Applying Physics and Nanotechnology for Making the Thermal Insulation Materials of Beyond Tomorrow - From Concept to Experimental Investigations - A Lecture in the Physics Motivation Series

Bjørn Petter Jelle[ab]

[a]Department of Materials and Structures,
SINTEF Building and Infrastructure, NO-7465 Trondheim, Norway.

[b]Department of Civil and Transport Engineering,
Norwegian University of Science and Technology (NTNU), NO-7491 Trondheim, Norway.

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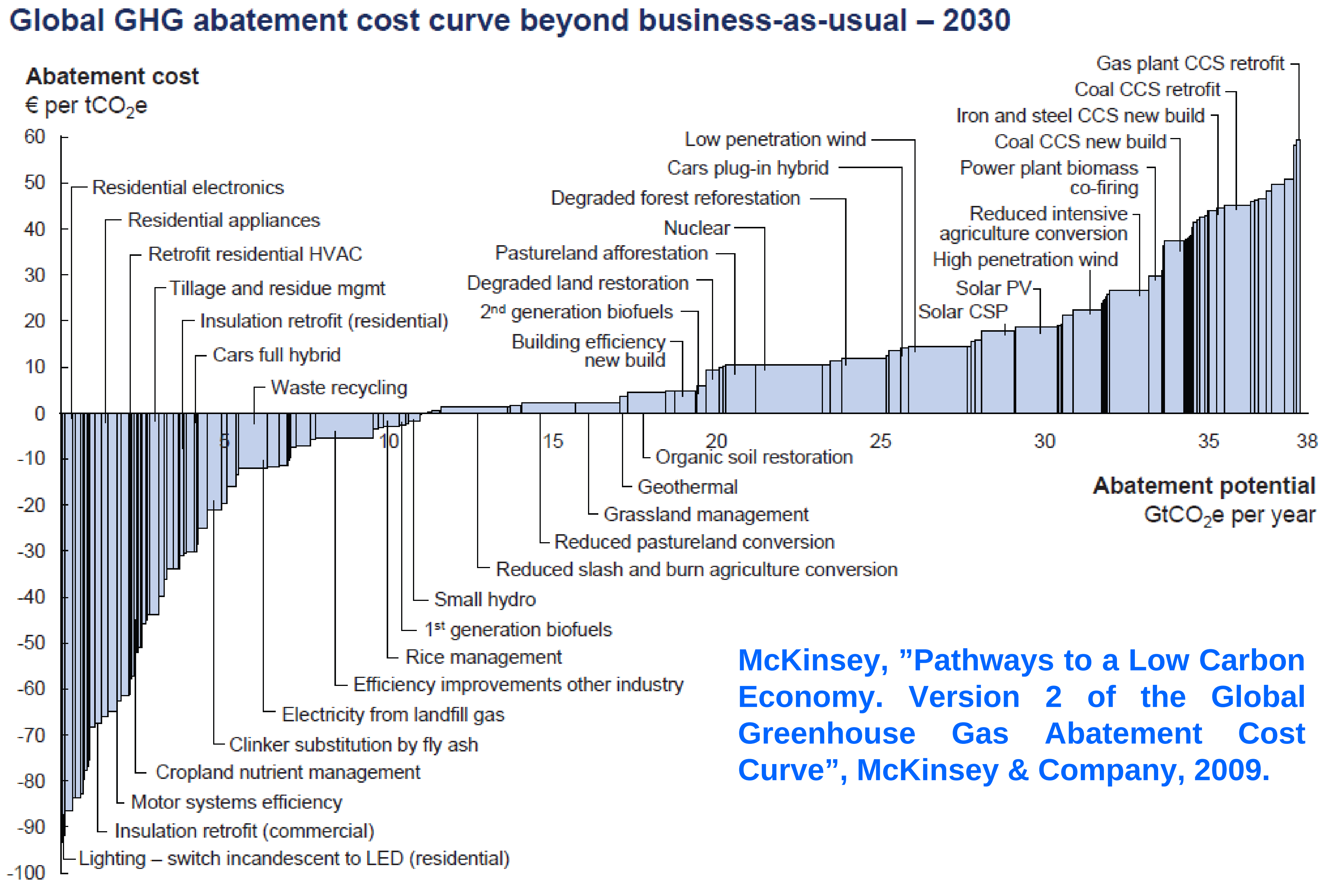
Lecture in the Physics Motivation Series, Trondheim, Norway, 5th of October, 2011.

Why is Thermal Insulation Important ?
- What Measures Amounts the Most ?



McKinsey, "Pathways to a Low Carbon Economy. Version 2 of the Global Greenhouse Gas Abatement Cost Curve", McKinsey & Company, 2009.

Note: The curve presents an estimate of the maximum potential of all technical GHG abatement measures below €60 per tCO_2e if each lever was pursued aggressively. It is not a forecast of what role different abatement measures and technologies will play.
Source: Global GHG Abatement Cost Curve v2.0

Thermal Background

- Thermal Conductivity Contributions

$$\lambda_{tot} = \lambda_{solid} + \lambda_{gas} + \lambda_{rad} + \lambda_{conv} + \lambda_{coupling} + \lambda_{leak}$$

λ_{tot} = total overall thermal conductivity

λ_{solid} = solid state thermal conductivity

λ_{gas} = gas thermal conductivity

λ_{rad} = radiation thermal conductivity

λ_{conv} = convection thermal conductivity

$\lambda_{coupling}$ = thermal conductivity term accounting for second order effects between the various thermal conductivities

λ_{leak} = leakage thermal conductivity

Traditional Thermal Insulation of Today

- What is Out There?

- **Mineral Wool**
  - Glass wool (fibre glass)
  - Rock wool
  - 30-40 mW/(mK)

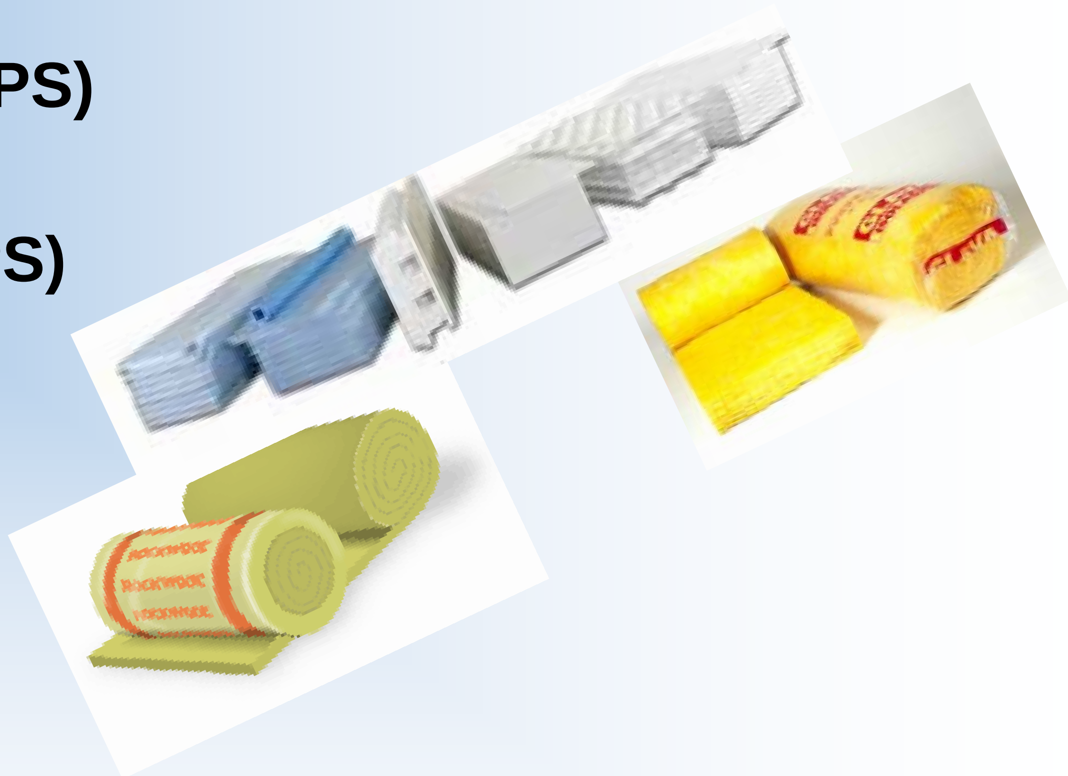
- **Expanded Polystyrene (EPS)**
  - 30-40 mW/(mK)

- **Extruded Polystyrene (XPS)**
  - 30-40 mW/(mK)

- **Cellulose**
  - 40-50 mW/(mK)

- **Cork**
  - 40-50 mW/(mK)

- **Polyurethane (PUR)**
  - Toxic gases (e.g. HCN) released during fire
  - 20-30 mW/(mK)



State-of-the-Art Thermal Insulation of Today
- What is Out There?

