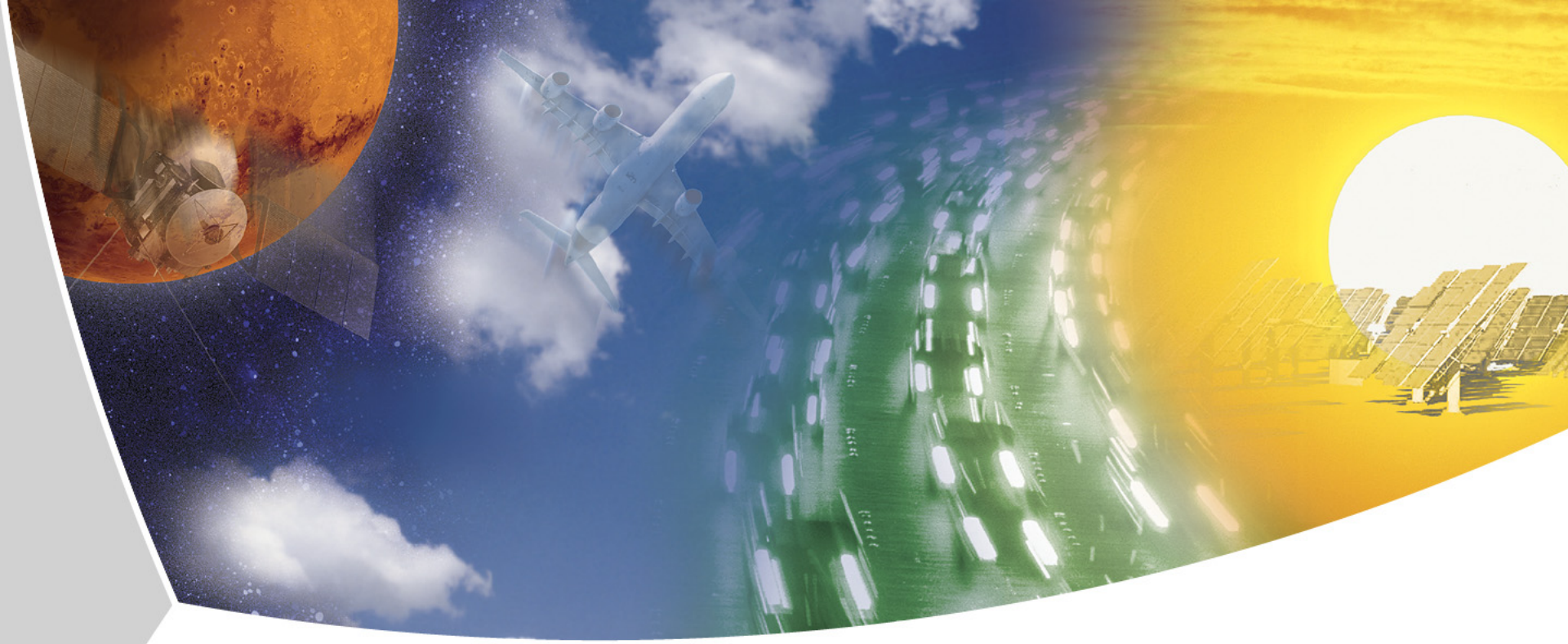

Aerogels - Structure, properties and applications

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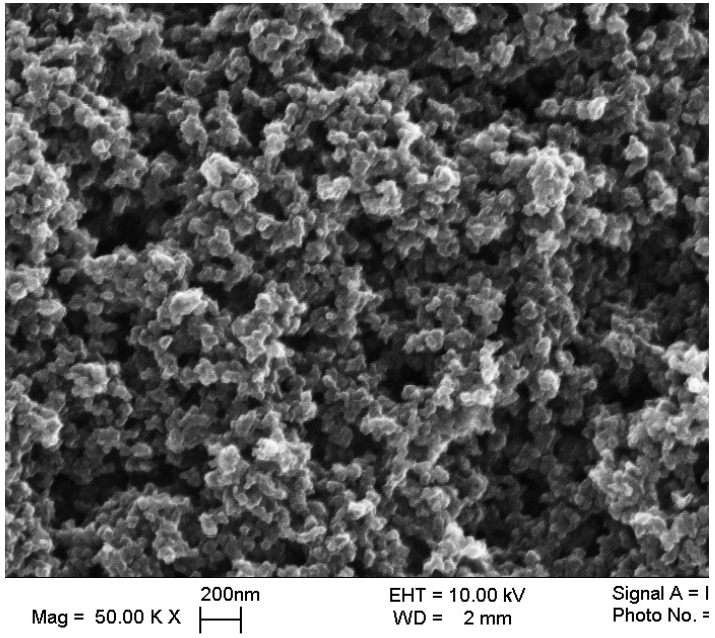
DLR Deutsches Zentrum für Luft- und Raumfahrt e.V.
in der Helmholtz-Gemeinschaft

What are aerogels?

Aerogels are

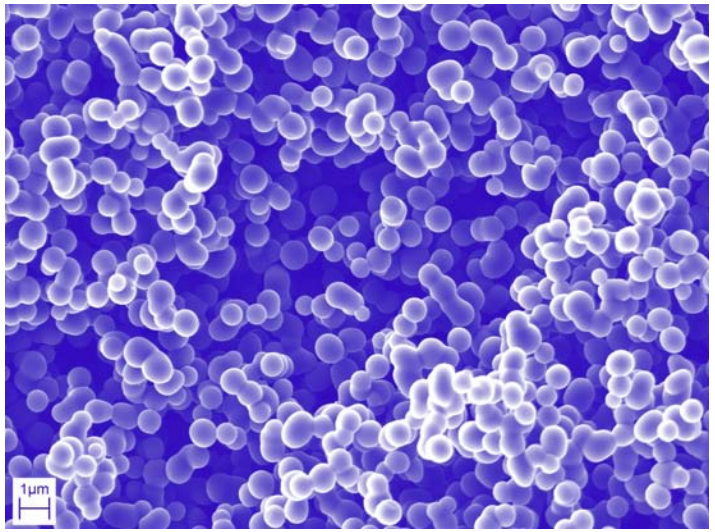
nanostructured, open porous

solids made via sol-gel technology



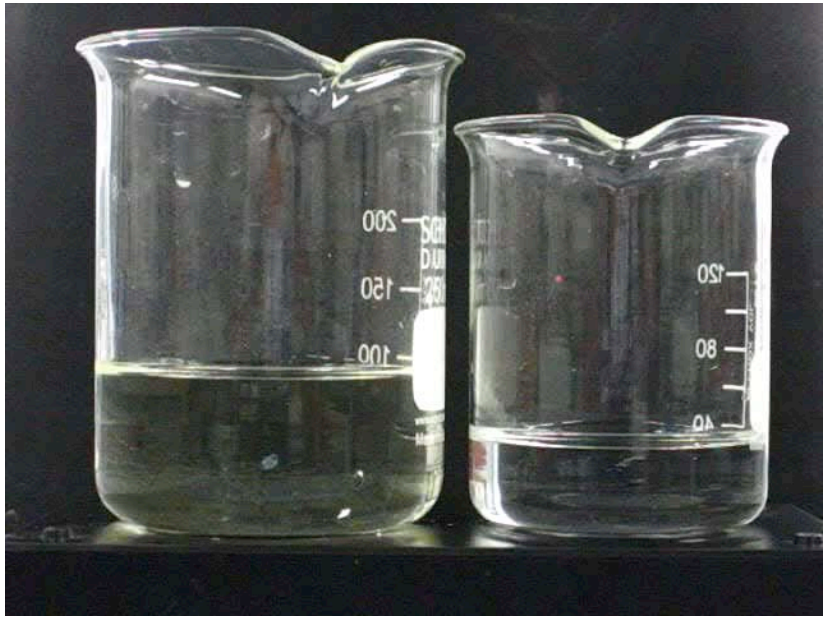
Types of aerogels

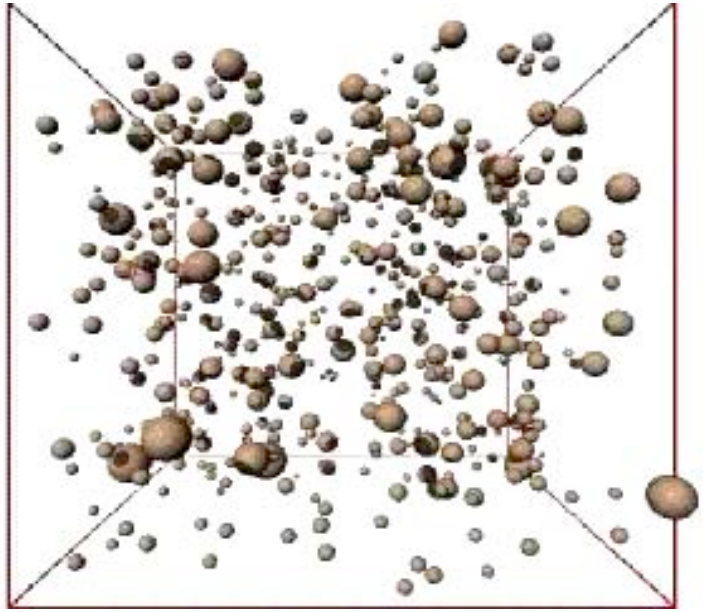
- Oxides (Quarz, Titania, Zirkonia. Mixed oxides)
- Polymers (Resorcin-, Melamin-Formaldehyd)
- Carbon (pyrolysed Polymere)
- cellulose, starch, alginates,...
- And almost everything that can be gelled



Synthesis of aerogels

- General technique is “sol-gel processing” meaning
  - Mixing of chemicals (alcoxides, water, alcohol, catalyst)
  - Gelation (catalyst, temperature, fluid flow)
  - Drying
  - Final product





DLCA-Simulation von B.Halperin , NWU Evanston

Synthesis of aerogels

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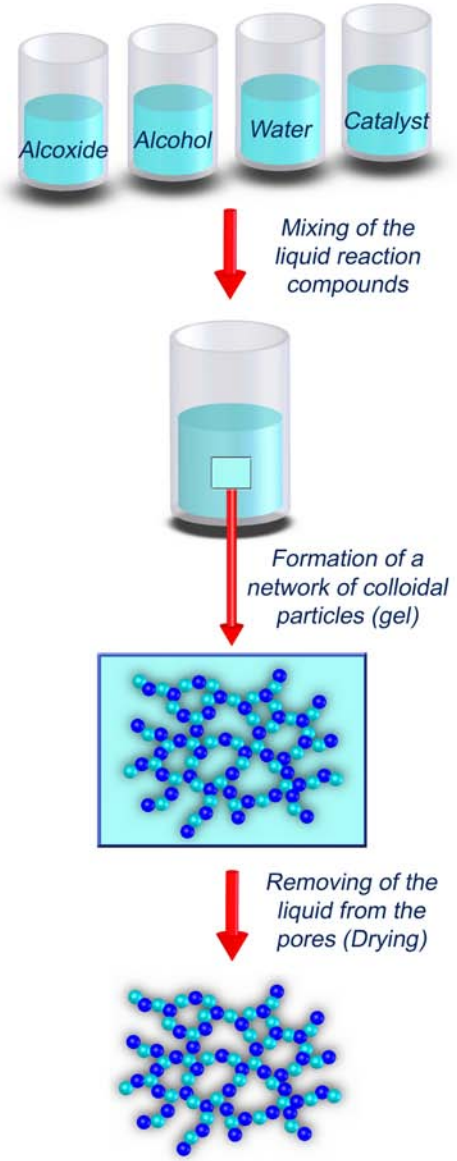
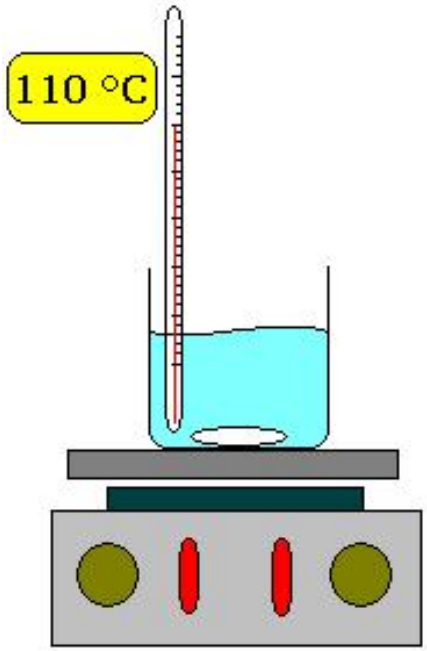


