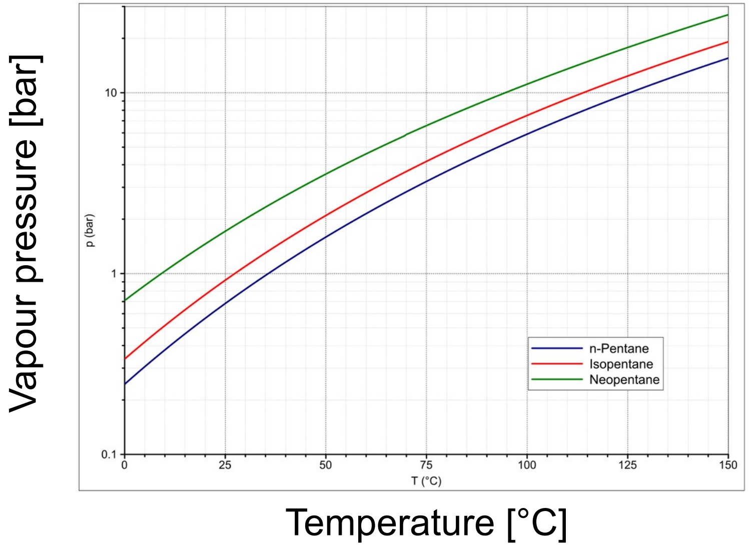
Physicochemical gas production

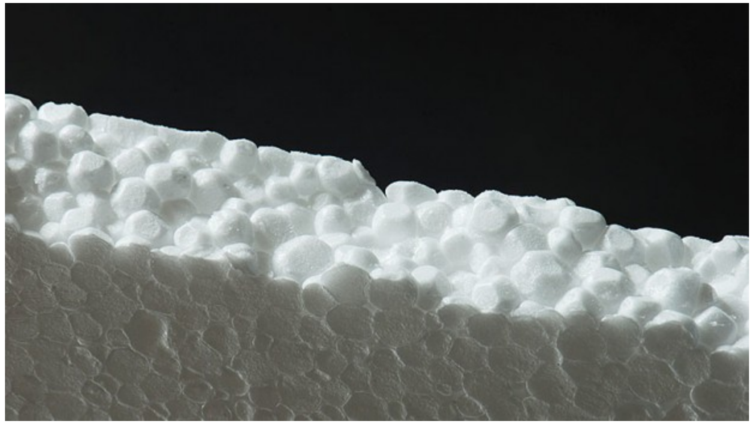
- Bubbles from phase transition
- Melted polymere saturated with pentane or CO_2 under high pressure
- Extrusion, expansion



Styropor (expanded Polystyrene)

- Polystyrene + embedded pentane (from polymerization)
- Cured with water steam
  - Polystyrene gets soft (temperature)
  - Pentane vaporizes → blows foam





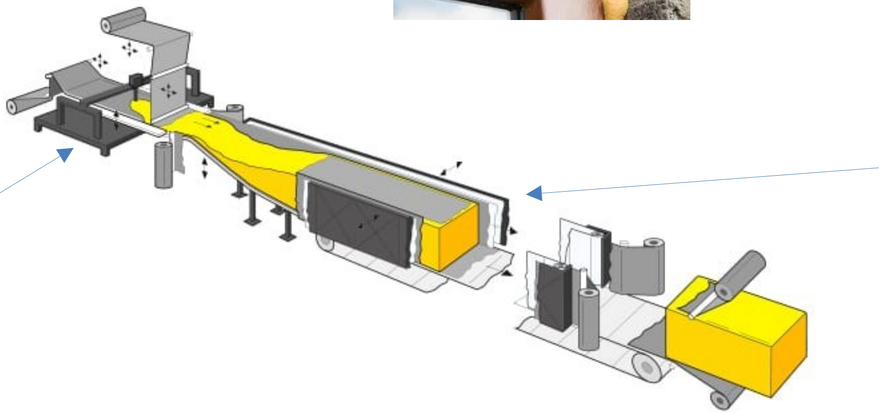
Chemical gas production

- Addition of water to isocyanate/polyol mixture
- Water reacts with isocyanate, forming CO_2
- CO_2 blows foam

$$\mathrm{R{-}N{=}C{=}O} + \mathrm{H_2O} \xrightarrow{\text{step 1}} \mathrm{R_1} - \underset{\underset{\mathrm{H}}{|}}{\mathrm{N}} - \overset{\overset{\mathrm{O}}{\|}}{\mathrm{C}} - \mathrm{O{-}H} \xrightarrow[\text{decomposes}]{\text{step 2}} \mathrm{R{-}NH_2} + \mathrm{CO_2(g)}$$

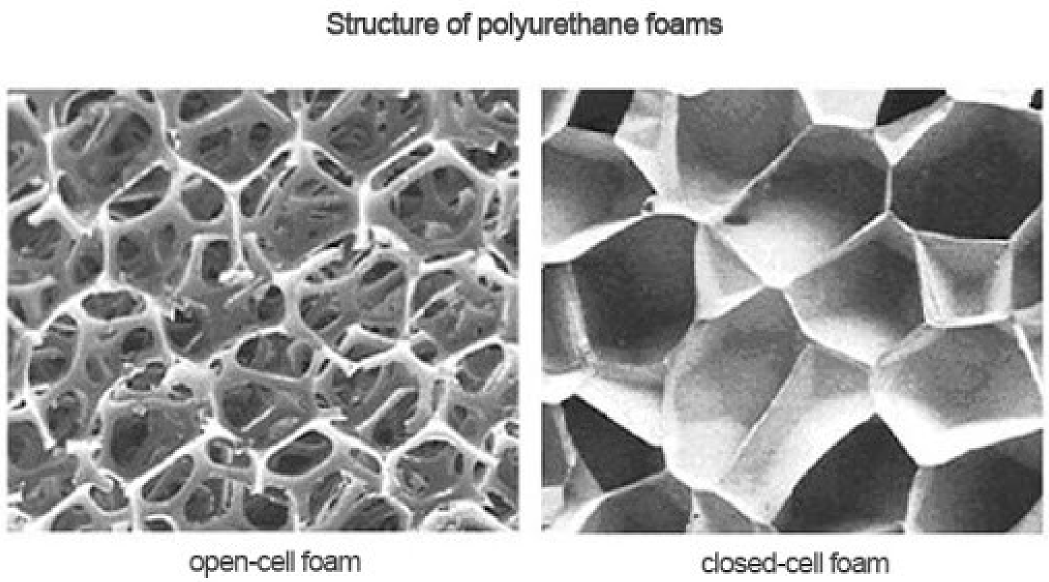
$$\mathrm{R{-}N{=}C{=}O} + \mathrm{R{-}NH_2} \xrightarrow{\text{step 3}} -\mathrm{R} - \underset{\underset{\mathrm{H}}{|}}{\mathrm{N}} - \overset{\overset{\mathrm{O}}{\|}}{\mathrm{C}} - \underset{\underset{\mathrm{H}}{|}}{\mathrm{N}} - \mathrm{R}-$$

https://www.youtube.com/watch?v=zi7am1We9SE



Closed vs. Open cell

- Every foam is initially closed-cell
- Film rupture leads to open-cell, depends on liquid fraction
- Can be triggered with special antifoams (in low concentration)
- Can be triggered by shock
- Significant difference in permeability, insulation, stability