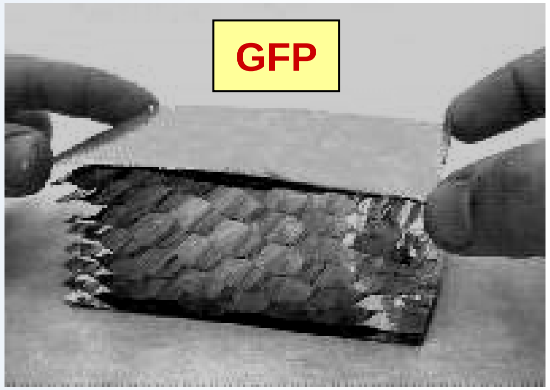
- **Vacuum Insulation Panels (VIP)**
  "An evacuated foil-encapsulated open porous material as a high performance thermal insulating material"
  - Core (silica, open porous, vacuum)
  - Foil (envelope) - 4 - 8 - 20 mW/(mK)

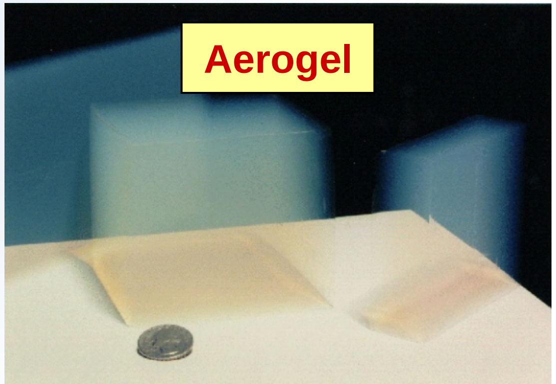
- **Gas-Filled Panels (GFP) - 40 mW/(mK)**

- **Aerogels - 13 mW/(mK)**

- **Phase Change Materials (PCM)**
  - Solid State ↔ Liquid
  - Heat Storage and Release

- **Beyond State-of-the-Art High Performance Thermal Insulation Materials ?**

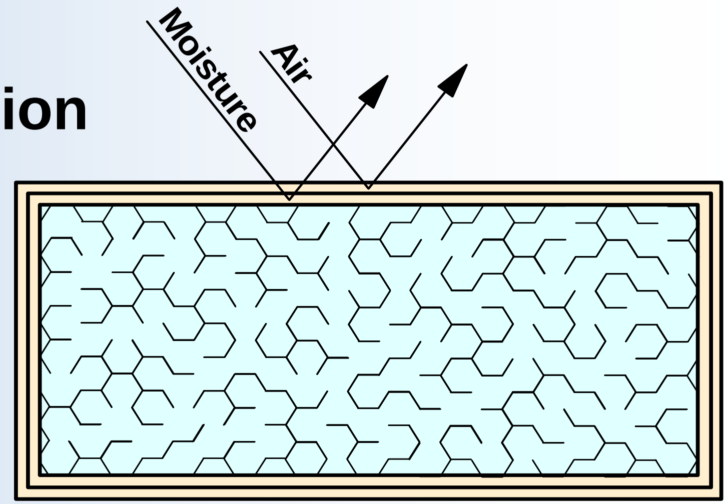




Major Disadvantages of VIPs

- **Thermal bridges at panel edges**
- **Expensive at the moment, but calculations show that VIPs may be cost-effective even today**

- Vacuum Core
- Air and Moisture Tight Envelope



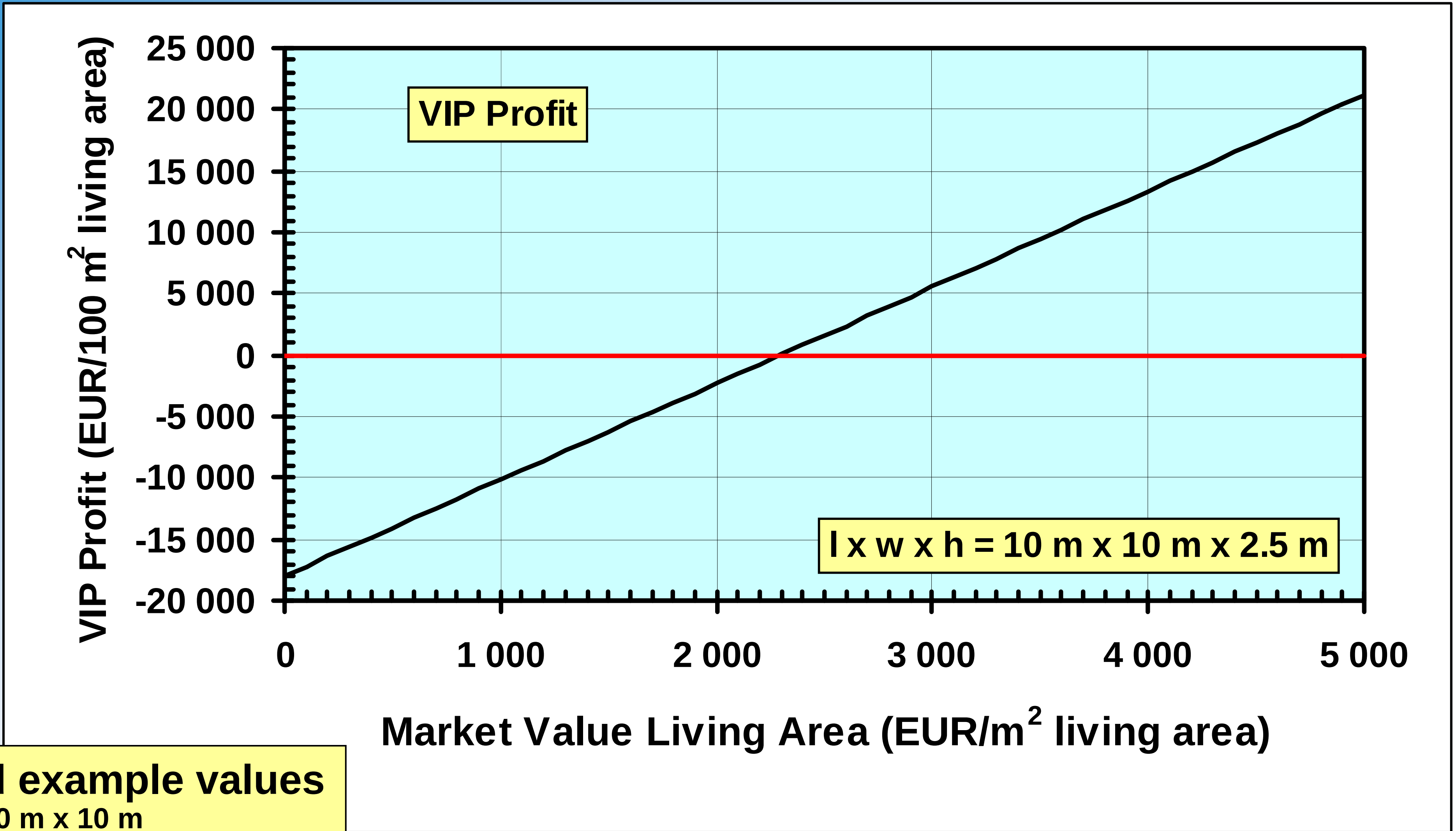
VIP

- **Ageing effects - Air and moisture penetration**
  - **4 mW/(mK) fresh**
  - **8 mW/(mK) 25 years**
  - **20 mW/(mK) perforated**
- **Vulnerable towards penetration, e.g nails**
  - **20 mW/(mK)**
- **Can not be cut or adapted at building site**
- **Possible improvements?**

VIPs – The Thermal Insulation of Today ?

- VIPs - Despite large disadvantages - A large leap forward
- Thermal conductivities 5 to 10 times lower than traditional insulation
  - 4 mW/(mK) fresh
  - 8 mW/(mK) 25 years
  - 20 mW/(mK) perforated
- Wall and roof thicknesses up to 50 cm as with traditional insulation are not desired
  - Require new construction techniques and skills
  - Transport of thick building elements leads to increased costs
- Building restrictions during retrofitting of existing buildings
  - Lawful authorities
  - Practical Restrictions
- High living area market value per m² $\Rightarrow$ Reduced wall thickness $\Rightarrow$ Large area savings $\Rightarrow$ Higher value of the real estate
- VIPs - The best solution today and in the near future?
- Beyond VIPs?

Potential Cost Savings by Applying VIPs



- **Assumed example values**
  - Building of 10 m x 10 m
  - Interior floor to ceiling height of 2.5 m
  - 20 cm wall thickness reduction
  - VIP costs 6 cm: 200 EUR/m²
  - Mineral wool costs 35 cm: 20 EUR/m²

B. P. Jelle, "Traditional, State-of-the-Art and Future Thermal Building Insulation Materials and Solutions - Properties, Requirements and Possibilities", *Energy and Buildings*, 43, 2549-2563, 2011.

Requirements of the Thermal Insulation of Tomorrow

Property	Requirements
Thermal conductivity – pristine	< 4 mW/(mK)
Thermal conductivity – after 100 years	< 5 mW/(mK)
Thermal conductivity – after modest perforation	< 4 mW/(mK)
Perforation vulnerability	not to be influenced significantly
Possible to cut for adaption at building site	yes
Mechanical strength (e.g. compression and tensile)	may vary
Fire protection	may vary, depends on other protection
Fume emission during fire	any toxic gases to be identified
Climate ageing durability	resistant
Freezing/thawing cycles	resistant
Water	resistant
Dynamic thermal insulation	desirable as an ultimate goal
Costs vs. other thermal insulation materials	competitive
Environmental impact (including energy and material use in production, emission of polluting agents and recycling issues)	low negative impact

Properties of Concrete – A Construction Material

- **Thermal Conductivity**

- **Concrete**
  - **150 – 2500 mW/(mK)**
- **Traditional Thermal Insulation**
  - **36 mW/(mK)**
- **Vacuum Insulation Panels (VIPs)**
  - **4 mW/(mK)**

Possible to decrease the thermal conductivity of concrete?

Properties of Concrete

Some key properties of concrete (example values)

Property	With Rebars	Without Rebars
Mass density (kg/dm^3)	2.4	2.2
Thermal conductivity (mW/mK)	2500	1700
Specific heat capacity (J/(kgK))	840	880
Linear thermal expansion coefficient (10^{-6}/K)	12	12
Compressive strength (MPa)	30	30
Tensile strength (MPa) [a]	500 [b]	3
Fire resistance	> 2 h	> 2 h
Environmental impact (incl. energy and material use in production, emission of polluting agents and recycling issues)	large CO_2 emissions	large CO_2 emissions

[a] As a comparison, note that carbon nanotubes have been manufactured with tensile strengths as high as 63 000 MPa and have a theoretical limit at 300 000 MPa. [b] Rebars.