Preparation of cellulose aerogels

Dissolution of cellulose in e.g. salt-hydrate melts

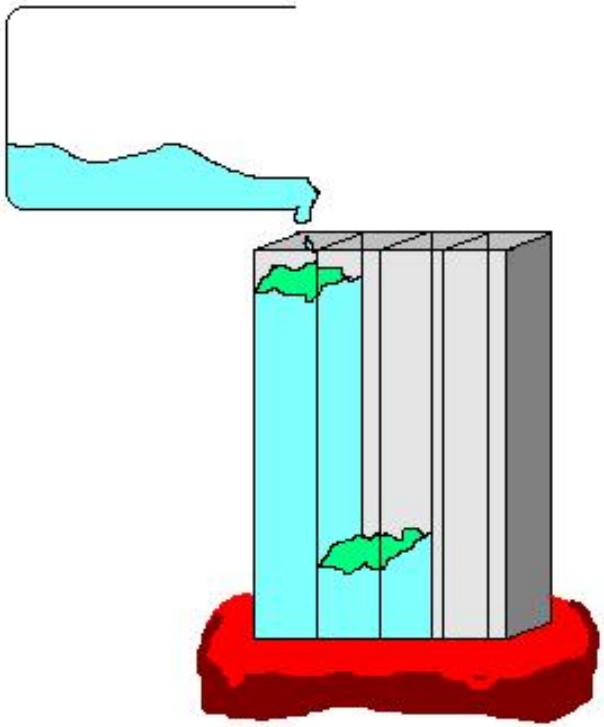
- dissolution
- gelation
- regeneration
- aging

Mixing



Dissolution

Gelation on cooling (80°C) and regeneration



The wet gel is ready and now?

Drying – determines everything*!

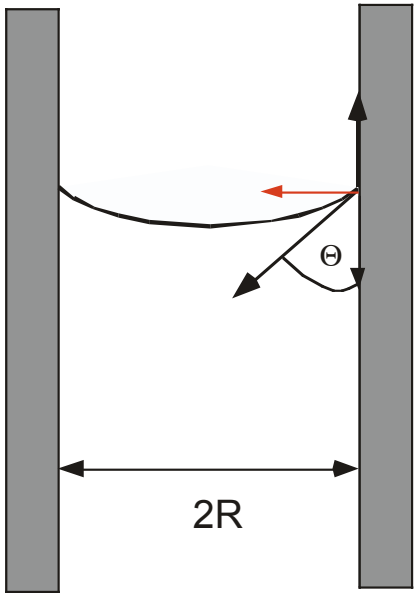
methods: air freeze drying supercritical

Drying under ambient condition leads to Xerogels

- huge shrinkage
- Destruction of the nanosized pore system
- Fragmentation of the gel body
- Porosity between 5 and 50 %
- but:

  proper drying routine can give perfectly shaped xerogels!

capillary forces



wetting stresses lead to a collapse of the gel network

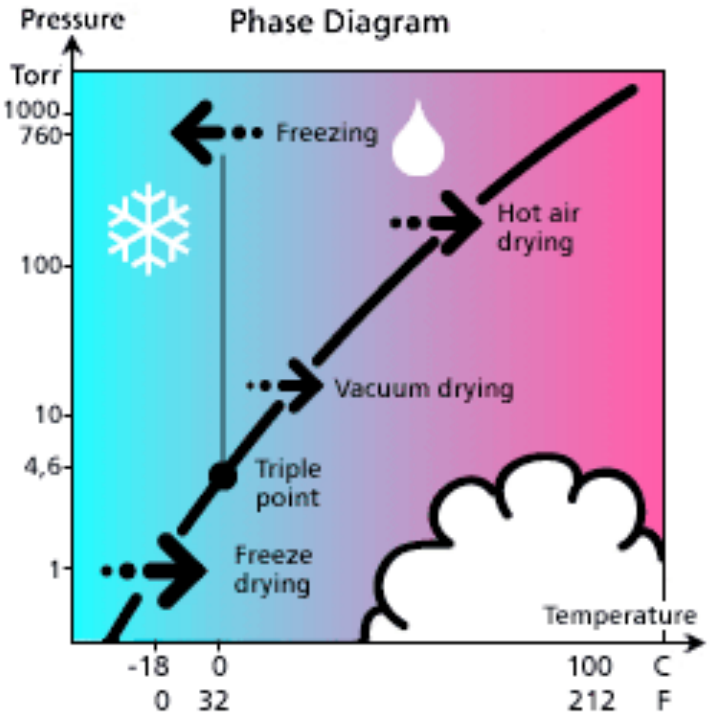
$p \approx 1/R$

* not really, but it is the essential step

Drying – determines everything!

methods: air freeze drying supercritical

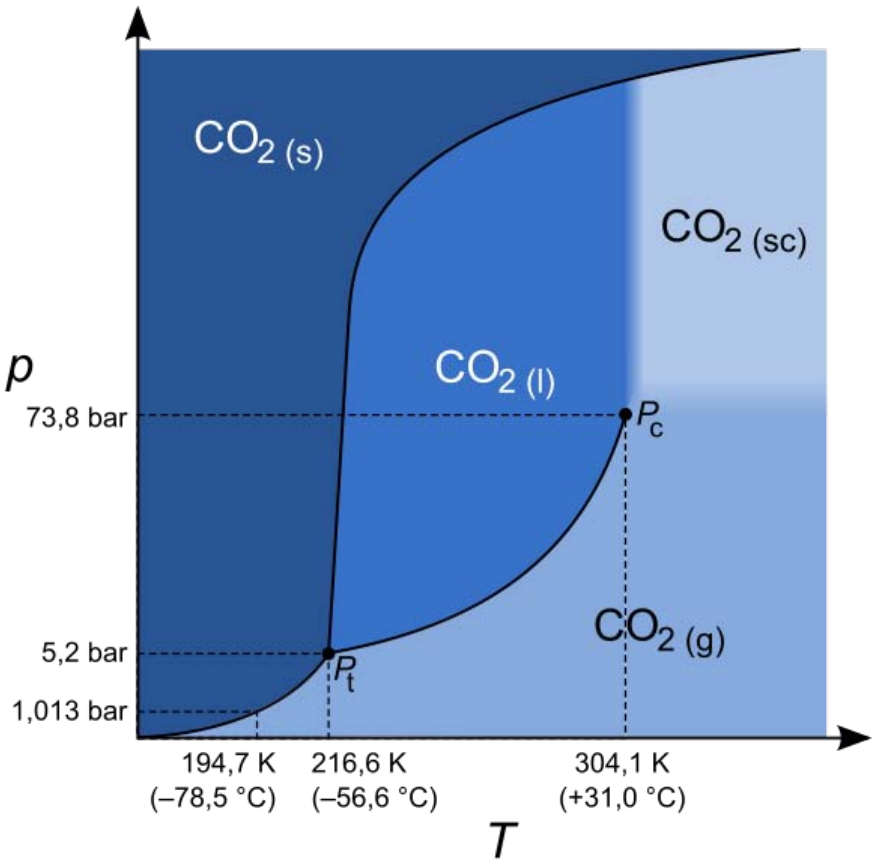
- Shock or rapid freezing (after solvent exchange) to minimize freezing effects on the solid gel structure
- Sublimation along the sublimation line by
  - pressure changes and
  - temperature increase



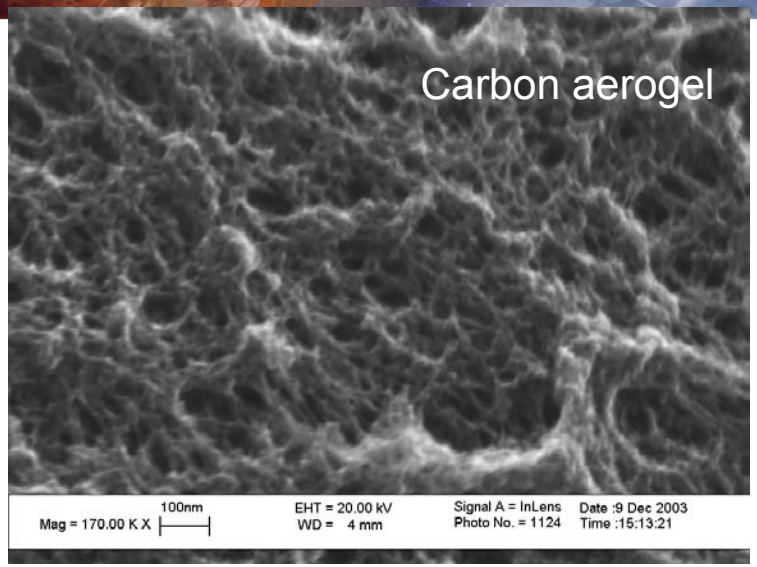
Drying – determines everything!