Structure

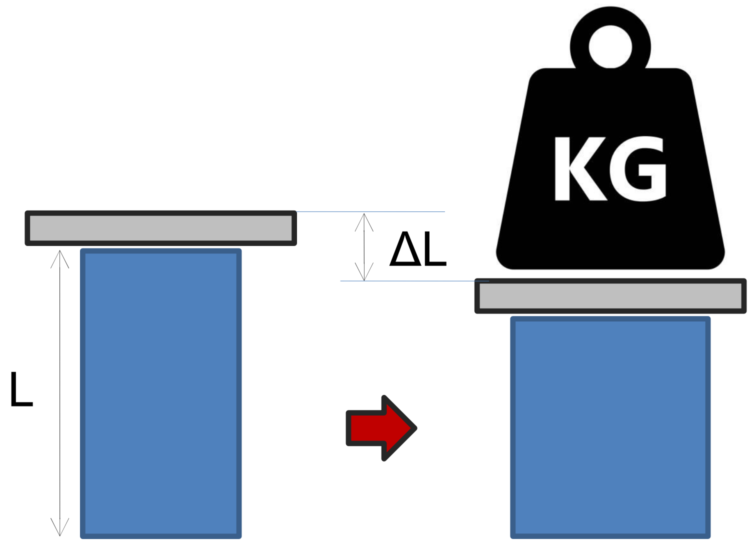
- Review lecture 10
- Solid foam production
- Solid foam mechanics
- Solid foam application

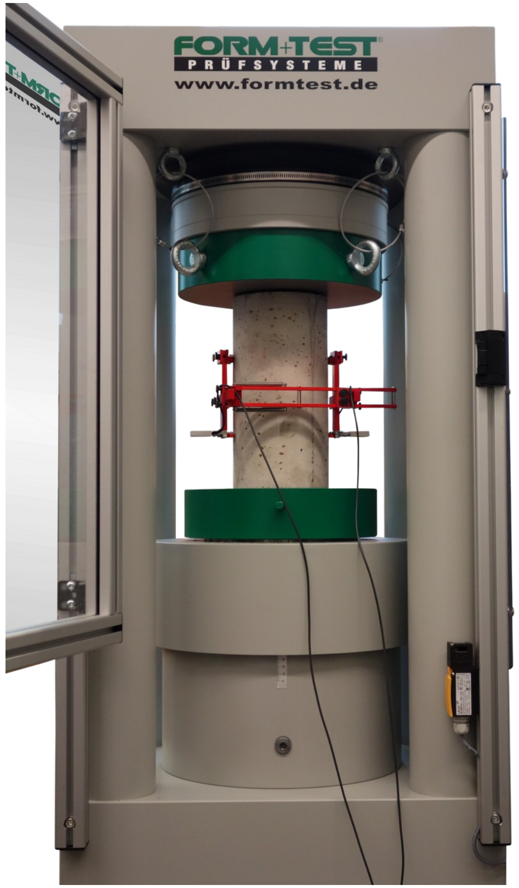
- Exam preparation

Youngs modulus

- 1-dimensional stress → (linear)elastic response
- Youngs modulus gives stiffness of the material (elastic deformation)

$$E = \frac{\sigma}{\varepsilon} = \frac{F/A}{\Delta L/L}$$





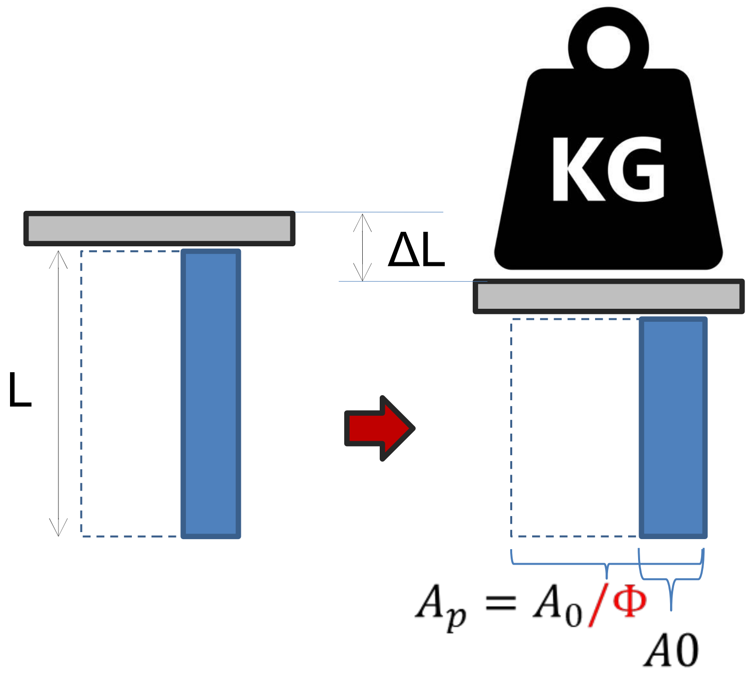
Voigts limit

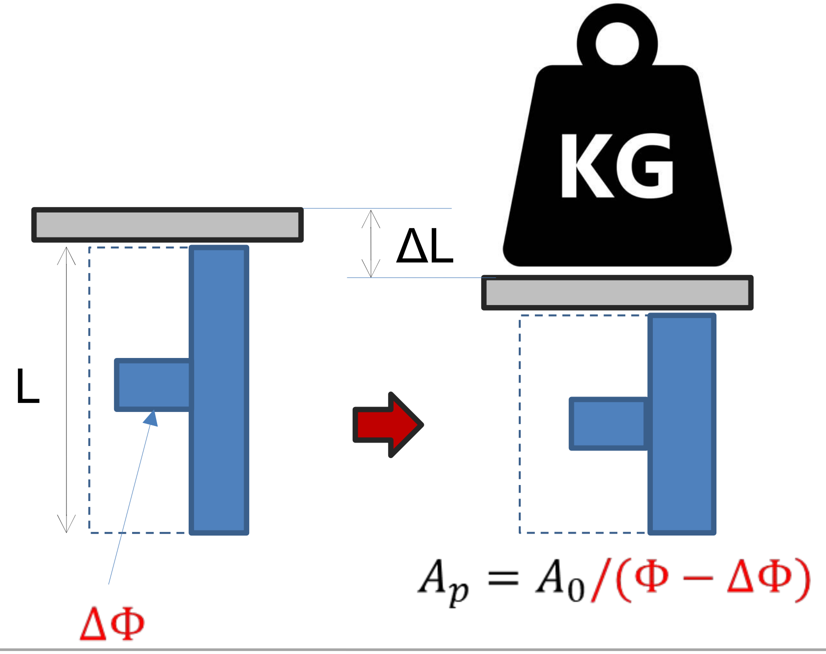
- Porous material with solid fraction Φ
- Efficiency of material usage