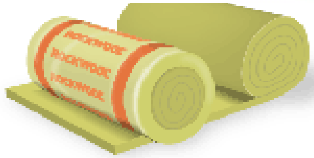
Large CO_2 Emissions from Cement Production

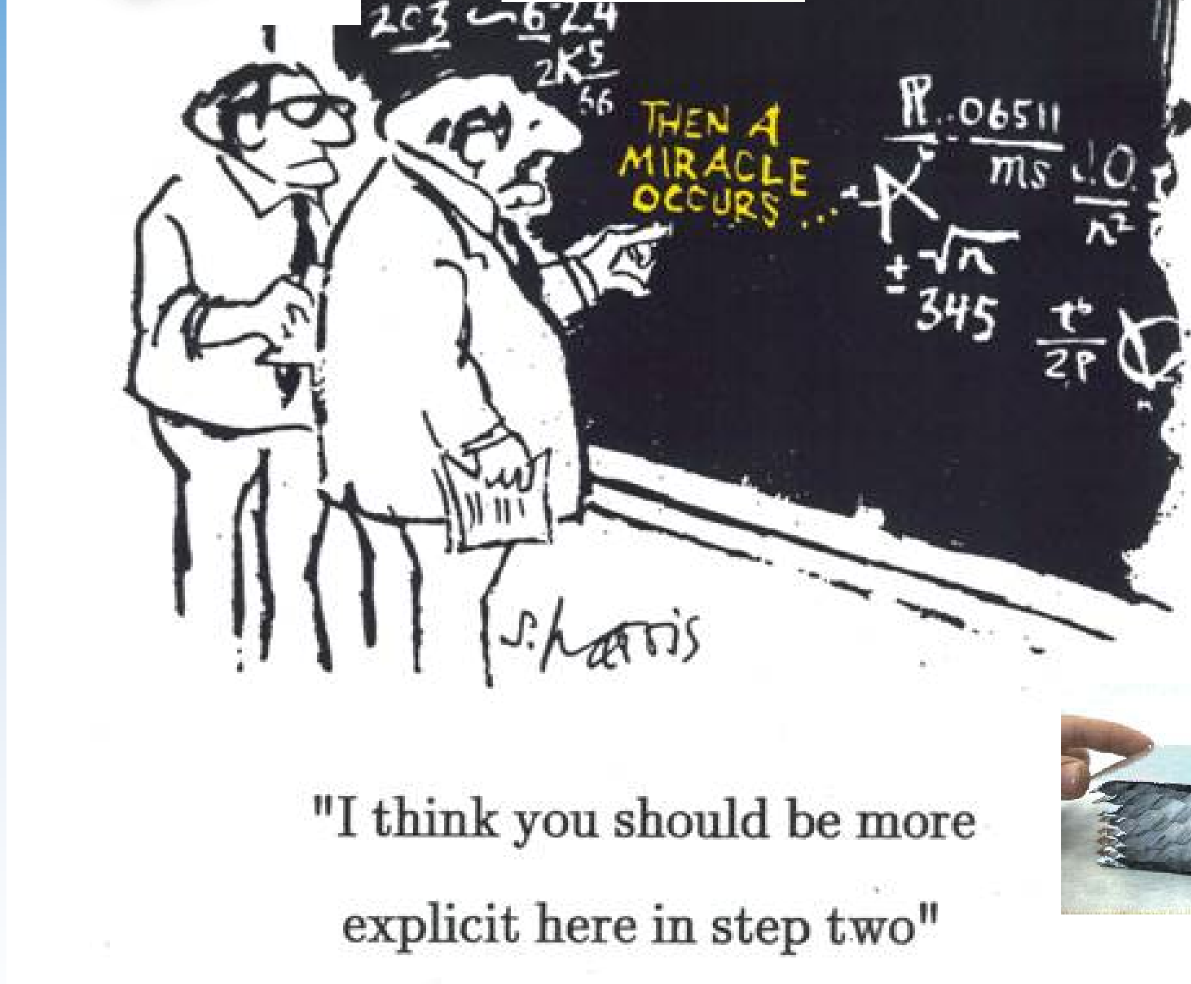
- The cement industry produces 5 % of the global man-made CO_2 emissions of which:
- 50 % from the chemical process
  - e.g.: $3CaCO_3 + SiO_2 \rightarrow Ca_3SiO_5 + 3CO_2$
    $2CaCO_3 + SiO_2 \rightarrow Ca_2SiO_4 + 2CO_2$
- 40 % from burning fossil fuels
  - e.g. coal and oil
- 10 % split between electricity and transport uses

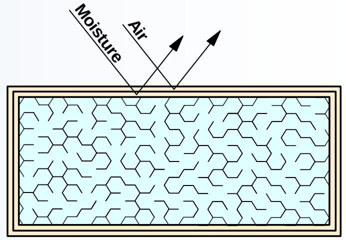
World Business Council for Sustainable Development, ”The cement sustainability initiative – Our agenda for action”, July 2002.

And let us not forget the corrosion issues with reinforced concrete…

Beyond Traditional Thermal Insulation?

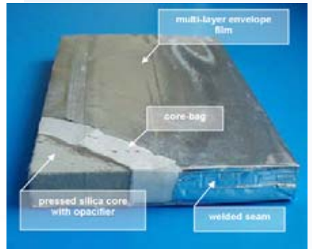






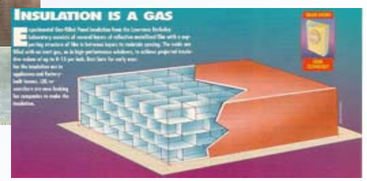
VIP

?

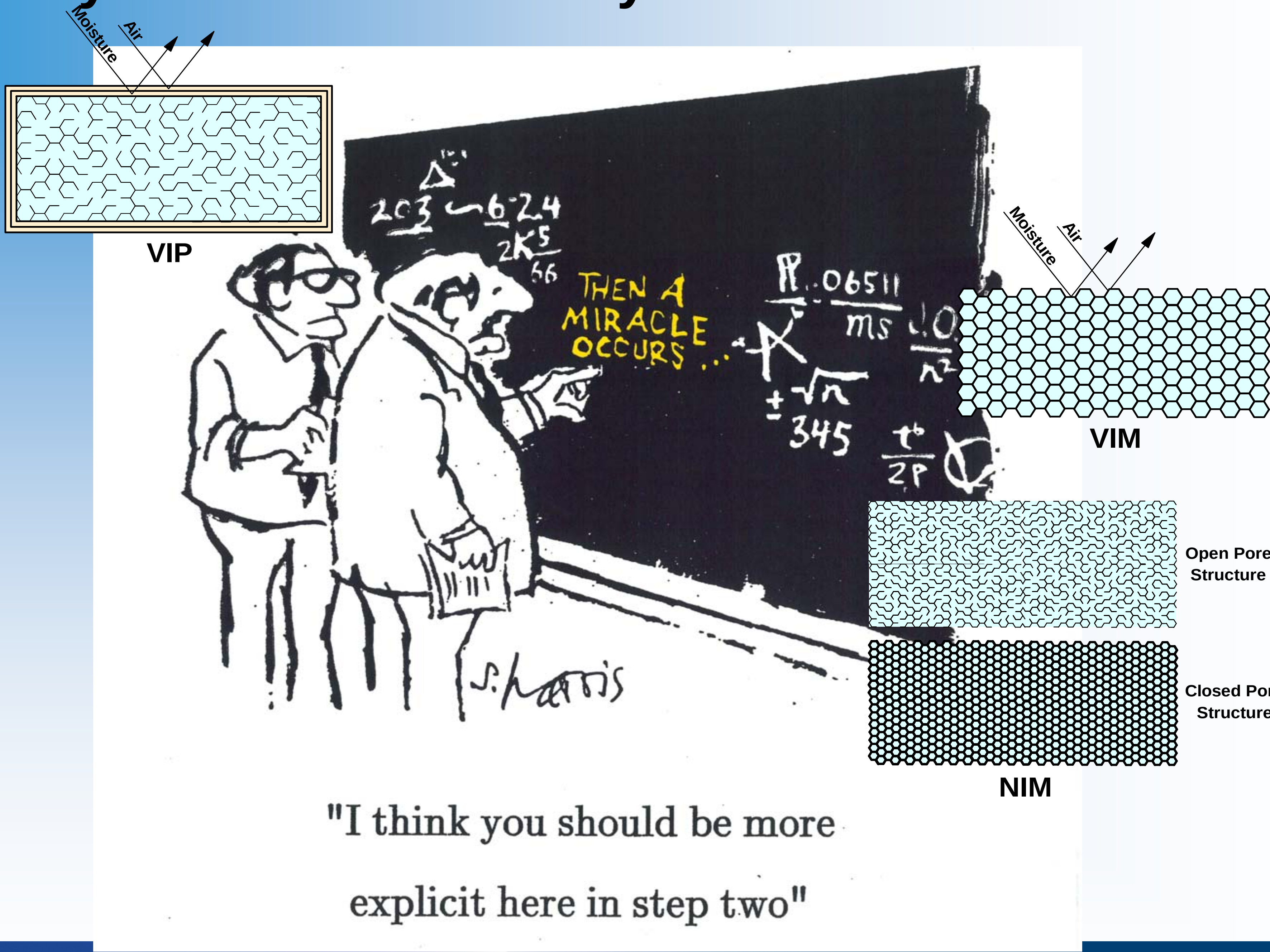


VIP

GFP

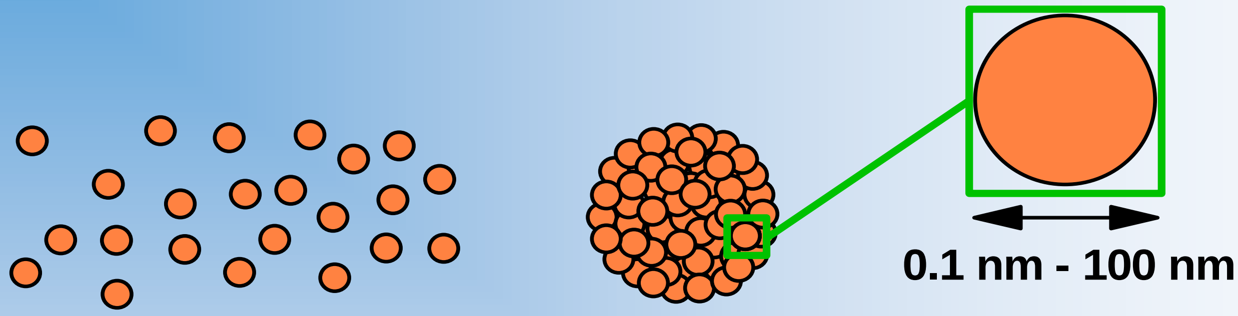


Beyond VIPs – How May It Be Achieved?