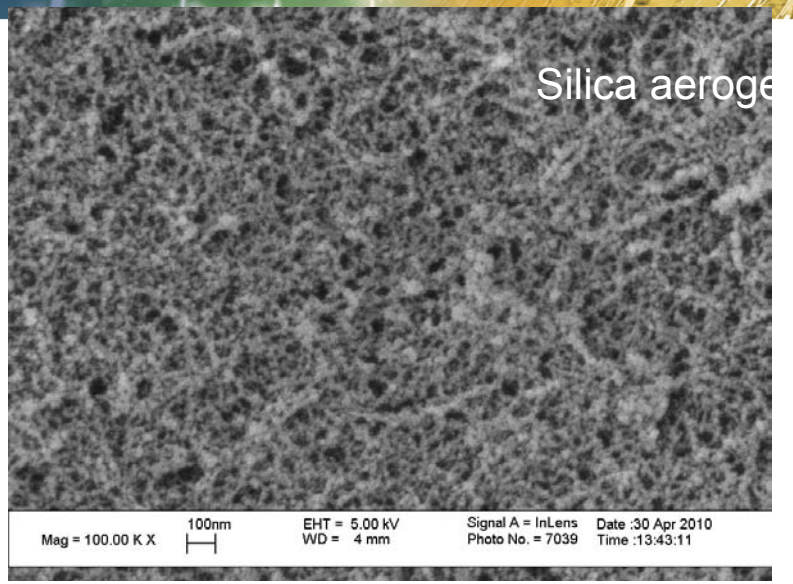
methods: air freeze drying supercritical

- Solvent exchange gel liquid against CO_2
- Temperature increase above critical point
- T_c=31.1°C, 73.8 bar.
- Real process ≈ 40 °C with pressure of ≈ 90 bar
- Slow depressurization

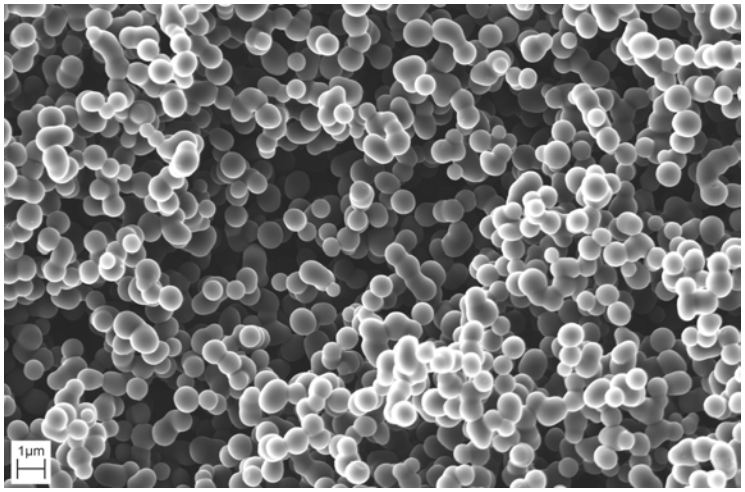


And the result?

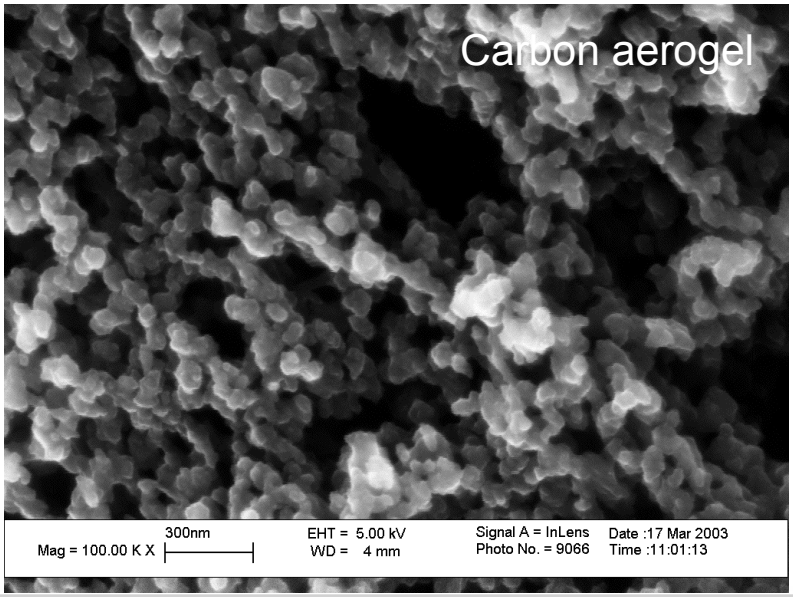


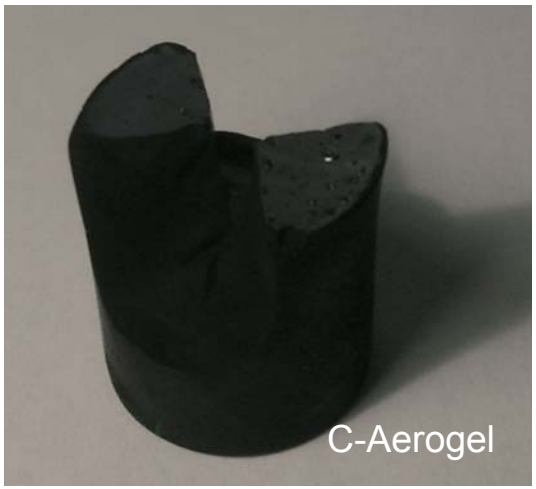


Answer: almost always a nanostructure

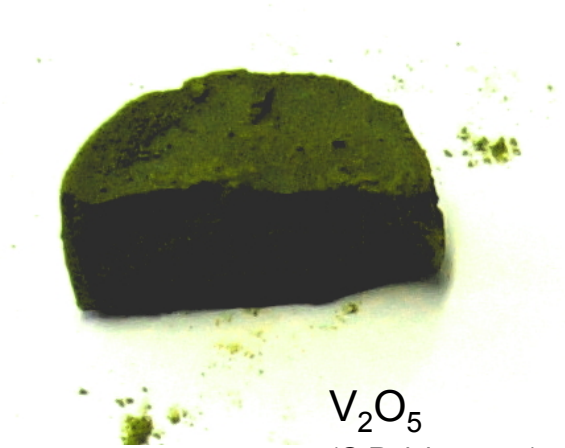


RF-Aerogel (HCl catalysed)



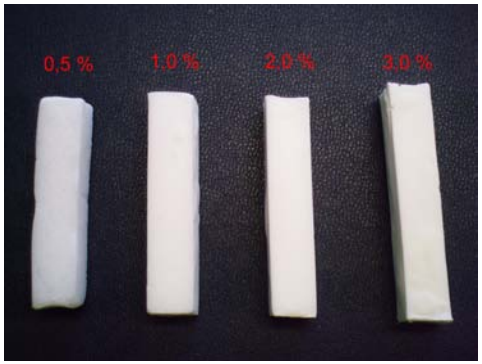


Appearance of some aerogels



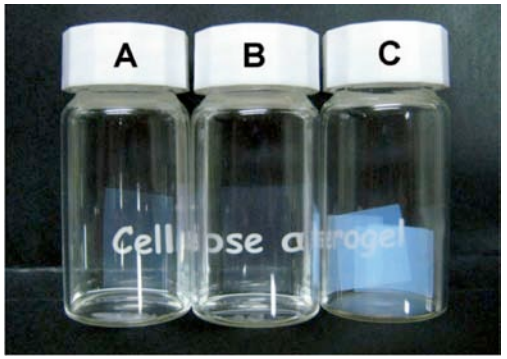
RF-Aerogel

Appearance and structure of Cellulose aerogels



Cellulose-Aerogels are generally opaque and milky with densities of around 5 - 60 kg/m^3

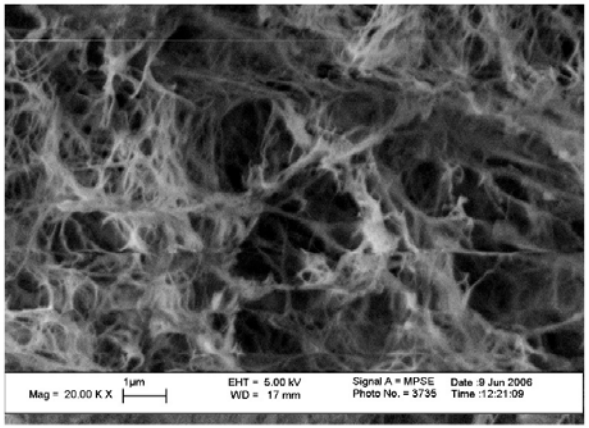
Structure: nanofelt of microfibrils



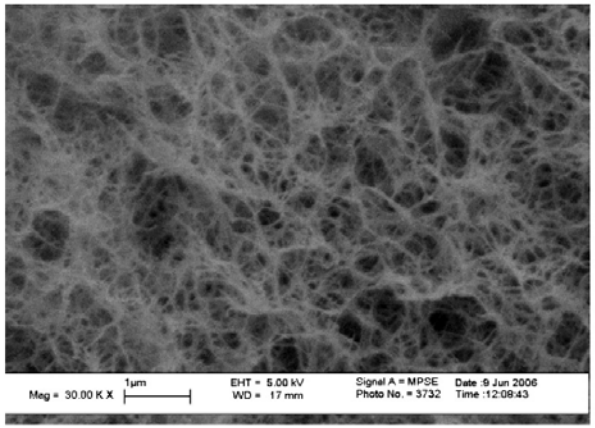
Cai et al, ChemSusChem 2008

Aerogels with

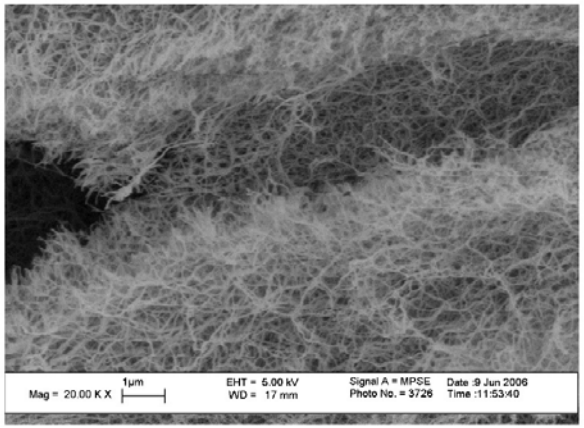
0,5 % Cellulose



1,0 % Cellulose



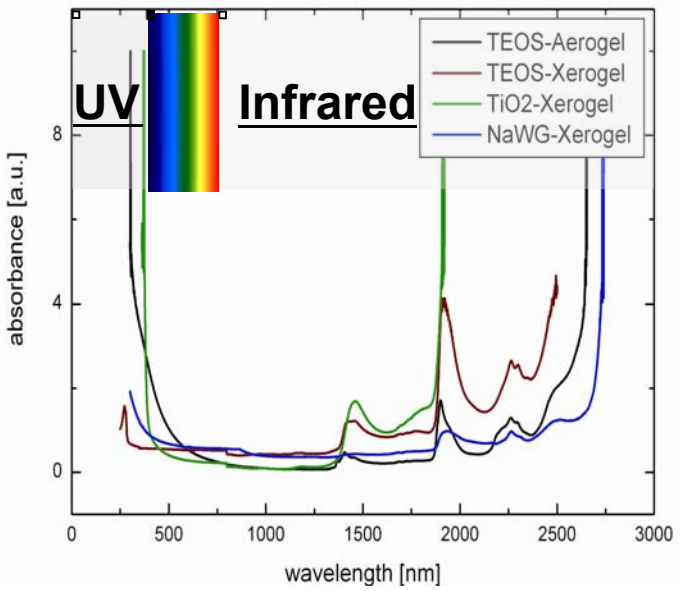
2,0 % Cellulose



Properties

Properties of aerogels

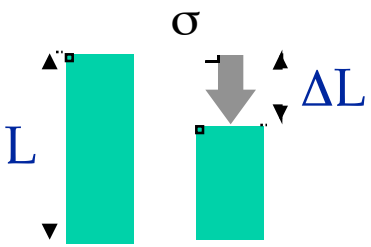
- Low density - high porosity
  - 90 - 99,9 % porosity
- Large sound absorption - low sound velocity
  - damping > 50 dB, $v_l \approx 100$ m/s
- Low thermal conductivity
  - 0.005 - 0.1 W/mK
- Transparent or opaque or can be coloured
  - variable refractive index (1,001 to 2,1)
- No reaction with metallic melts up to 950°C (Silica and some other oxide aerogels)
- Huge internal surface
  - 10 - 2000 m^2/g
- Surface can be functionalized
  - Hydrophobic by polymeric residues ($-CH_3$)
  - CVD deposition of magnetic layers
- Functionalisation of the gel body
  - Embedding of particles (e.g. dyes, ferroelectrics)
  - Interpenetrating hybrid aerogel networks