Voigts limit: $\frac{E_p}{E_0} \leq \Phi$

$$E_0 = \frac{\sigma}{\varepsilon} = \frac{F}{A_0}\frac{L}{\Delta L} \qquad E_p = \frac{\sigma}{\varepsilon} = \frac{F}{A_0/\Phi}\frac{L}{\Delta L} = \Phi E_0$$

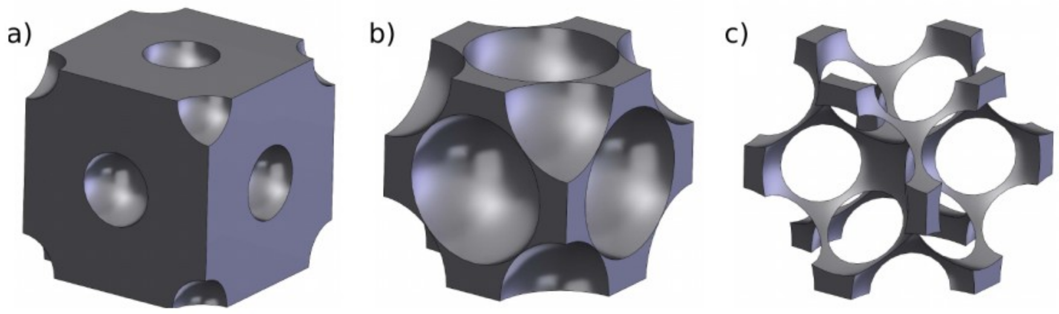
$$E_p = \frac{\sigma}{\varepsilon} = \frac{F}{A_0/(\Phi - \Delta\Phi)}\frac{L}{\Delta L} = (\Phi - \Delta\Phi)E_0 < \Phi E_0$$

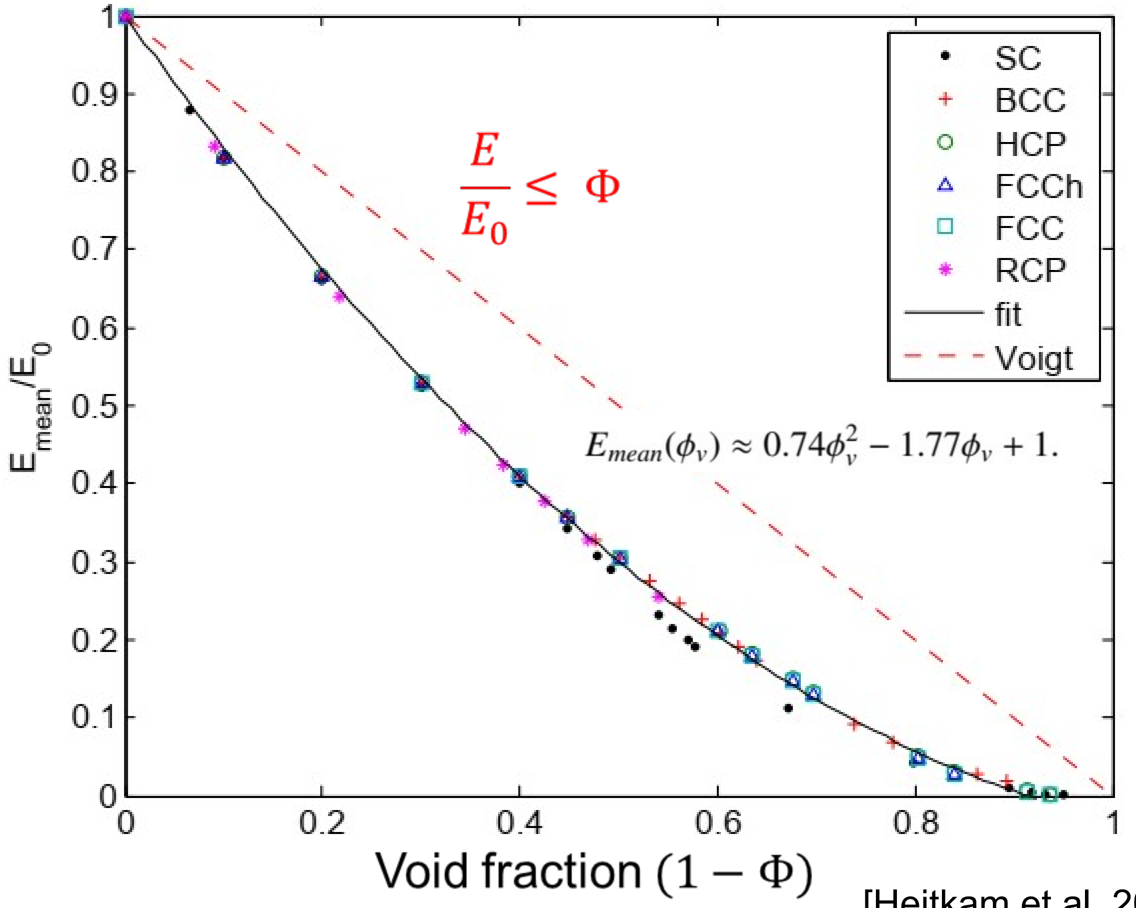




Youngs modulus of porous material

- Spherical voids in different packing structure
- Youngs modulus nearly independent from structure