Nano Technology

Nanotechnology:
Technology for controlling matter of dimensions between 0.1 nm - 100 nm.



For comparison:

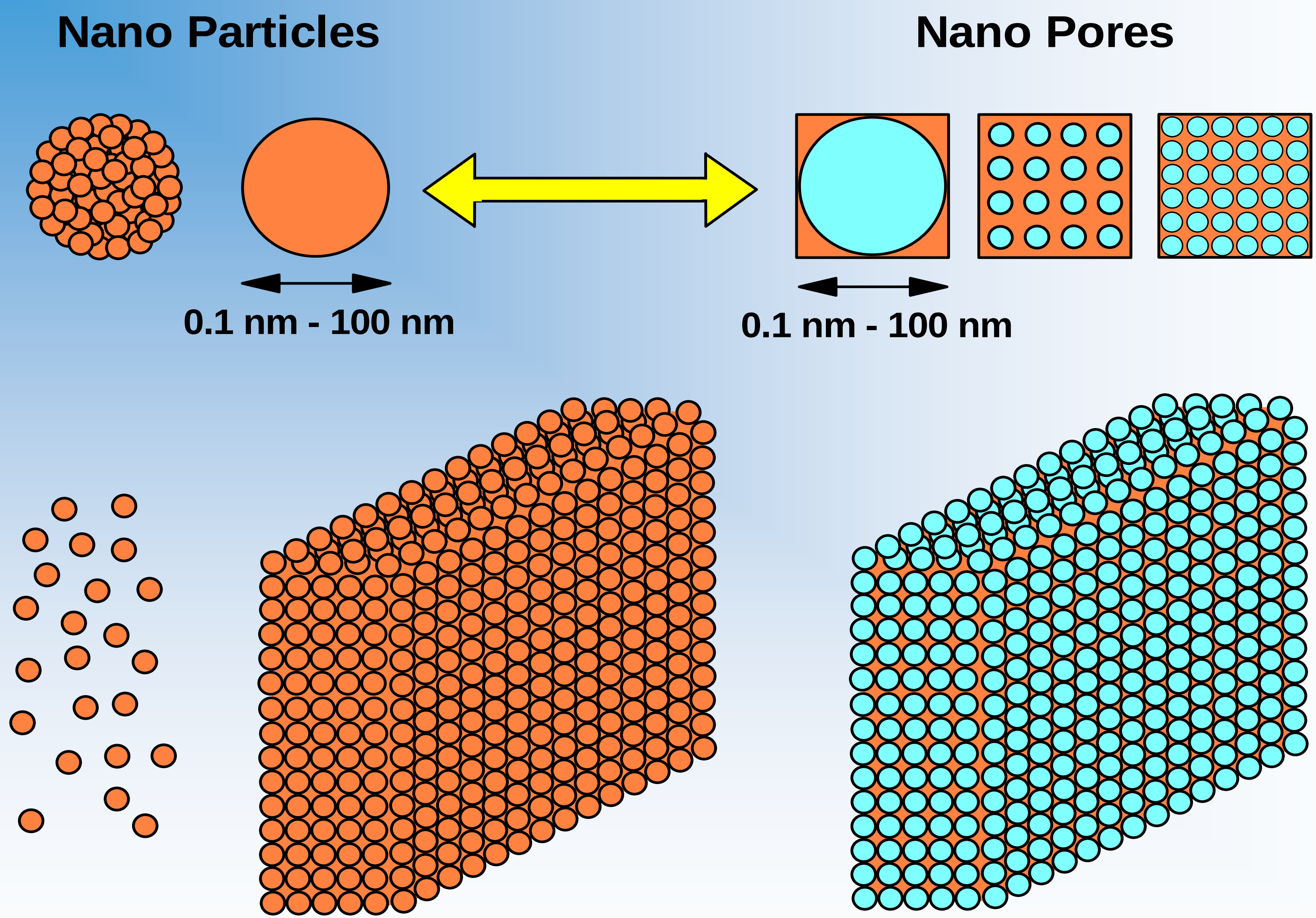
Solar radiation: 300 nm - 3000 nm

Atomic diameters: Hydrogen: 0.16 nm
Carbon: 0.18 nm
Gold: 0.36 nm

Molecular length: Stearic Acid: 2.48 nm ($C_{17}H_{35}COOH$)

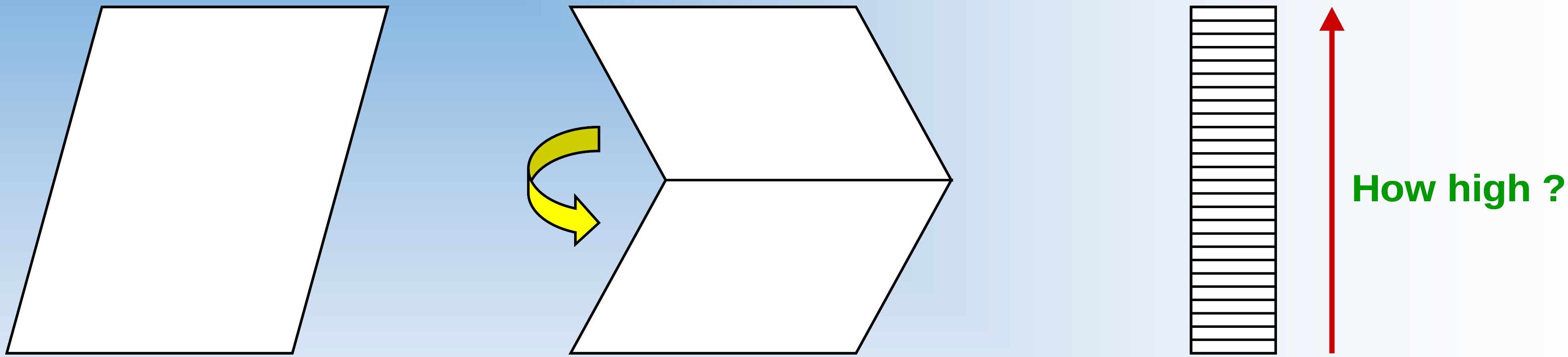
Nanotechnology:
Technology for controlling matter at an atomic and molecular scale.

Nano Technology and Thermal Insulation



How Good are You at Guessing?

The A4 Paper Folding



- **Fold an A4 paper 100 times.**
- **Press out all air between the paper sheets.**
- **Put the paper pile on the table in front of you.**
- **Guess how far above the table does the paper pile reach ?**

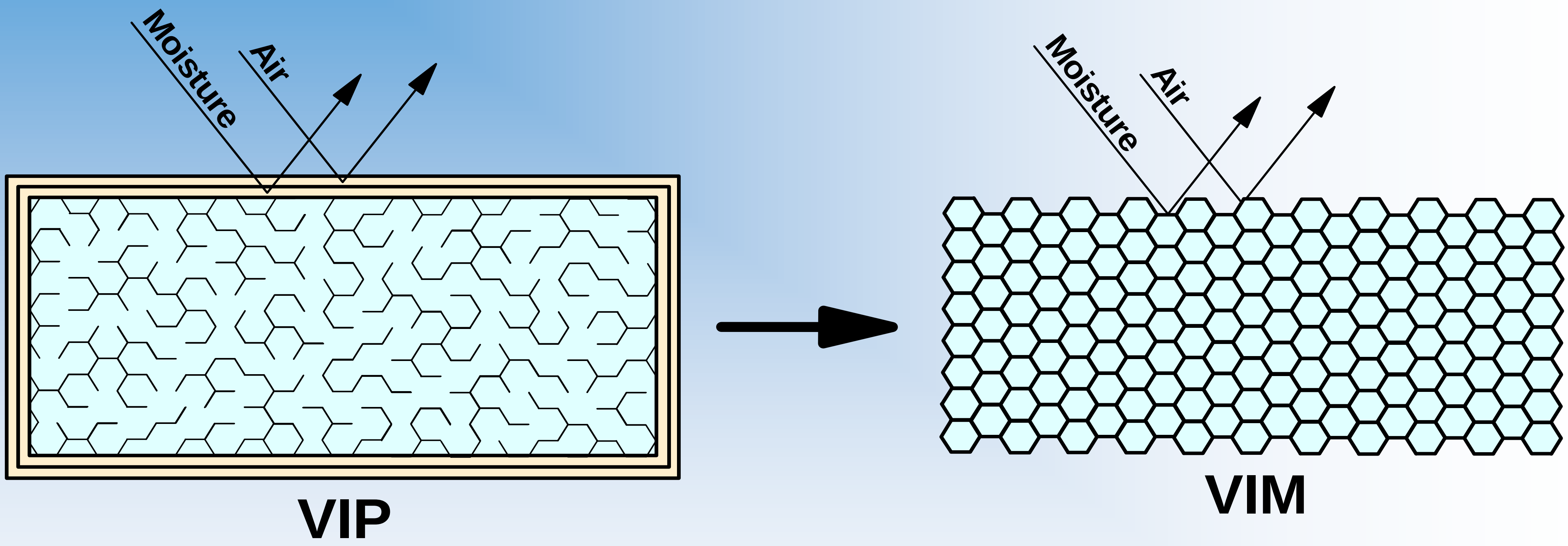
Beyond VIPs – How May It Be Achieved?