Mechanical properties of aerogels

Young's modulus

pressure

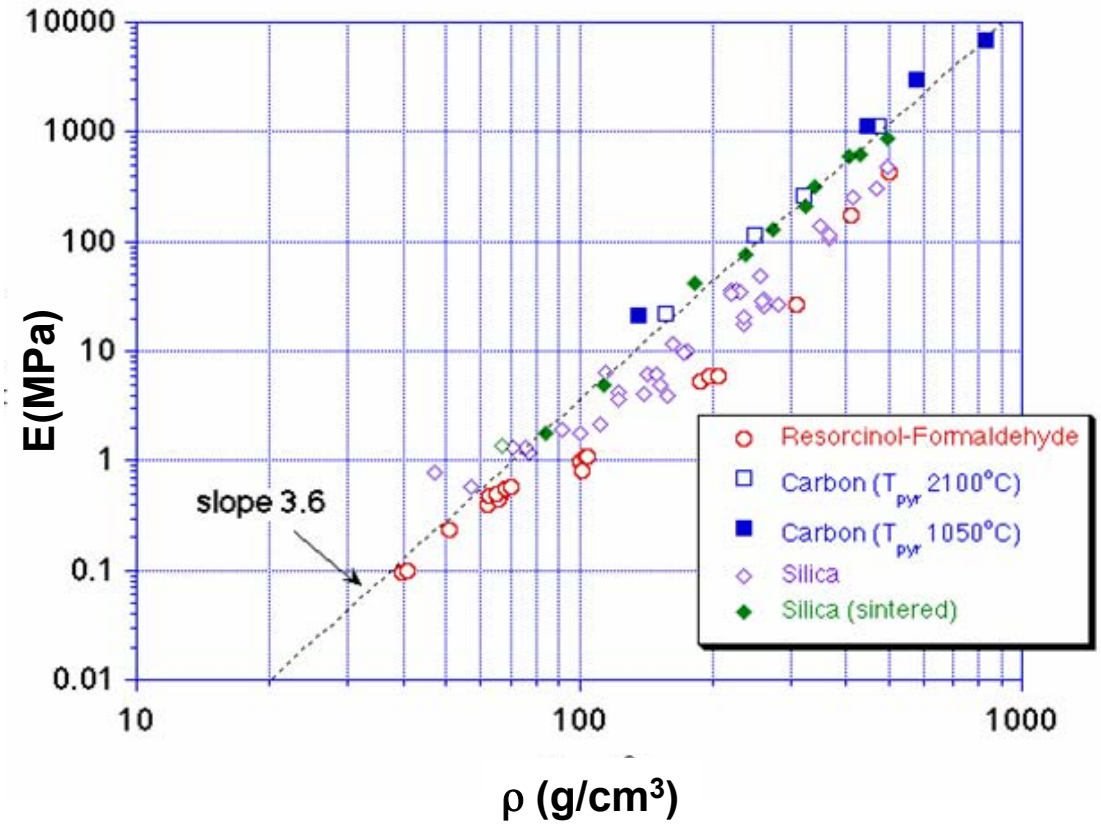


$$\sigma = \frac{\Delta L}{L_0} \cdot E = \varepsilon \cdot E$$

Fracture strength:

Silica-Aerogels: 20 kPa bis 2 MPa
RF-Aerogels: 100 kPa bis 10 MPa

after Gross et al. JNCS 1992

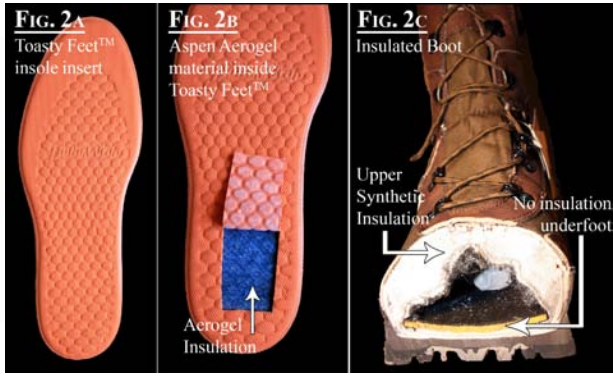


$$\sigma_B \propto \rho^{1.5} \qquad E \propto \rho^{3.6}$$

Are there applications?

Industrial areas of application

- thermal insulation
  - **home building**, vehicles, **pipelines, packaging**
- electronic components
  - **capacitors**, humidity sensors, batteries, fuel cell, soft magnets, Geiger counter, IR detector
- foundry technology
  - **aerogelic binders, aerogel granules for foundry sands**
- architecture
  - **illumination, superlight concrete, wall isolation**
- superlight composites
- non-linear optics (SHG)
- Cosmetics
- Pharmacy (drug delivery)
- Apparel & sportsware
  - Tennis rackets
  - Security shoes
  - Sport shoes
- Space
  - Space suits
  - Anti-sloshing in tanks
  - Cryogenic tank insulation



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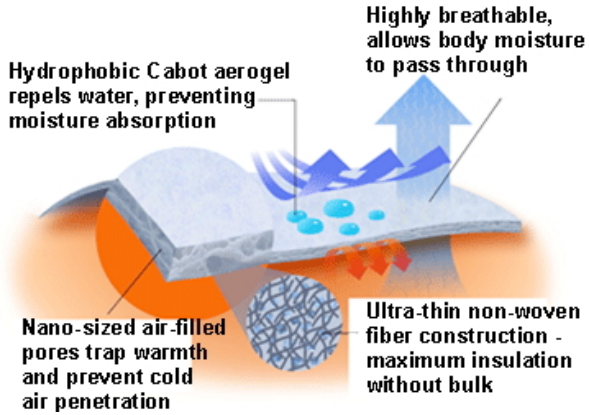
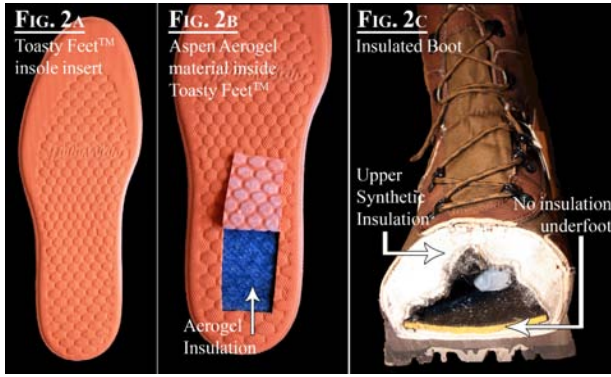




Suppliers? Vendors? Who delivers what?

Aerogel granulates

Company: Cabot (Frankfurt)

- Material: water glass
- Shape: polyhedric 0.5 - 4 mm
- transparent
- super hydrophobic
- price ≈ 2000 € /cbm
- dried at ambient conditions

Company: Dow Corning

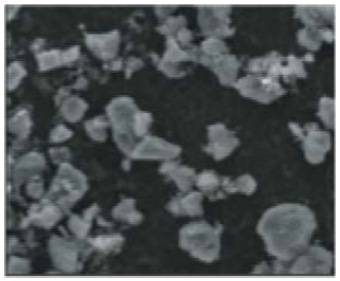
- material: pure quartz
- super hydrophobic

- Application in cosmetic products

TL - Translucent

Particle Size Range:	≈ 0.5 to 4.0 mm (0.02 to 0.16 in)
Pore Diameter:	≈ 20 nm
Porosity:	> 90%
Bulk Density:	90 to 100 kg/m³ (5.6 – 6.2 lb/ft³)
Surface Chemistry:	Fully Hydrophobic
Thermal Conductivity:	0.018 W/m-K at 25°C (0.125 Btu-in/hr-ft²-°F)
Surface Area:	600 to 800 m²/g
CAS RN:	102262-30-6

density	40 - 100 kg/cbm
Particle size	5 - 15 µm
Surface area	600 - 800 m²/g
porosity	> 90%



Aerogel tiles

company: Airglass (Schweden)

- material: Silica (precursor TMOS:Methanol)
- Hydrophilic
- Drying is made supercritically (methanol)

Density	50 - 200 kg/m³
Refractive index	1.02 - 1.05
Heat transfer coeff.	0.021 W/m°C At 20°C(68°F) rising to 0.2 at 300°C(570°F)
Non deforming	up to 750°C(1380°F)
Chemical composition	99.99%SiO2
Standard size today	60 x 60 x 2 cm³ (2 ft x 2 ft x 3/4 inch)
Grain size	10 - 30 nm in diameter

price:

- tiles 10 x 10 x 1 inch ≈ 500 €
- granulate 1 L ≈ 150 €

Airglass AB
BOX 150
245 22 Staffanstorp
SWEDEN

www.airglass.se
TEL: +46 46 255200
FAX: +46 46 25692

Aerogel pieces & papers

company: MarkeTech (USA)

- material:
  - Silica (TEOS:Methanol)
  - RF aerogel pieces and paper
  - Carbon aerogel (pieces and paper
- hydrophilic
- shape: small tiles and pieces
- price:
- Random pieces: 100 g ≈ 880 US$
- Tiles (4x8x0,5“) = 1228 US$

Marketech International Inc.
107B Louisa Street
Port Townsend, WA 98368
Tel: 360-379-6707
Toll Free: 877-452-4910
Fax: 360-379-6907
info@mkt-intl.com

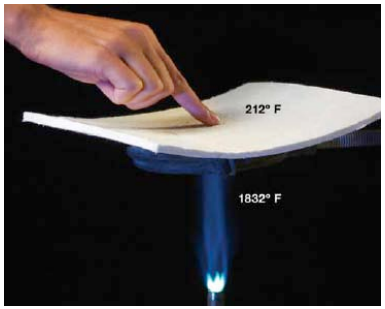
Properties	Value
Density	0.1 (0.3 - 0.05) g/cm^3
Dielectric Constant	1.14 (18 - 40 Ghz)
Surface Area, BET	800 m^2/g
Percent Solids	0.13 - 15%
Mean Pore Diameter	~20 nm
Primary Particle Diameter	2 - 5 nm
Index of Refraction	1.0 - 1.05
Thermal Tolerance	to 500°C
Poisson's Ratio	0.2
Young's Modulus	10^6 - 10^7 Nm^2
Tensile Strength	16 kPa
Fracture Toughness	~0.8 kPa*m$^{1/2}$
Compressive Modulus	0.3 MPa
Coefficient of Thermal Expansion (CTE)	2 ppm/C° @20 - 80°C
Electrical Resistivity	10^{15} ohm-cm
Thermal Conductivity in Air	0.016 W/m/°K
Thermal Conductivity in Vacuum	0.004 W/m/°K
Sound Velocity Through the Medium	100 m/sec
Color	translucent

http://www.mkt-intl.com/index.shtml

Aerogel blankets

company: Aspensystems (USA)