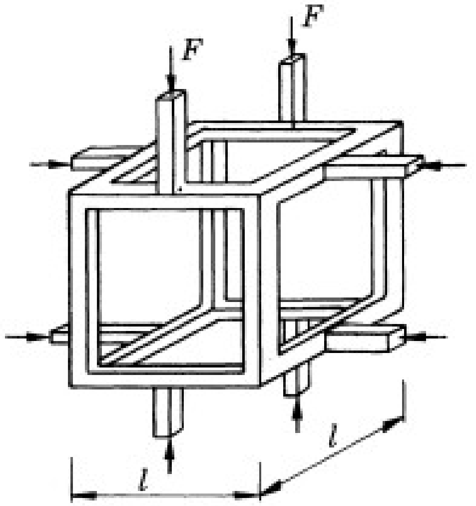




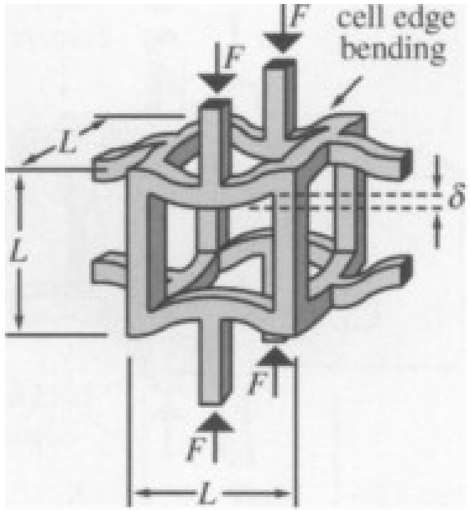
[Heitkam et al. 2016]

Youngs modulus of porous material

- Elastic behaviour dominated by bending of Plateau borders
- Gibson-Ashby model from idealized structure:



$$\Phi \sim \frac{t^2 L}{L^3} \sim \frac{t^2}{L^2}$$



=ΔL

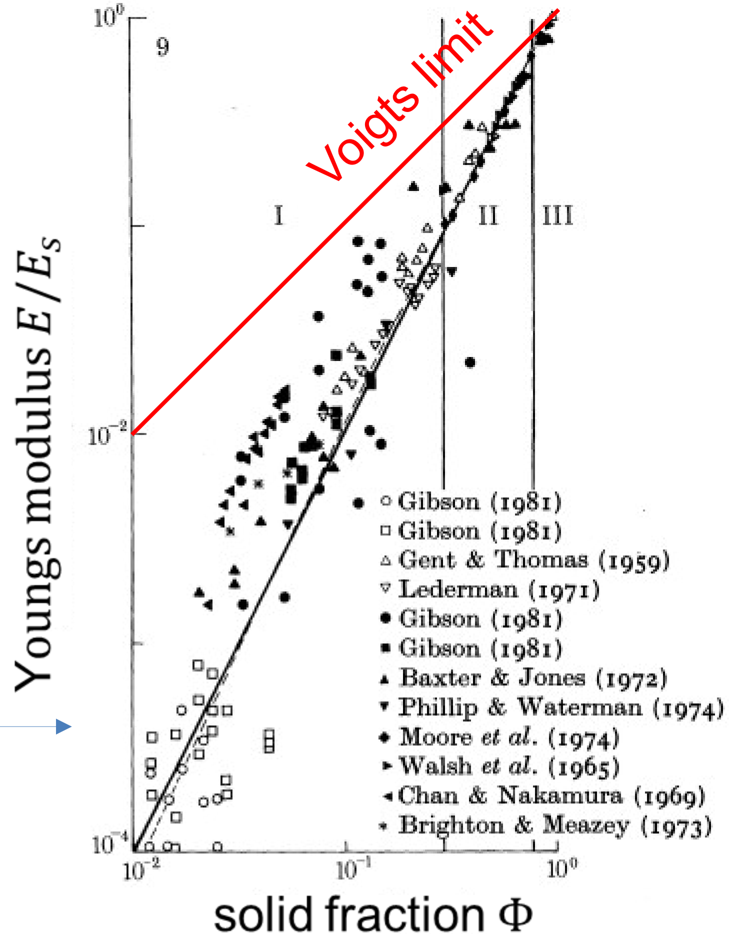
$$E = \frac{\sigma}{\varepsilon} = \frac{F}{A}\frac{L}{\Delta L} \sim \frac{F}{L}\frac{1}{\Delta L} \sim \frac{F}{L}\frac{E_s\, I}{F\, L^3} \sim \frac{F}{L}\frac{E_s t^4}{F\, L^3} \sim E_s \frac{t^4}{L^4} = E_s \Phi^2$$