Introducing New Concepts as

- **Advanced Insulation Materials (AIM):**
- **Vacuum Insulation Materials (VIM)**
- **Gas Insulation Materials (GIM)**
- **Nano Insulation Materials (NIM)**
- **Dynamic Insulation Materials (DIM)**

B. P. Jelle, A. Gustavsen and R. Baetens, ”The Path to the High Performance Thermal Building Insulation Materials and Solutions of Tomorrow”, *Journal of Building Physics*, **34**, 99-123, 2010.

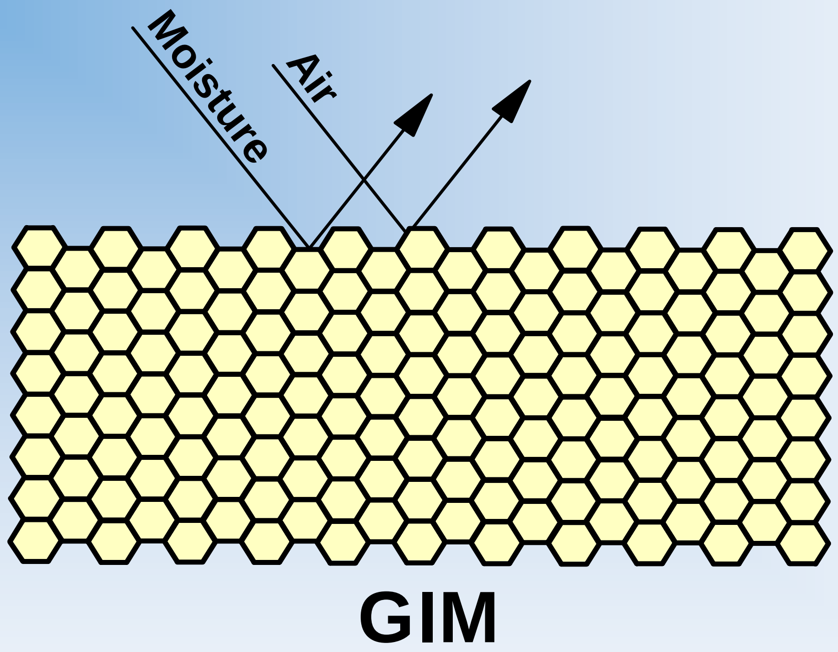
Vacuum Insulation Material (VIM)



VIM - A basically homogeneous material with a closed small pore structure filled with vacuum with an overall thermal conductivity of less than 4 mW/(mK) in the pristine condition

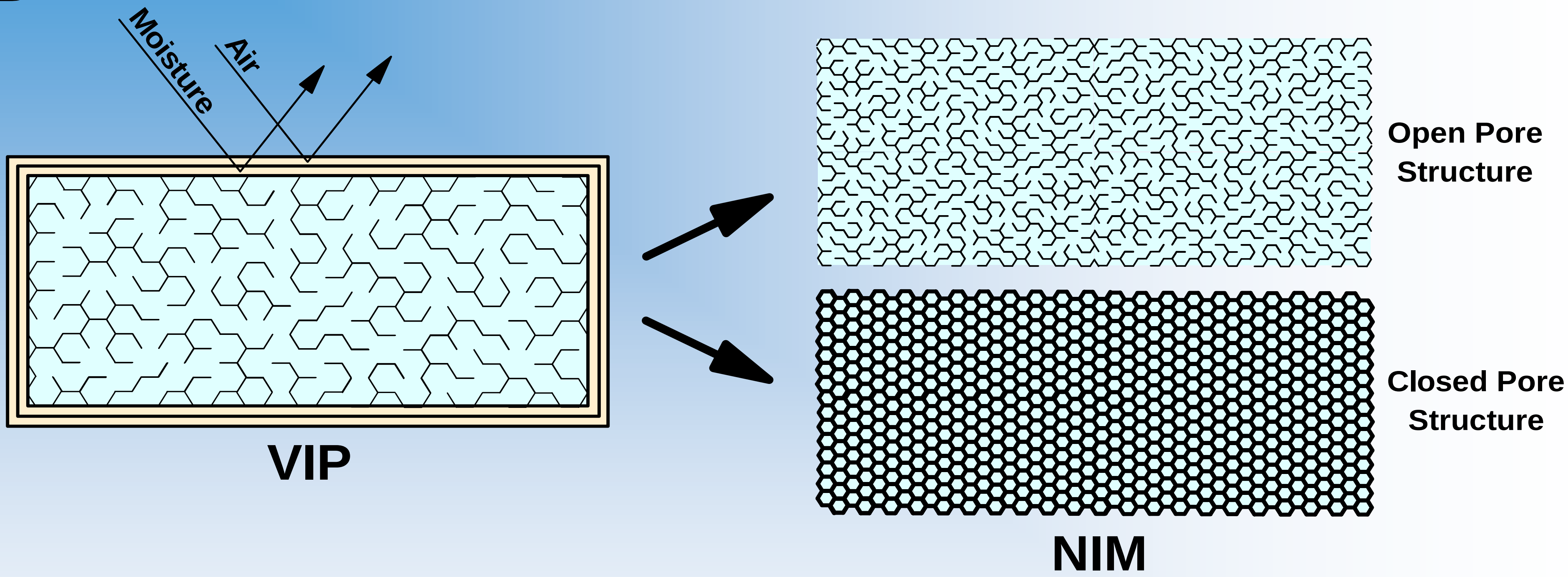
Gas Insulation Material (GIM)

… and analogously with VIM we may define GIM as follows:



GIM - A basically homogeneous material with a closed small pore structure filled with a low-conductance gas with an overall thermal conductivity of less than 4 mW/(mK) in the pristine condition

Nano Insulation Material (NIM)



NIM - A basically homogeneous material with a closed or open small nano pore structure with an overall thermal conductivity of less than 4 mW/(mK) in the pristine condition

The Knudsen Effect – Nano Pores

Gas Thermal Conductivity λ_{gas}

$$\lambda_{gas} = \frac{\lambda_{gas,0}}{1+2\beta Kn} = \frac{\lambda_{gas,0}}{1+\frac{\sqrt{2}\beta k_B T}{\pi d^2 p \delta}}$$

$\sigma_{mean} > \delta \Rightarrow$ low λ_{gas}

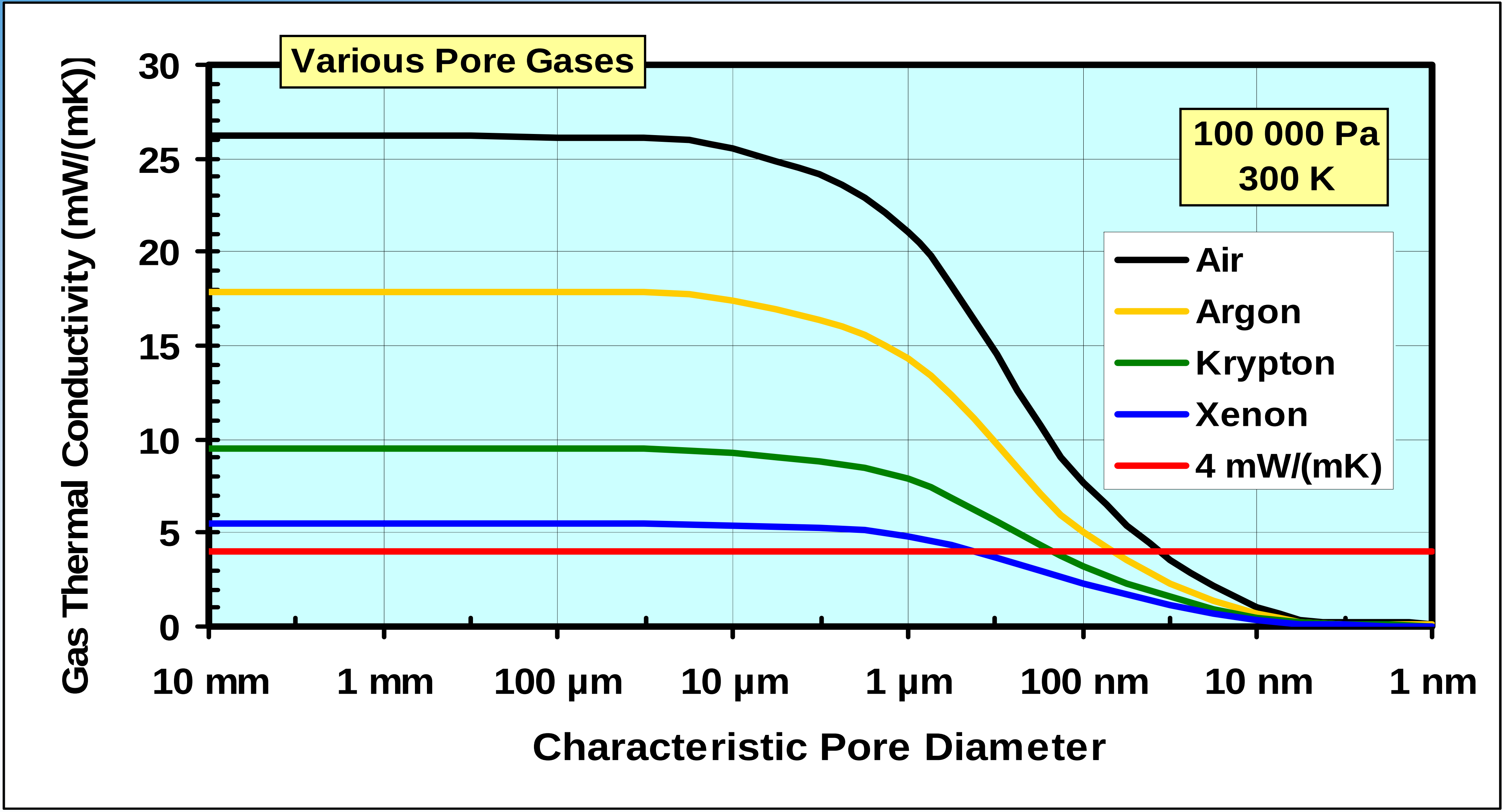
where

$$Kn = \frac{\sigma_{mean}}{\delta} = \frac{k_B T}{\sqrt{2}\pi d^2 p \delta}$$

λ_{gas} = gas thermal conductivity in the pores (W/(mK))
$\lambda_{gas,0}$ = gas thermal conductivity in the pores at STP (standard temperature and pressure) (W/(mK))
β = coefficient characterizing the molecule - wall collision energy transfer efficiency (between 1.5 - 2.0)
$Kn = \sigma_{mean}/\delta = k_B T/(2^{1/2}\pi d^2 p\delta)$ = the Knudsen number
k_B = Boltzmann's constant $\approx 1.38 \cdot 10^{-23}$ J/K
T = temperature (K)
d = gas molecule collision diameter (m)
p = gas pressure in pores (Pa)
δ = characteristic pore diameter (m)
σ_{mean} = mean free path of gas molecules (m)