- material: fibre composite
  - Silica-Aerogel on polymeric fiber felt
  - Silica-Aerogel on glass fibers
- superhydrophobic



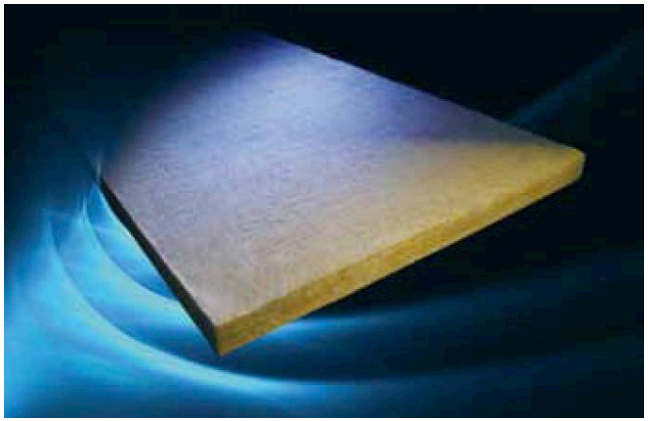
ASPEN AEROGELS, INC.
30 Forbes Road, Building B
Northborough, MA 01532
USA
Tel: 1.508.691.1111
Fax: 1.508.691.1200

Product Name	Nominal Thickness		Thermal Conductivity		Density		Maximum Use Temperature	
	mm	in	mW/m-K	Btu-in/hr-ft^2-°F	g/cc	lb/ft^3	°C	°F
Cryogel™ 6000 Data Sheet MSDS-English	6.0	0.24	13.5	0.094	0.13	8.0	40	100
Spaceloft™ 3251 Data Sheet MSDS-English	3.0	0.12	14.0	0.097	0.15	9.4	200	390
Spaceloft™ 6251 Data Sheet MSDS-English	6.0	0.24	14.0	0.097	0.15	9.4	200	390
Spaceloft™ 9251 Data Sheet MSDS-English	9.0	0.36	14.0	0.097	0.15	9.4	200	390
Spaceloft™ 6250 Data Sheet MSDS-English	6.0	0.24	12.5	0.087	0.13	8.0	200	390
Pyrogel® 2250 Data Sheet MSDS-English MSDS-French MSDS-Italian	2.0	0.08	15.5	0.107	0.17	10.7	250	480
Pyrogel® 6250 Data Sheet MSDS-English MSDS-French MSDS-Italian	6.0	0.24	15.5	0.107	0.17	10.7	250	480
Pyrogel® 6350 Data Sheet MSDS-English MSDS-French MSDS-Italian	6.0	0.24	15.5	0.107	0.17	10.7	350	660

http://www.aerogel.com/

Aerogel blankets

Composite of mineral wool and silica aerogel



Koebel 2007

Brand name: Aerowoλλe®

Thermal conductivity 0.019 W/mK

And some other companies

- Aerogel Composite
  - Product: Polymeric (RF) and Carbon aerogels, crushed and compressed into arbitrary shapes
  - http://www.aerogelcomposite.com

PROPERTIES OF CARBON AEROGELS	
Density (g/cm^3)	0.1 - 0.6
Surface Area (m^2/g)	
Average Pore Size (nm)	4 - 30
Electrical Conductivity (S/cm)	1 - 10

- American Aerogel
  - Product: VIPs
  - http://www.americanaerogel.com

- Nano High-tech Co, China
  - Products: everything all others fabricate

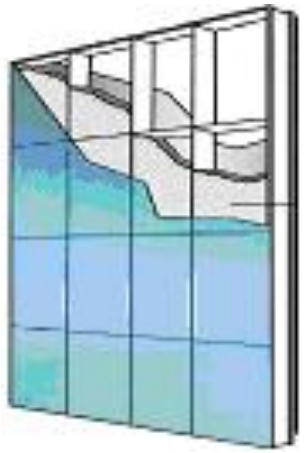
    Granular materials, tiles, blankets, hydrophobic, fibre reinforced...

Examples of industrial applications

Illuminating systems - diffusers

Basic idea: transparent to translucent aerogel granules scatter light into all directions
Technology: fill hollows plates with aerogel grains.
Company: Cabot (brand name: Nanogel) in co-operation with window companies

Effects:
a) Diffusive illumination of rooms
b) Thermal insulation



before

after

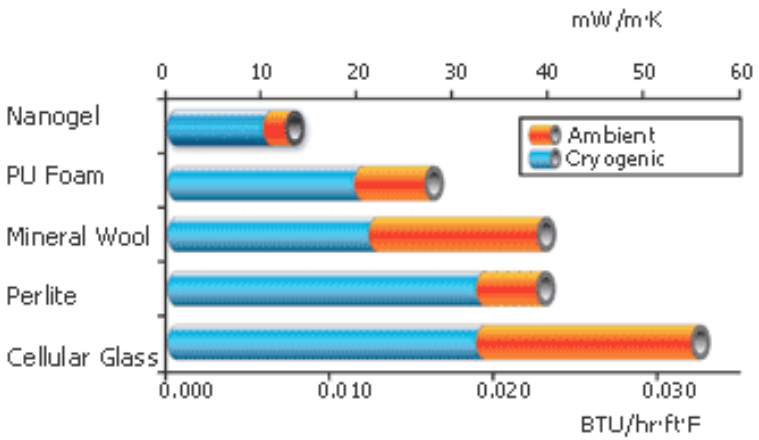
Isolation of subsea pipelines

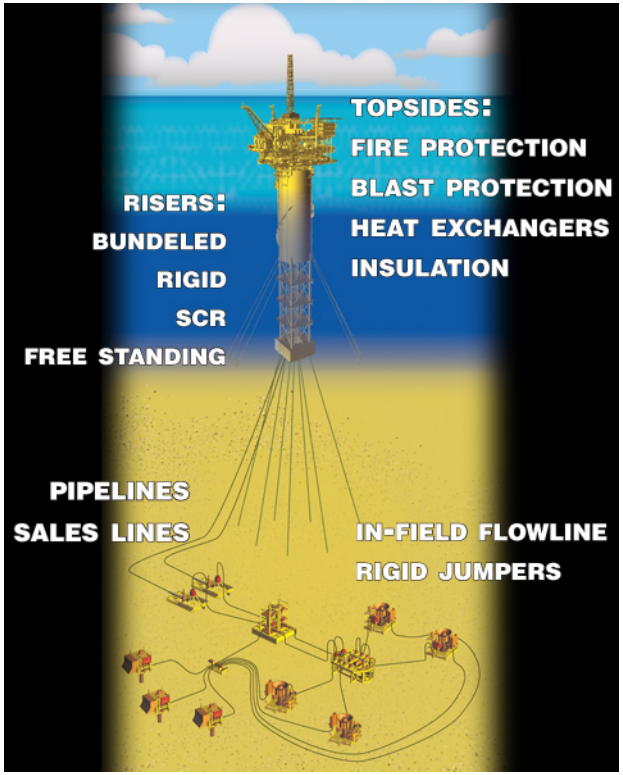
Basic idea:

Utilize low thermal conductivity of aerogels

Challenges:

- Huge mechanical loads in subsea double walled pipelines (dynamic and static)
- High temperature of the raw oil -> cooling leads to clogging
- High service life





Insulation of Pipelines - solutions

Vendors:

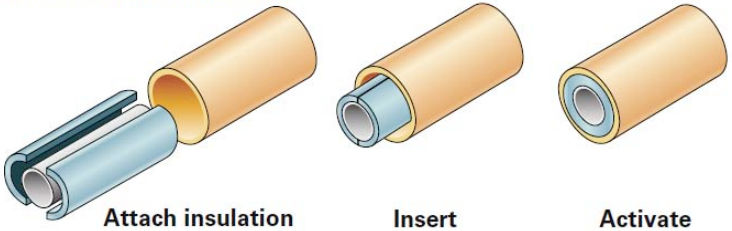
- Cabot
- Aspenssystems

Different technical solutions

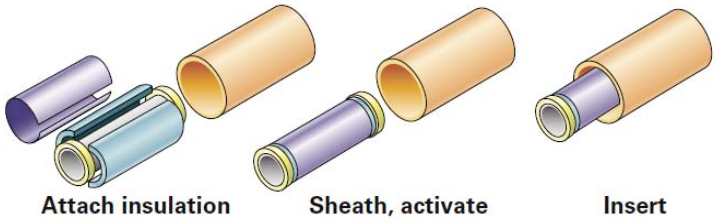
Cabot: Compression/Expansion-Pack

Aspen: aerogel blankets

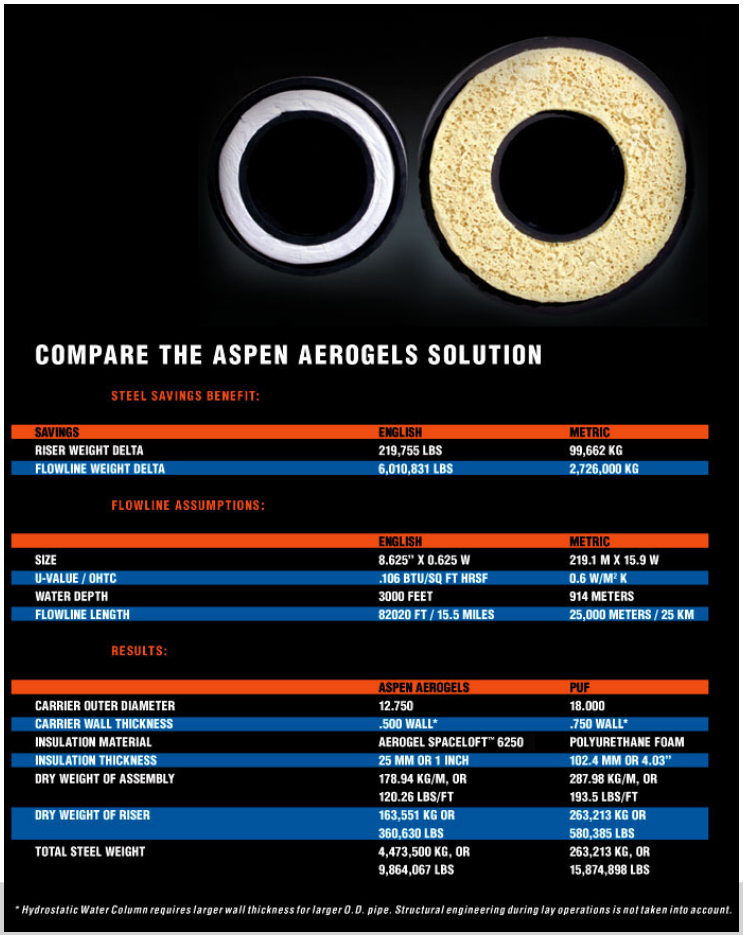
EXPANSION PACK INSTALLATION



COMPRESSION PACK INSTALLATION



source: Cabot.com



COMPARE THE ASPEN AEROGELS SOLUTION

STEEL SAVINGS BENEFIT:

SAVINGS	ENGLISH	METRIC
RISER WEIGHT DELTA	219,755 LBS	99,662 KG
FLOWLINE WEIGHT DELTA	6,010,831 LBS	2,726,000 KG

FLOWLINE ASSUMPTIONS:

	ENGLISH	METRIC
SIZE	8.625" X 0.625 W	219.1 M X 15.9 W
U-VALUE / OHTC	.106 BTU/SQ FT HRSF	0.6 W/M² K
WATER DEPTH	3000 FEET	914 METERS
FLOWLINE LENGTH	82020 FT / 15.5 MILES	25,000 METERS / 25 KM

RESULTS:

	ASPEN AEROGELS	PUF
CARRIER OUTER DIAMETER	12.750	18.000
CARRIER WALL THICKNESS	.500 WALL*	.750 WALL*
INSULATION MATERIAL	AEROGEL SPACELOFT™ 6250	POLYURETHANE FOAM
INSULATION THICKNESS	25 MM OR 1 INCH	102.4 MM OR 4.03"
DRY WEIGHT OF ASSEMBLY	178.94 KG/M, OR 120.26 LBS/FT	287.98 KG/M, OR 193.5 LBS/FT
DRY WEIGHT OF RISER	163,551 KG OR 360,630 LBS	263,213 KG OR 580,385 LBS
TOTAL STEEL WEIGHT	4,473,500 KG, OR 9,864,067 LBS	263,213 KG, OR 15,874,898 LBS

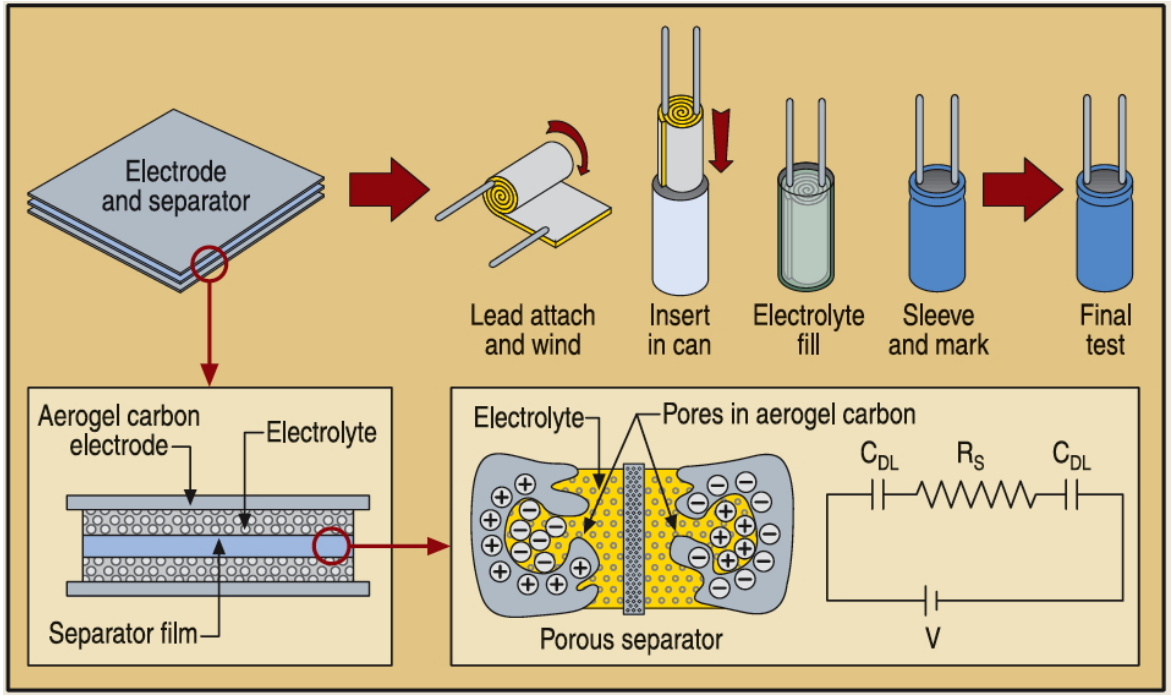
* Hydrostatic Water Column requires larger wall thickness for larger O.D. pipe. Structural engineering during lay operations is not taken into account.

Electronic components - capacitors

Basic idea: use the large internal surface of aerogels

capacity is proportional to area!

Material: Carbon aerogels as thin films



Specific values
100 - 300 F/g

Fibre reinforced and CNT additions of aerogels lead to ≈ 750 F/g

1225 Broken Sound Pkwy. Suite F Boca Raton, FL 33487
Tel: +1-561-998-4100 Toll Free: +1-888-414-2645 Fax: +1-561-241-6640

Home building & insulation - Challenges

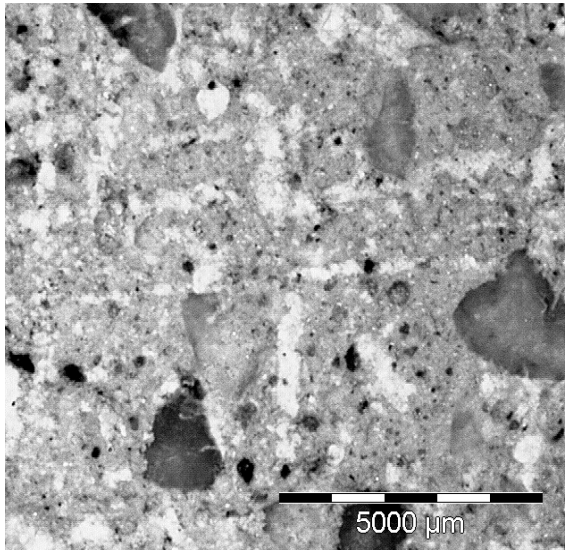
- Energy savings by thermal isolation measures
- Regulation of indoor climate
- Light weight material (1-person structural panel)
- High fire protection class (> F120)
- Utilization of natural construction materials
- No colonization by fungi
- Low cost material

A solution

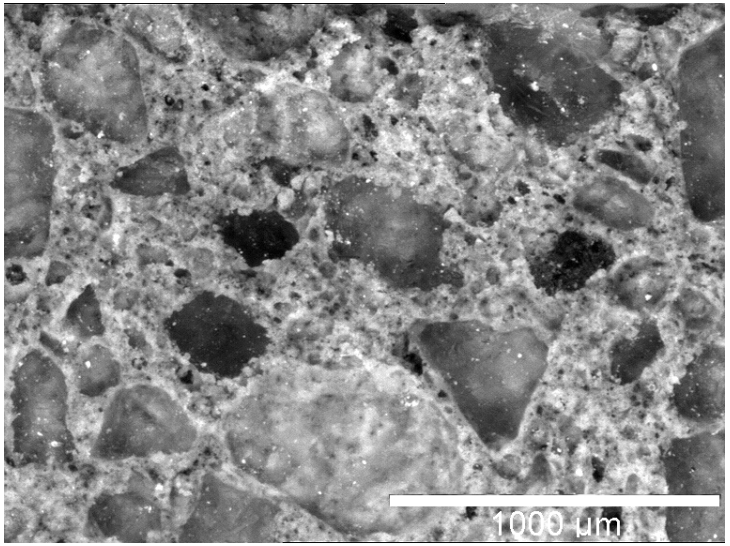
aerogel concrete

Aerogel concrete is a

- composite made from
  - hydrophobic Aerogel granulate and
  - inorganic Binder/Matrix
- binder / matrix materials
  - gypsum or plaster
  - cement or rendering
- technical challenges
  - Extreme density difference aerogel / matrix
  - Bonding strength aerogel-matrix interface

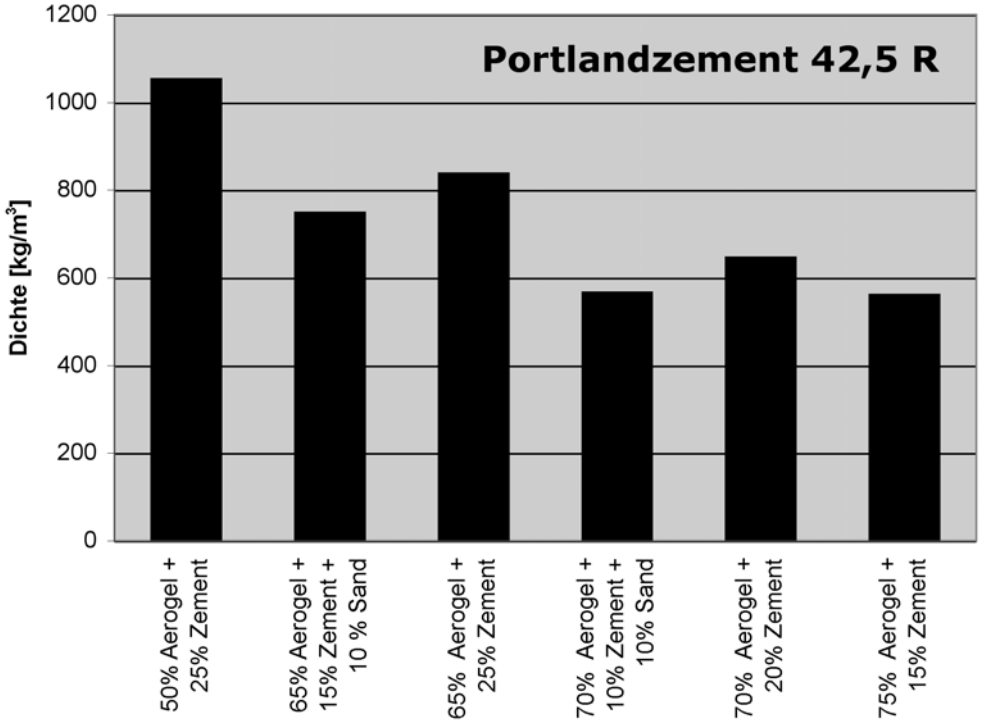


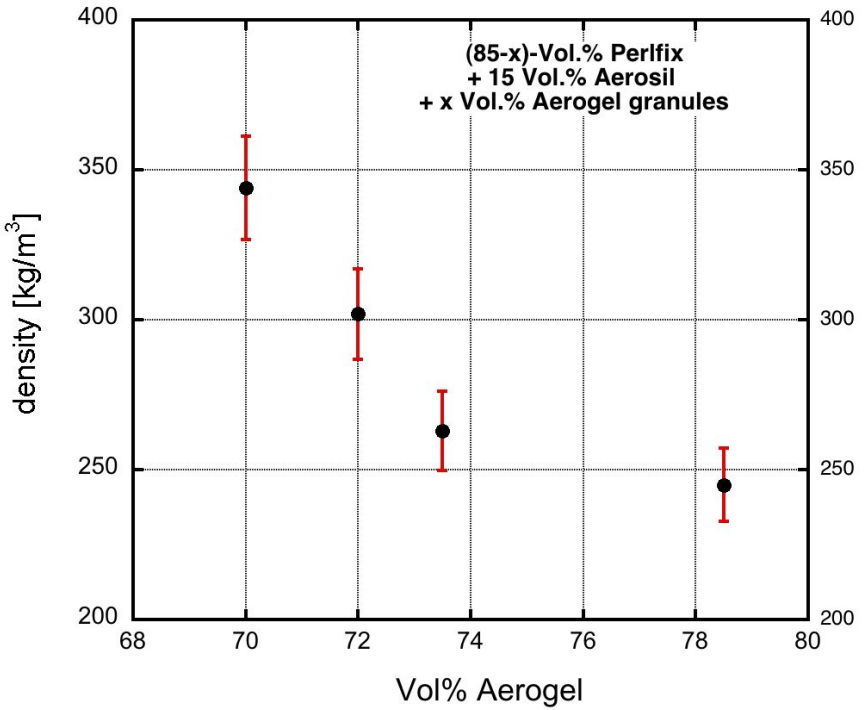
Aerogel granules + Goldband ™



Aerogel granules + cement

Density





Lowest density with hydrophobic Aerogel granules:

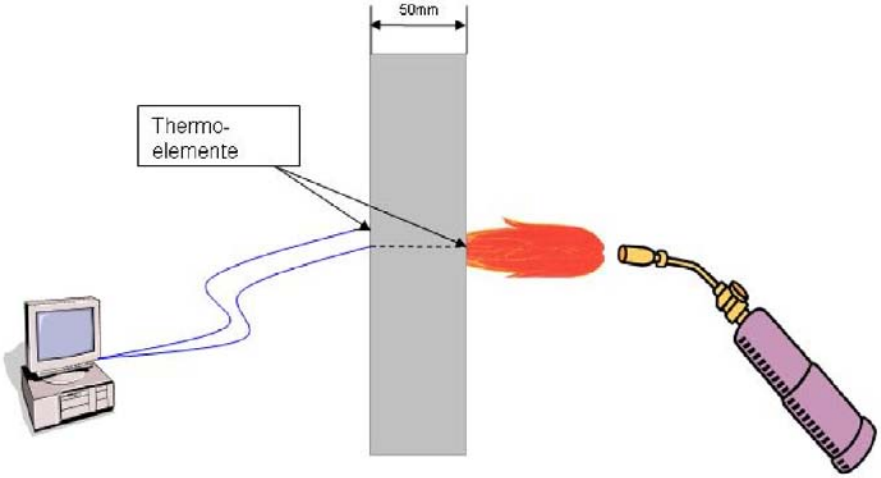
Values between 600 and 1100 kg/m^3

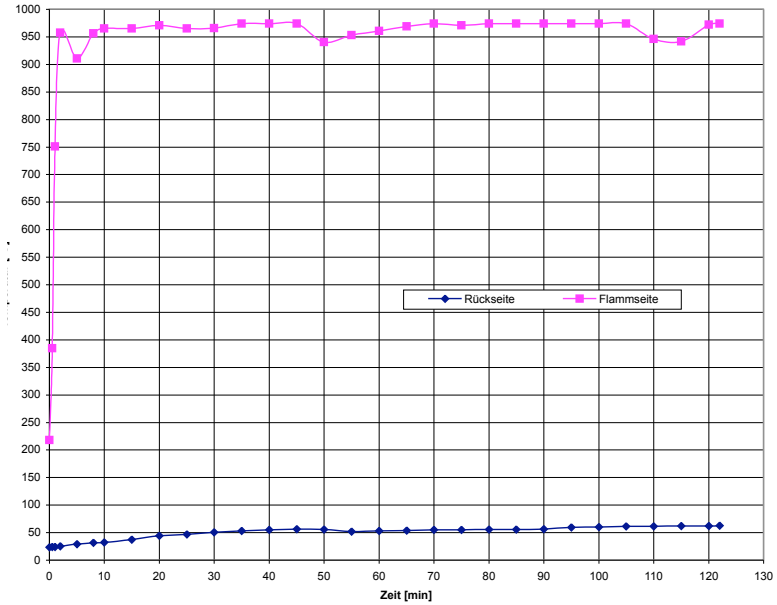
Lowest density material made by us:

Pure building plaster with ≈ 80% aerogel granules at 250 kg/m^3

Fire protection

- requirement: better than fire class F90
- Laboratory tests close to DIN-Norm





Thermal conductivity and U-value

Aerogel content [vol%]	Heat conduction [W/mK]	U-value (25 cm wall thickness)
65% (+10% Sand)	0,16	0,64
70% (+10% Sand)	0,11	0,44
70% (without Sand)	0,13	0,52

construction material	wall thickness	U-value [W/m²K]
massive concrete	25 cm	3,3
common brick	24 cm	1,5
common brick (17,5 cm) plus PUR damping	30 cm	0,32
honeycomb brick	25 cm	0,34 - 0,46
massive wood	20,5 cm	0,5
timber frame construction	25 cm	0,15 - 0,2

The future of aerogel concrete in the Netherlands?

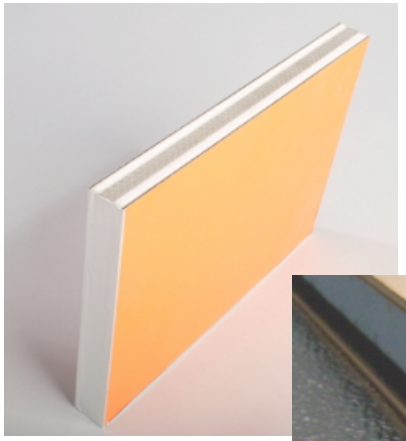
Built by students of the University Duisburg-Essen

Canoe made form high strength concrete and aerogel to save weight.

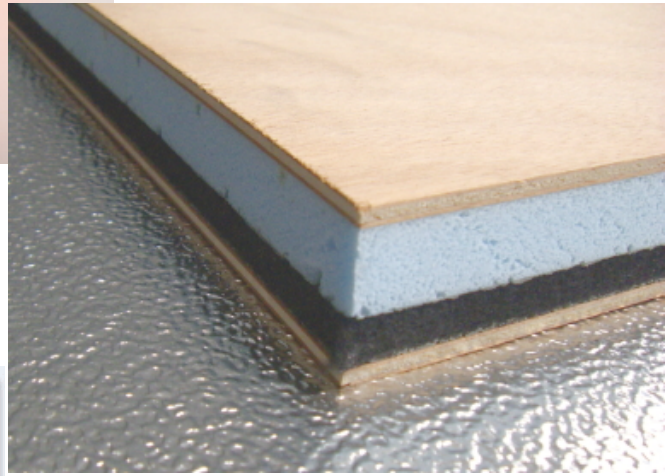
Other solutions

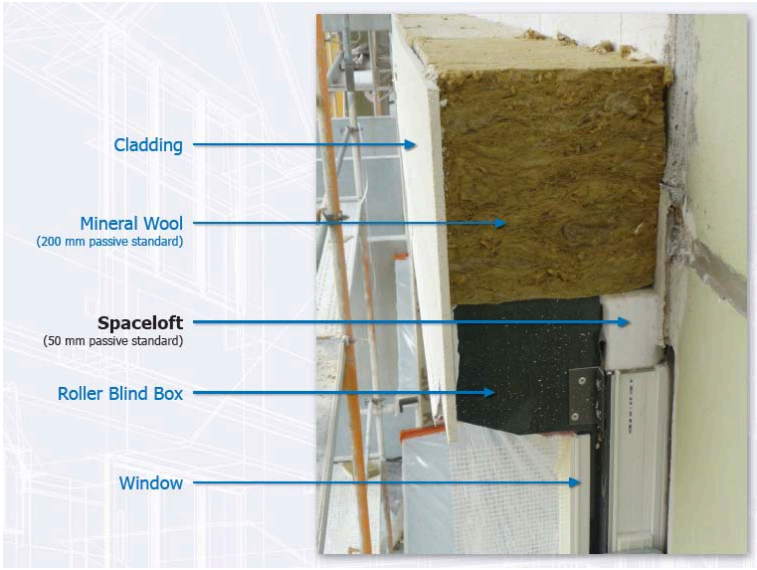
- Structural panels:
  - Composite of PU-foams or styrofoams plates with aerogel-infiltarted felts

    U-value=0.34
- Aerogel wrap for storefront



Stadur-Süd





Foundry applications

Casting of metals in a mould needs a mould material

Mould materials: sands = sand casting

metals = permanent mould casting

ceramics = investment casting

Sand grains must be bonded!

Binders used:

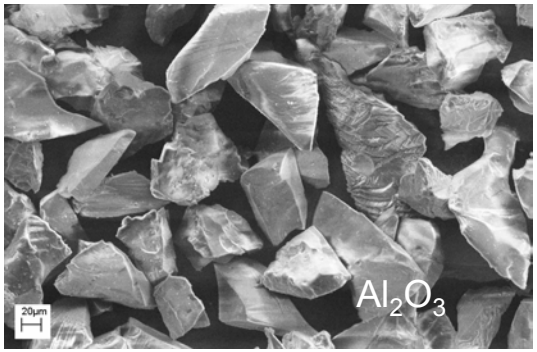
oils, polymers (phenol based, polyurethane, epoxy resins,...)

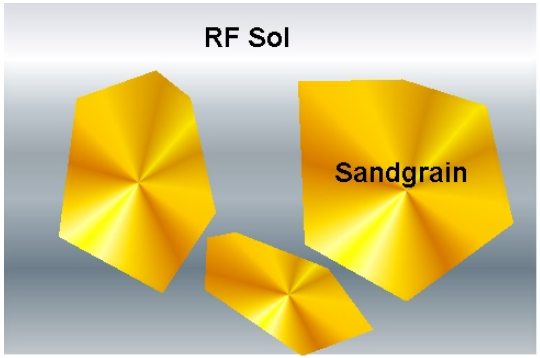
water glass,...

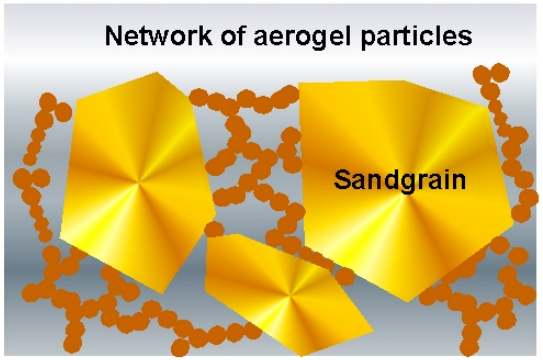
new: binder = RF Aerogel = AeroSand

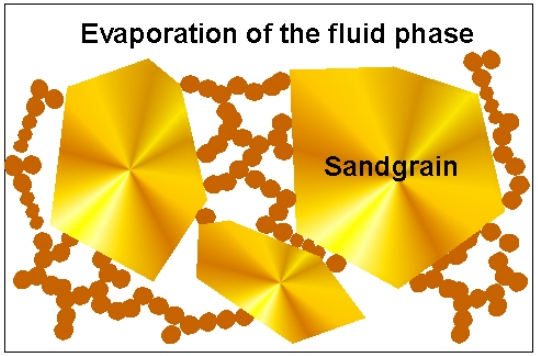
Technology:

Preparation of RF-sol, mixing with sand, core shooting, ambient drying, ready!