$$\Delta L \sim \frac{F\, L^3}{E_s\, I}$$

Euler-Bernoulli beam theory

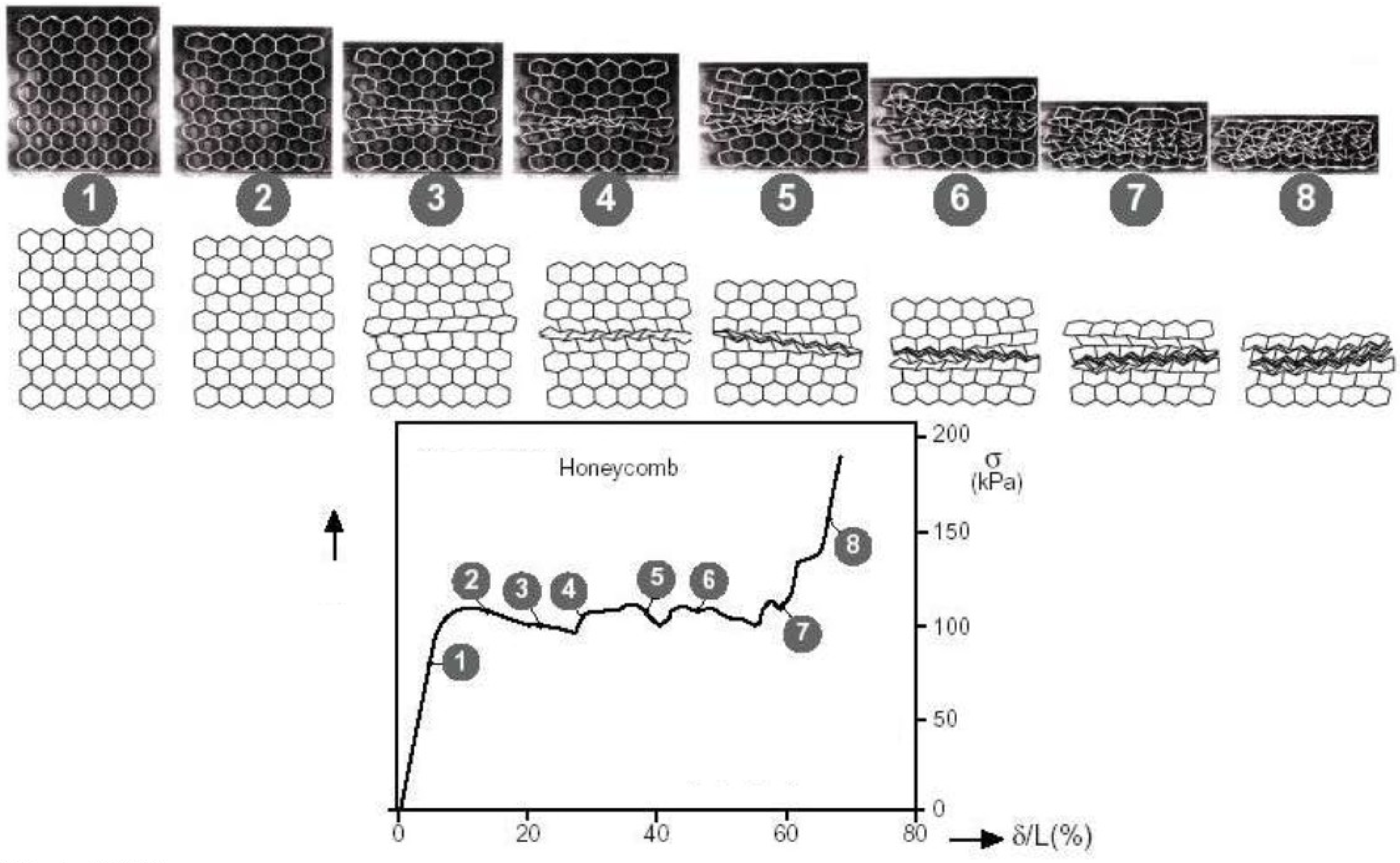
$$I = \frac{t^4}{12}$$

Second moment of area



Youngs modulus of porous material

- Collapse of foam structure above a critical stress
- Plateau in stress under consecutive collapse of structure



Dr. André Moreira, BASF AG

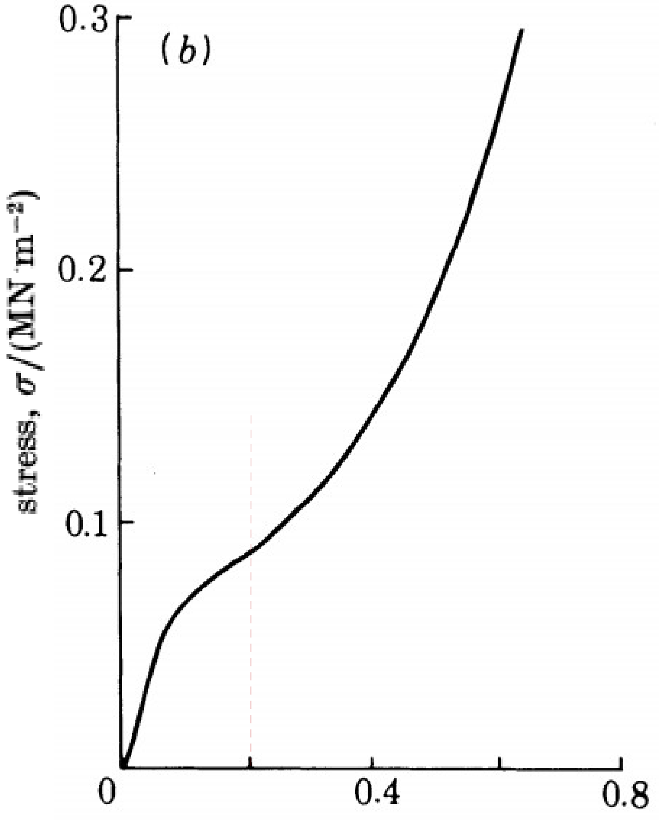
ΔL/L [%]

Exercise: Youngs modulus of porous material

- What is the difference of the Youngs modulus between closed-cell and open-cell polymer?
- Estimate the fraction of stress that is required due to the compressibility of the entrapped air
- Relative length change: ΔL/L =0.2

$$E_0 = \frac{\sigma}{\varepsilon} = \frac{F}{A}\frac{L}{\Delta L}$$

PE-foam, closed-cell, 7.6% PE



ΔL/L

Exercise: Youngs modulus of porous material

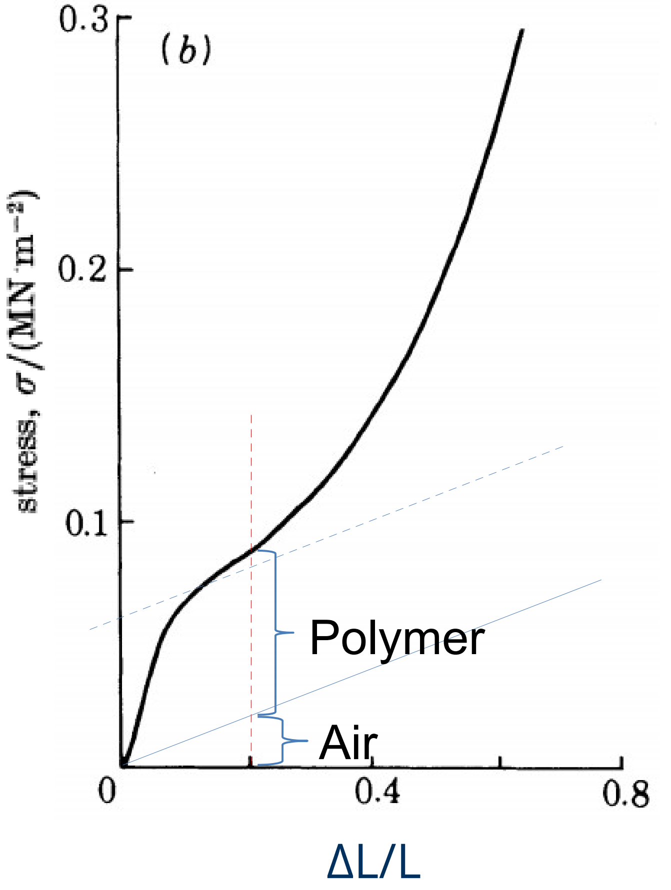
- What is the difference of the Youngs modulus between closed-cell and open-cell polymer?
- Estimate the fraction of stress that is required due to the compressibility of the entrapped air (isothermal!)
- Relative length change: ΔL/L =0.2

$$\frac{p\,V}{T} = nR = const$$

$$\frac{\Delta\,V}{V} \approx -\frac{\Delta\,p}{p}$$

$$\frac{\Delta\,V}{V} = 0.2 \approx -\frac{\Delta\,p}{p} \rightarrow \Delta\,p \approx 0.2\,p_0 = 20\,kPa = 0.02\,MPa$$