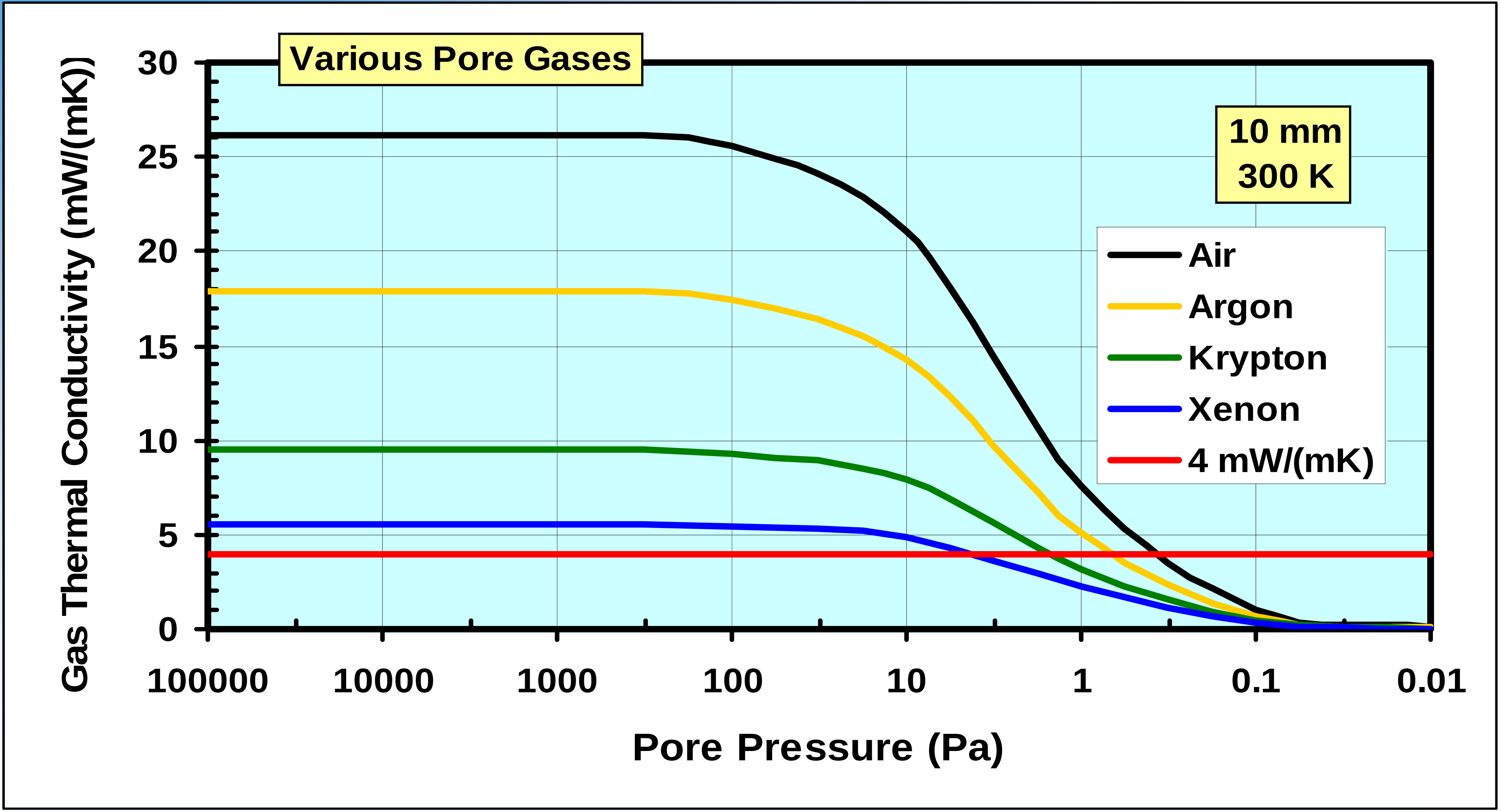
Gas Thermal Conductivity

Conductivity vs. Pore Diameter

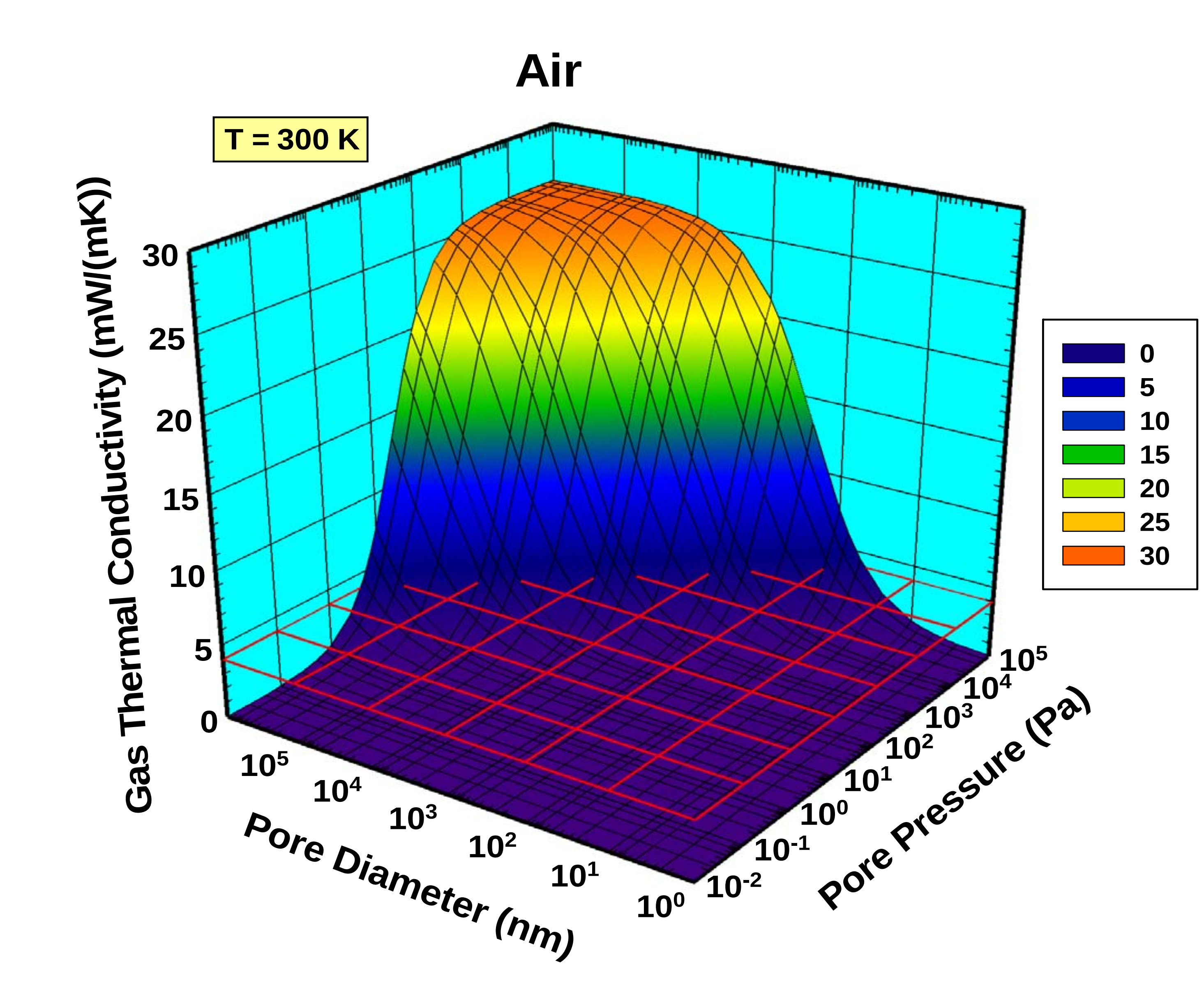


Gas Thermal Conductivity

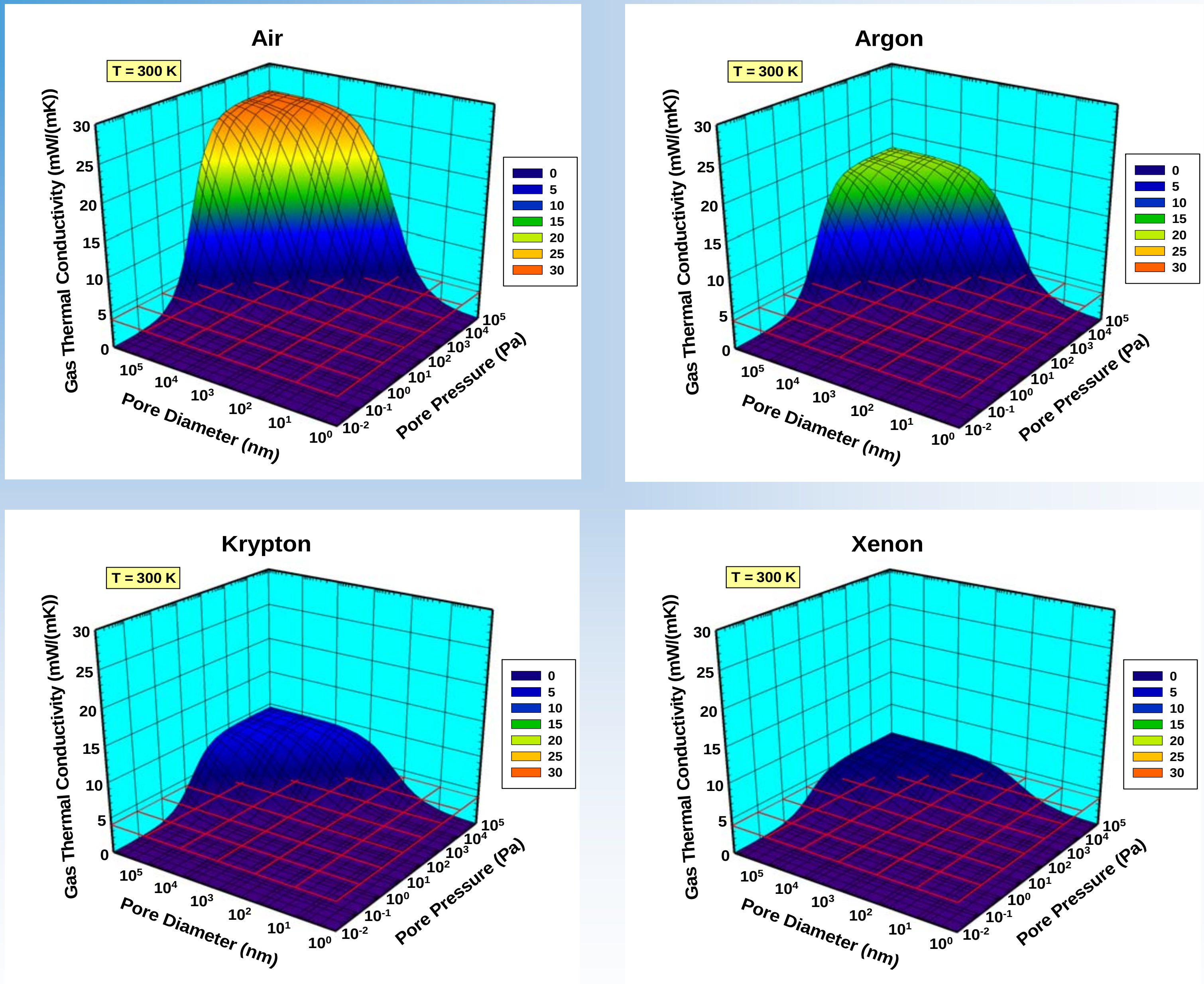
Conductivity vs. Pore Pressure



Gas Thermal Conductivity



Gas Thermal Conductivity



Nano Pores – Thermal Radiation

- Knudsen effect ⇒ $\sigma_{mean} > \delta$ ⇒ low gas thermal conductivity λ_{gas}
- What about the thermal radiation in the pores?
- "Classical" – from Stefan-Boltzmann's law (Linear λ_{rad} vs. δ relationship):

$$\lambda_{rad} = \frac{\pi^2 k_B^4 \delta}{60\hbar^3 c^2 \left[\frac{2}{\varepsilon} - 1\right]} \frac{(T_i^4 - T_e^4)}{(T_i - T_e)}$$

λ_{rad} = radiation thermal conductivity in the pores (W/(mK))
$\sigma = \pi^2 k_B^4/(60\hbar^3 c^2)$ = Stefan-Boltzmann's constant ≈ $5.67 \cdot 10^{-8}$ W/(m²K⁴)
k_B = Boltzmann's constant ≈ $1.38 \cdot 10^{-23}$ J/K
$\hbar = h/(2\pi) \approx 1.05 \cdot 10^{-34}$ Js = reduced Planck's constant (h = Planck's constant)
c = velocity of light ≈ $3.00 \cdot 10^{8}$ m/s
δ = pore diameter (m)
ε = emissivity of inner pore walls (assumed all identical)
T_i = interior (indoor) temperature (K)
T_e = exterior (outdoor) temperature (K)
ξ_{ir} = infrared radiation wavelength (m)

- Pore diameter δ small ⇒ low thermal radiation conductivity λ_{rad}