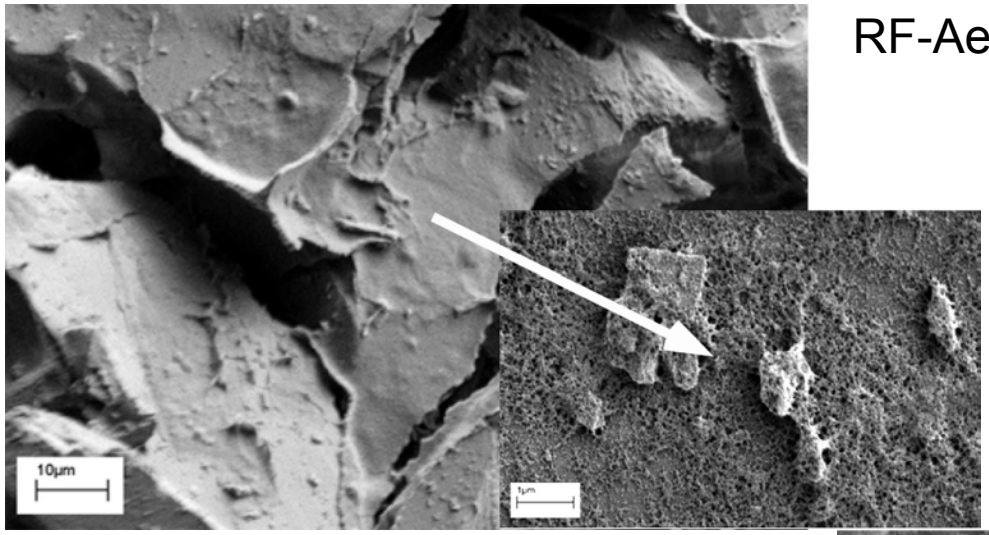




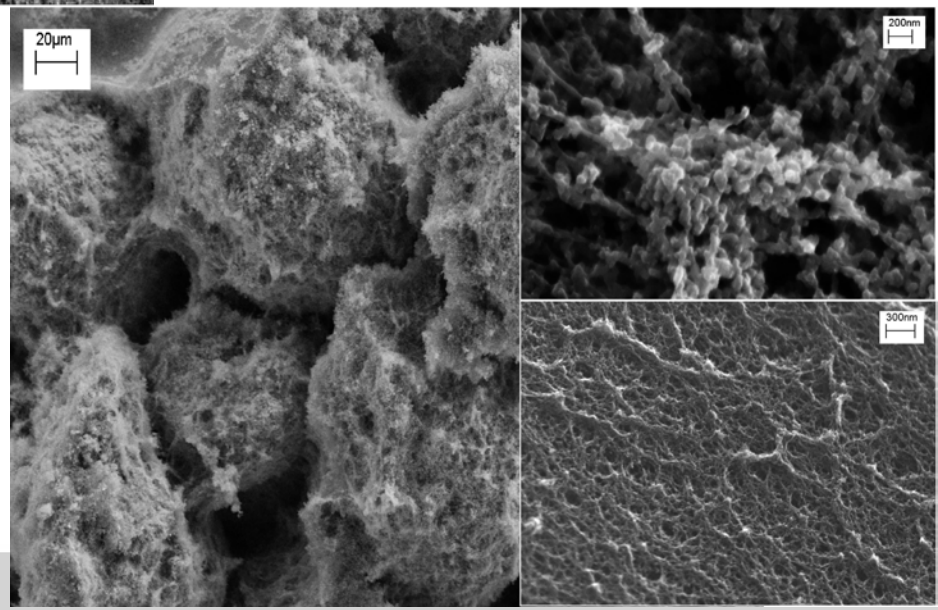


Brück-Ratke Giessereiforschung 56 (2004) 55 - 65
Voss-Ratke Giessereiforschung 57 (2005) 18-25
Reuß-Ratke Giessereiforschung 61 (2009) 24 - 33

AeroSands - real structure



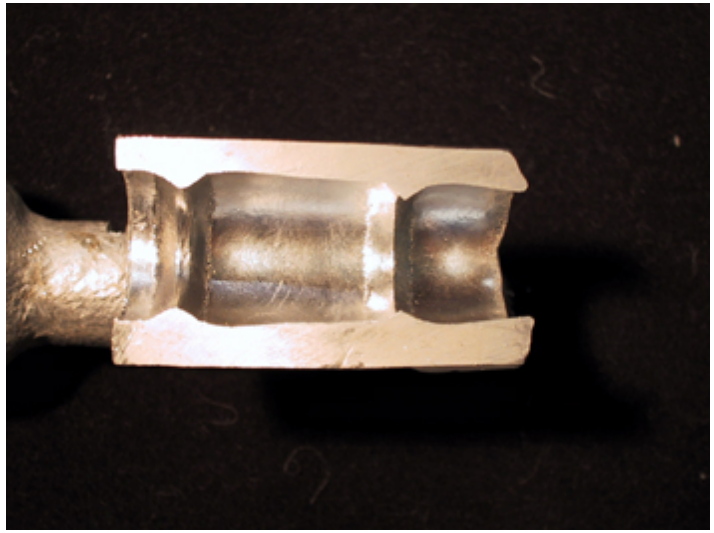
RF-Aerogel with corundum sand

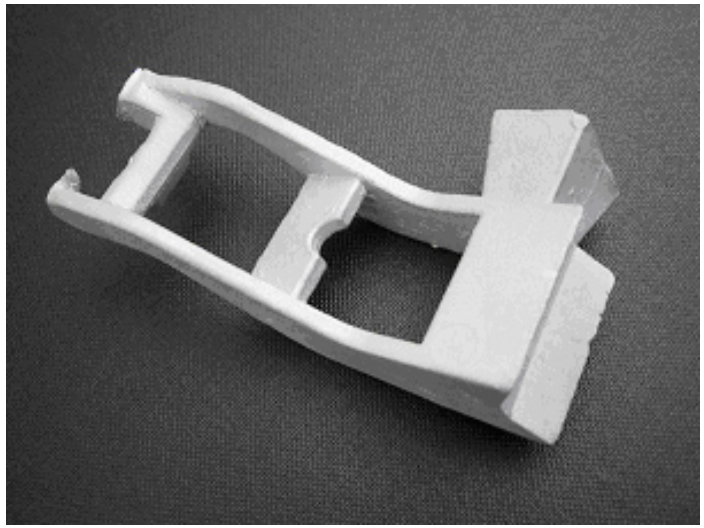


Carbon aerogel with
Corundum sand

AeroSands - properties

- Easy core removal
- Thermal conductivity 0,3 - 2 W/Km
- High strength 100 to 600 N/cm^2
- Smooth surfaces
- No shrinkage
- No gas release during casting
- Insensitive to humidity

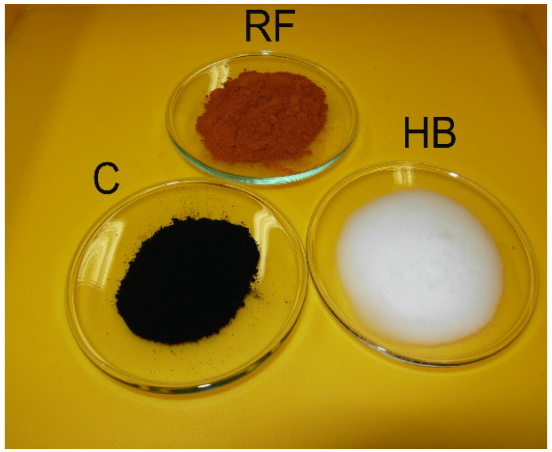




Aerogel based additives

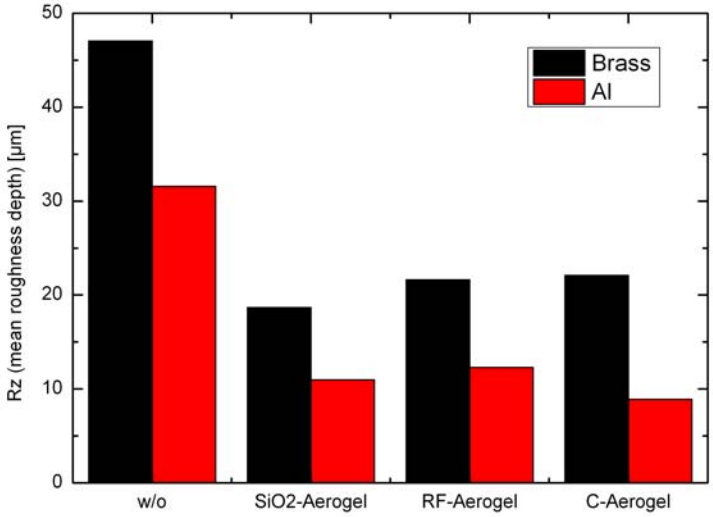
idea:
Mix aerogel granules with foundry sands to improve the cast piece and work without a facing

utilizing:
- Large surface area
- High adsorption capability
- Non-wetting with metals

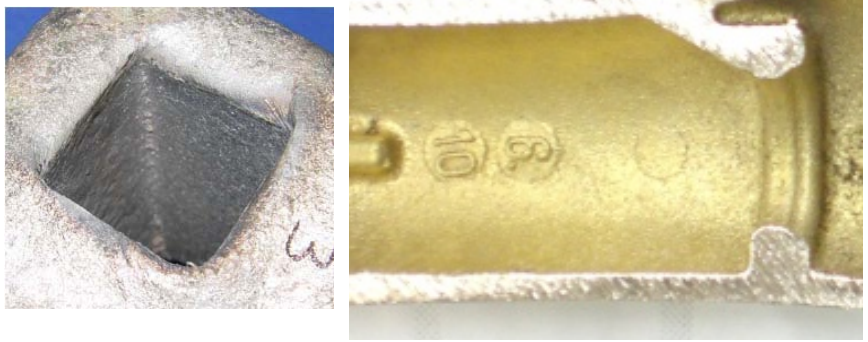


- Granulate from
  - Silica-Aerogel (sc and ambient dried)
  - RF Aerogel
  - Carbon aerogel
- Particle size:
  - Fits to sand grain size
  - Volume fraction: ≤ 5 Vol.%
- Binder:
  - Whatever is used in a foundry shop
  - RF-aerogel binder

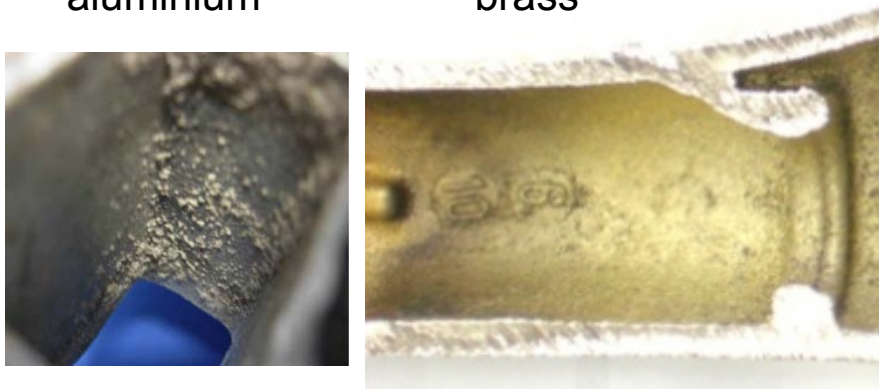
Aero-Additives



with 1.5 vol.-% RF-Aerogel



aluminium brass



w/o Nano-Additives

Effects of aerogels in brass, aluminium and bronze castings

Summary

Oxide aerogels, polymeric aerogels, mixed aerogels, hybrids, composites with fibers and felts offer a wide variety of applications going far beyond what is explored today and is on the market.

„The global market for aerogels is expected to grow up from $62 Million in 2006 (700t) to $951 Million in 2011 (12,679t).“

JOM 58 (August 2006) 10-11