PE-foam, closed-cell, 7.6% PE



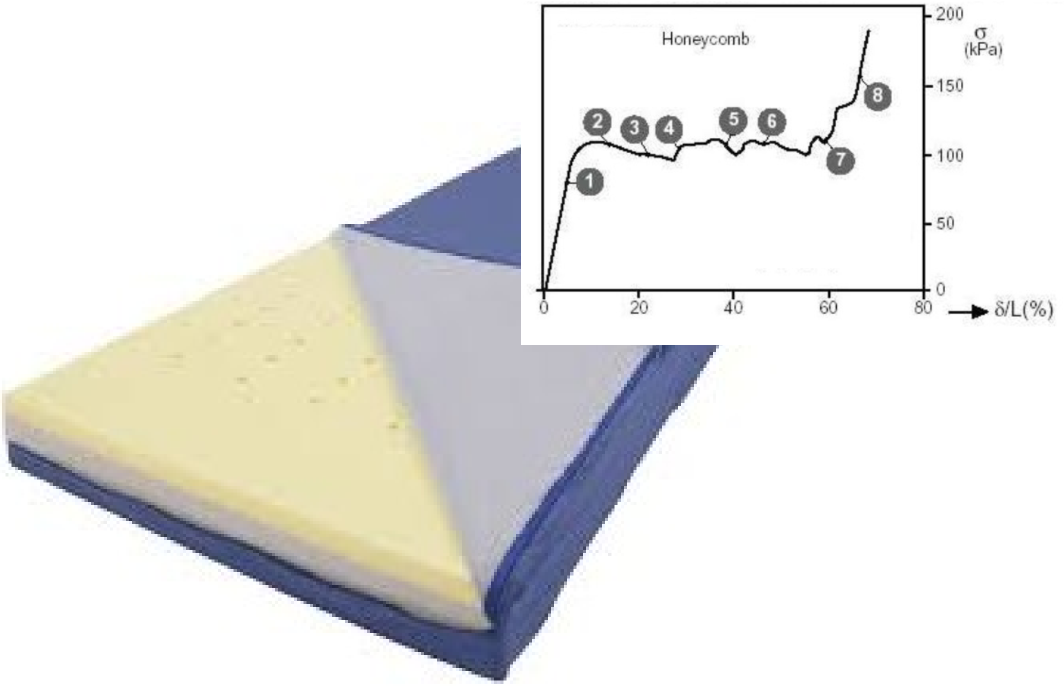
Structure

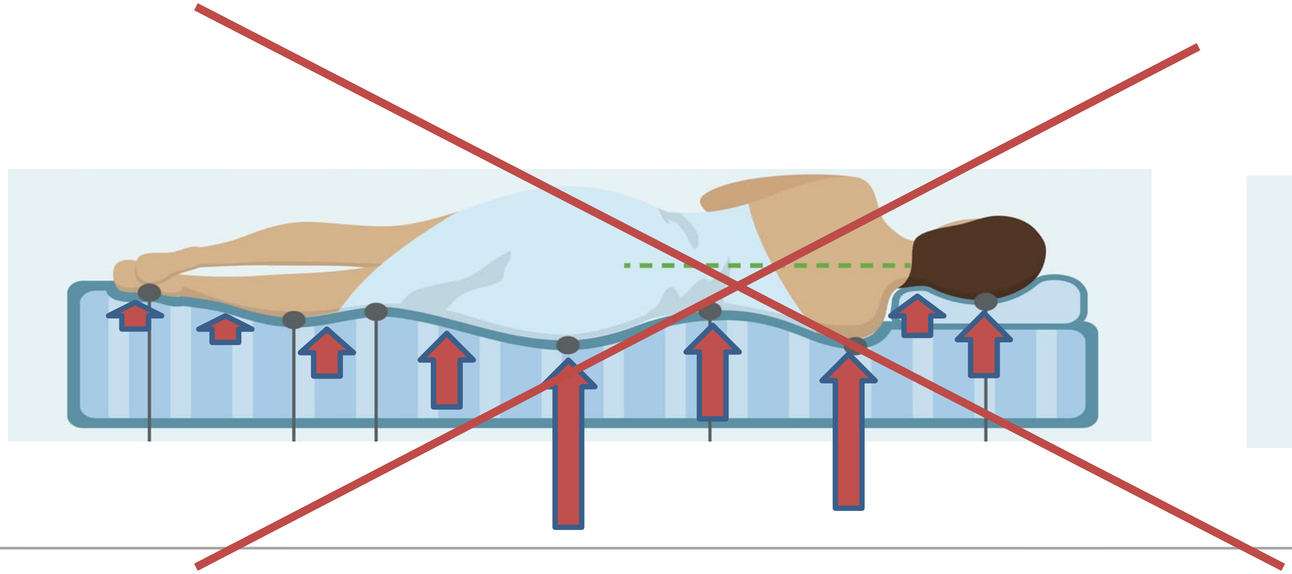
- Review lecture 10
- Solid foam production
- Solid foam mechanics
- Solid foam application