- But what happens when $\xi_{ir} > \delta$? (IR wavelength > pore diameter)
- $\xi_{ir} > \delta$ ⇒ high thermal radiation conductivity λ_{rad} ?
- Tunneling of evanescent waves
- Indications that the large thermal radiation is only centered around a specific wavelength (or a few) ⇒
- The total thermal radiation integrated over all wavelengths is not that large (?)
- Currently looking into these matters…

Thermal Radiation in Nano Pores

Stefan-Boltzmann's Law

Total Radiation Heat Flux $J_{rad,tot}$

$$J_{rad,tot} = \frac{\sigma}{n\left[\frac{2}{\varepsilon} - 1\right]}(T_i^4 - T_e^4)$$

$\lambda_{rad} = J_{rad,tot}\delta/(T_{k-1} - T_k)$ is found by applying the approximation $(T_{k-1} - T_k) = (T_i - T_e)/n$

λ_{rad} = radiation thermal conductivity in the pores (W/(mK))
$\sigma = \pi^2 k_B^4/(60\hbar^3 c^2)$ = Stefan-Boltzmann's constant $\approx 5.67\cdot10^{-8}$ W/(m^{2}K^4)
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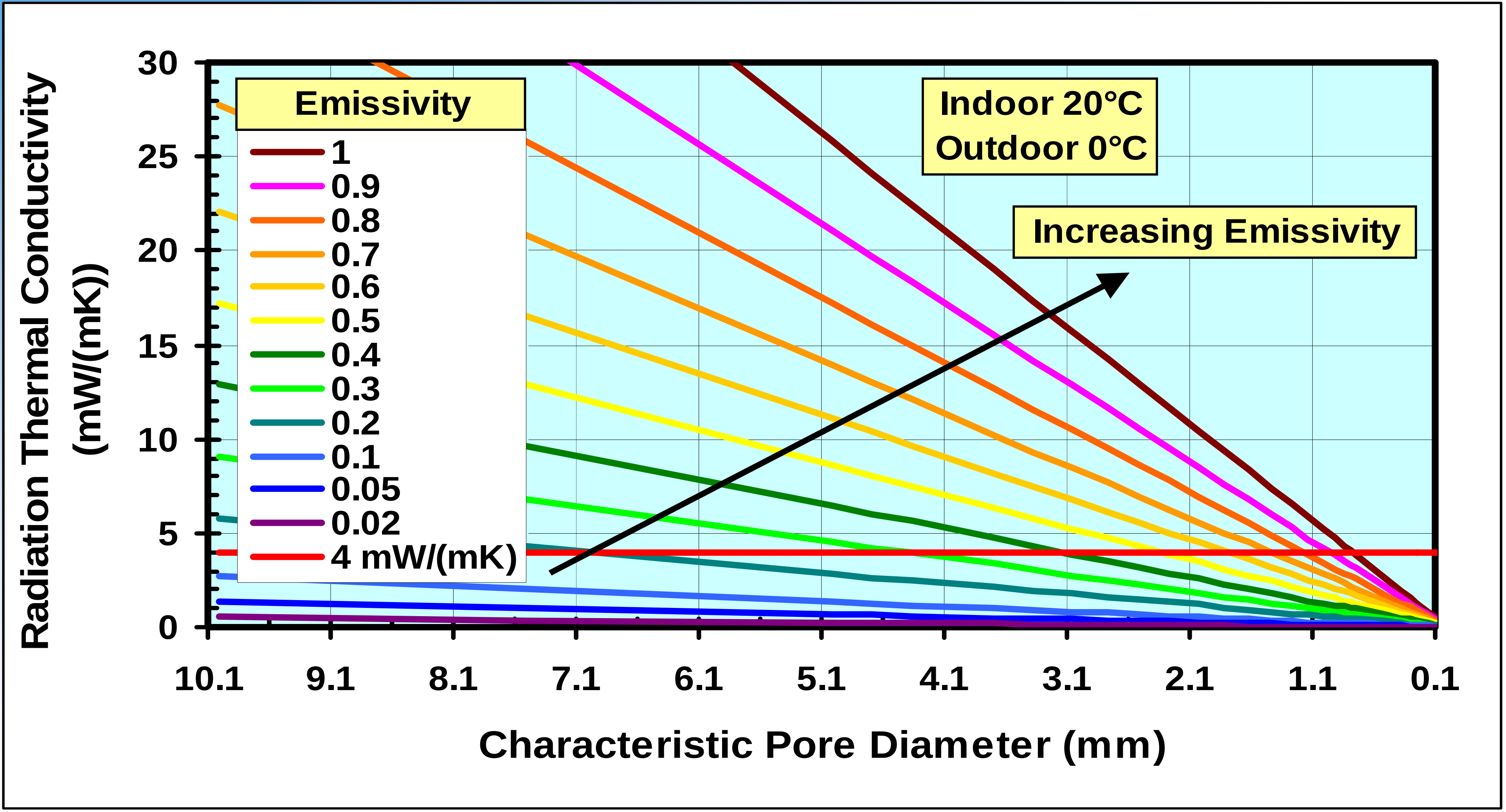
c = velocity of light $\approx 3.00\cdot10^{8}$ m/s
δ = pore diameter (m)
ε = emissivity of inner pore walls (assumed all identical)
T_i = interior (indoor) temperature (K)
T_e = exterior (outdoor) temperature (K)
$J_{rad,tot}$ = total radiation heat flux (W/m^2)
n = number of pores along a given horizontal line in the material