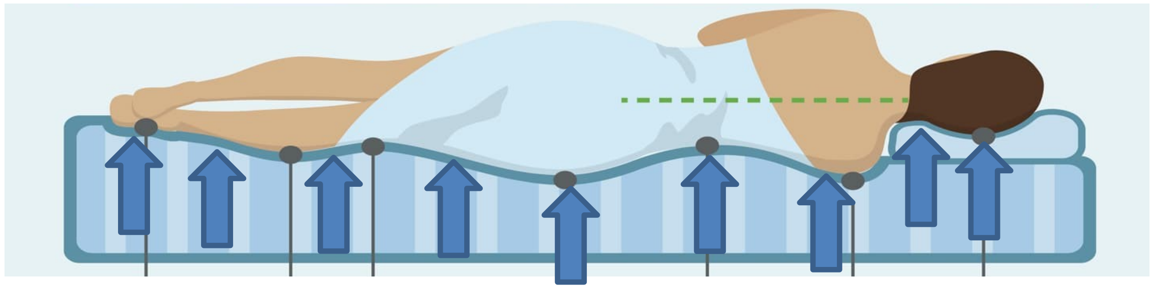
- Exam preparation

Cushioning

- Plateau in stress-strain curve
- ▭ more homogeneous force distribution

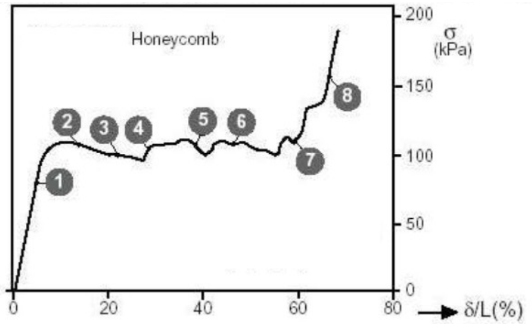


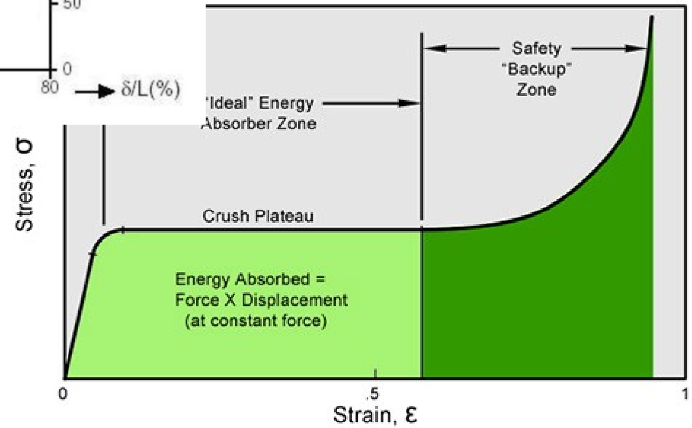


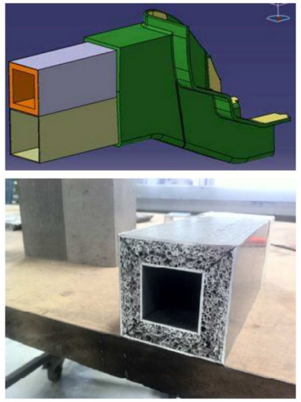


Shock absorption

- Impact energy is consumed by (plastic) deformation of the structure
- Happens at low stress level
- Plateau in stress-strain curve flattens force peaks

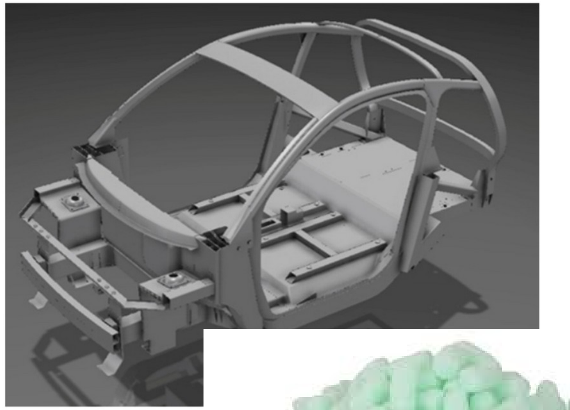


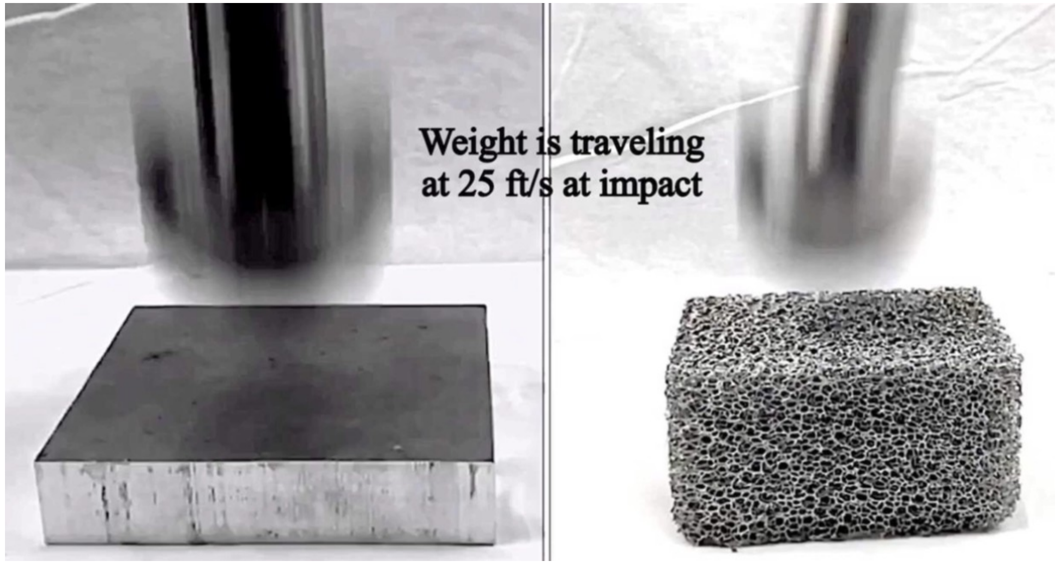




(a)

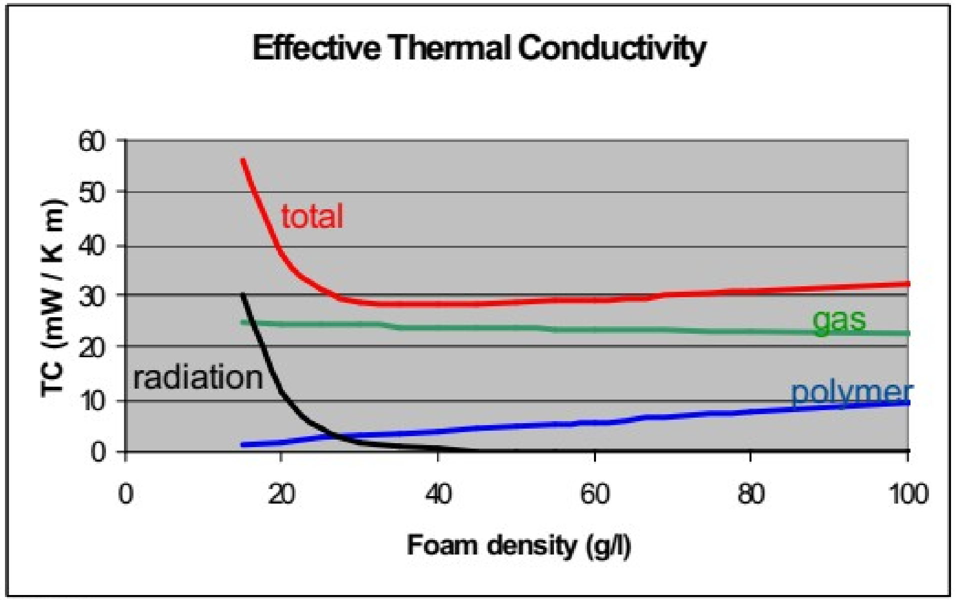
[Garcia-Moreno 2016]



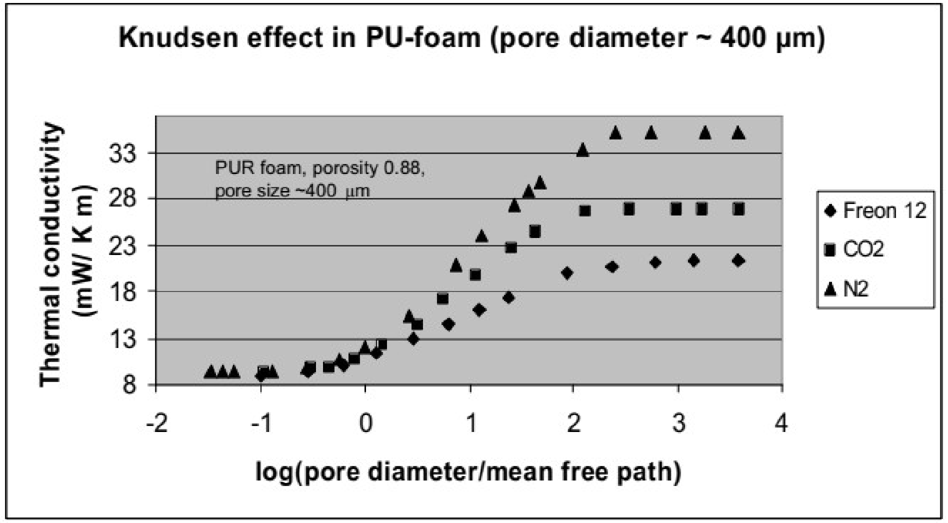


Thermal insulation

- Very low total thermal conductivity
- Combined effect of
  - radiation
  - convective transport (gas)
  - conduction (polymer)
- Controlled by solid fraction and pore size



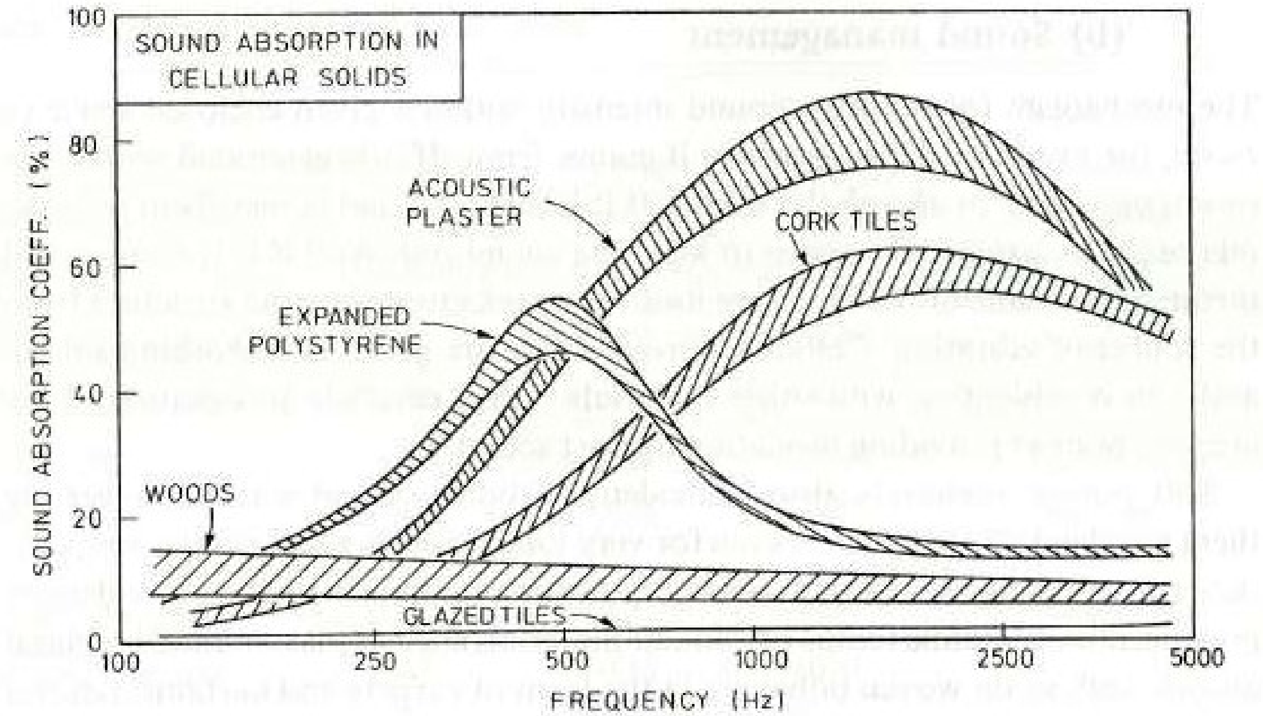
Dr. André Moreira, BASF AG



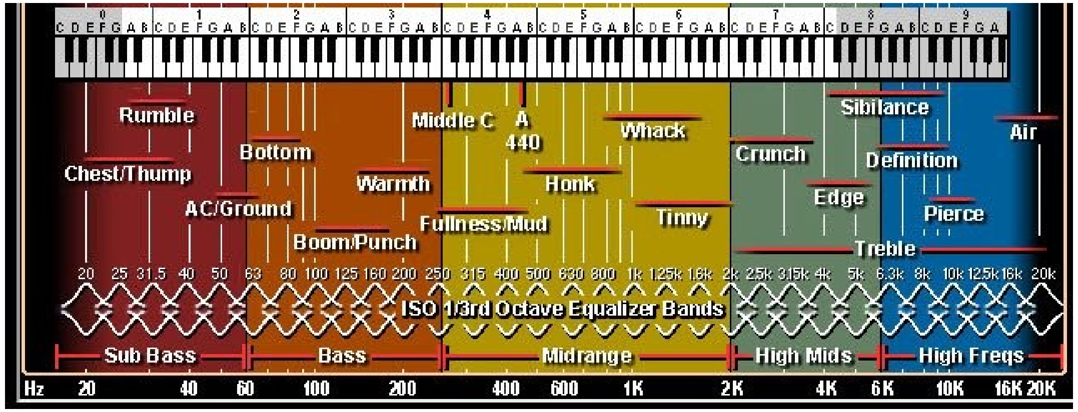
Experimental data from Harper and Sahrigi, I & EC Fundamentals **3**, 318 (1964)

Sound design

- Low Youngs modulus
- → Sound wave is (partially) conducted into the foam stru
- Multiple interfaces → diffuse scatter of wave



Source: Gibson and Ashby, *Cellular Solids*



Filters, heat exchanger

- Open-cell foam
- High effective surface
- High-temperature application

[Garcia-Moreno 2016]

Structure

- Review lecture 10
- Solid foam production
- Solid foam mechanics
- Solid foam application