Radiation Thermal Conductivity λ_{rad}

$$\lambda_{rad} = \frac{\sigma\delta}{\left[\frac{2}{\varepsilon} - 1\right]}\frac{(T_i^4 - T_e^4)}{(T_i - T_e)} = \frac{\pi^2 k_B^4 \delta}{60\hbar^3 c^2\left[\frac{2}{\varepsilon} - 1\right]}\frac{(T_i^4 - T_e^4)}{(T_i - T_e)}$$

Radiation Thermal Conductivity

Conductivity vs. Pore Diameter



First Experimental Attempts towards NIMs:

Hollow Nanospheres

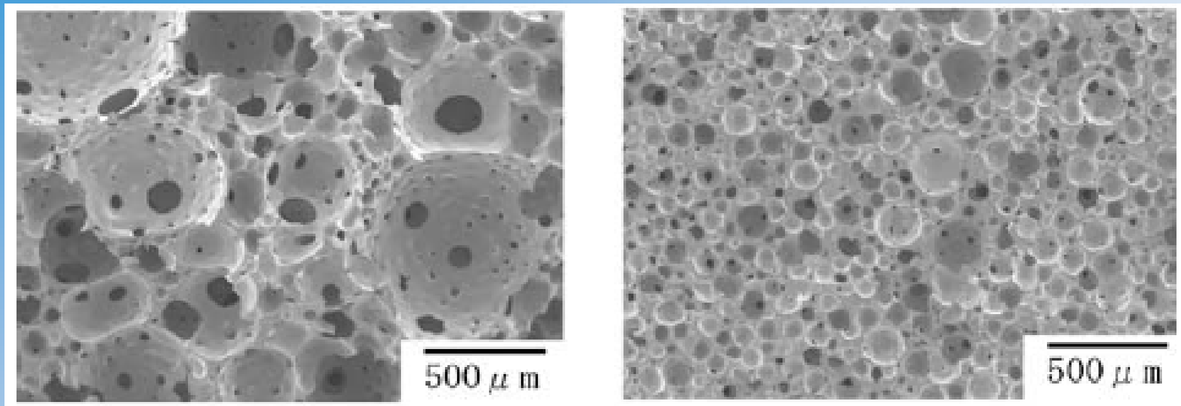
Three Main Preparation Methods:

1. **Membrane Foaming:** Use a membrane to prepare foam with nanoscale bubbles, followed by hydrolysis and condensation of a precursor within bubble walls to make a solid structure.

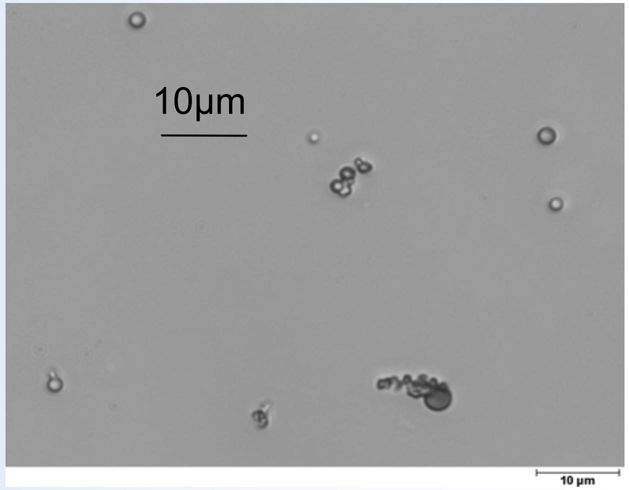
2. **Internal Gas Release:** Controlled decomposition or evaporation of a component to form nanobubbles in a liquid system, followed by formation of a solid shell at the bubble perimeter.

3. **Templating:** Formation of a nanoscale liquid or solid structure, followed by reactions to form a solid shell at the perimeter. Finally, the core is removed to make a hollow sphere.

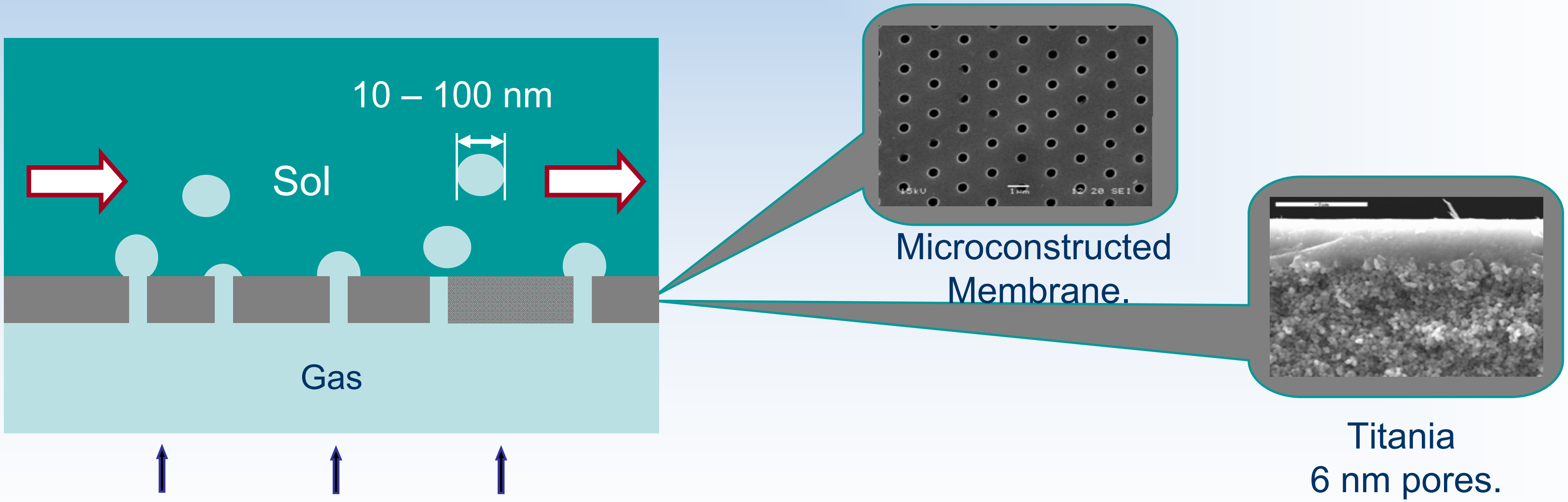
Membrane Foaming



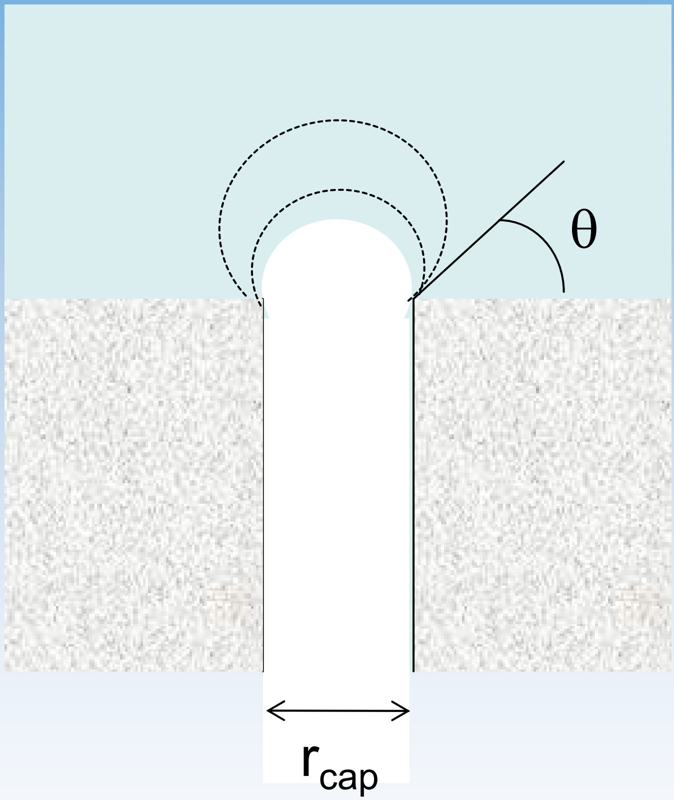
Silica sol stir foamed at 1000 (left) and 2500 (right) mPas
T. Tomita et al. *J. Porous Mater.* **12** (2005) 123.



Gas capsules by membrane emulsification. J. Yang et al. SINTEF.



Foam Formation



Requirement for nanosized bubbles:

Controlled pressure to avoid continuous gas stream.

$\Delta\rho$: Density difference between gas and liquid, should be large.

r_{cap}: Pore radius, should be small.

σ_l : Surface tension of liquid, should be small.

θ : Contact angle, should be large.

Foam walls should be thin and stable:

η : Liquid viscosity, should be low.

σ_l : Surface tension of liquid, should be small.

Stability: Requires surfactant bialayers.

Membrane Foaming – Attempted the Following:

Rapid Hydrolysis and Condensation:

$Ti(OR)_4 + H_2O \rightleftarrows (RO)_3\text{-}Ti\text{-}OH + ROH$

$(RO)_3\text{-}Ti\text{-}OH + HO\text{-}Ti\text{-}(RO)_3 \rightleftarrows (RO)_3\text{-}Ti\text{-}O\text{-}Ti\text{-}(RO)_3 + H_2O$

$(RO)_3\text{-}Ti\text{-}OR + HO\text{-}Ti\text{-}(RO)_3 \rightleftarrows (RO)_3\text{-}Ti\text{-}O\text{-}Ti\text{-}(RO)_3 + ROH$

Should proceed upon exposure to $H_2O + CO_2$ to form a gel shell around bubbles

Not successful

- Reaction too slow; bubbles broke (with smoke).
- No suitable surfactant systems found to stabilize alcohol-based foams!

Internal Gas Release

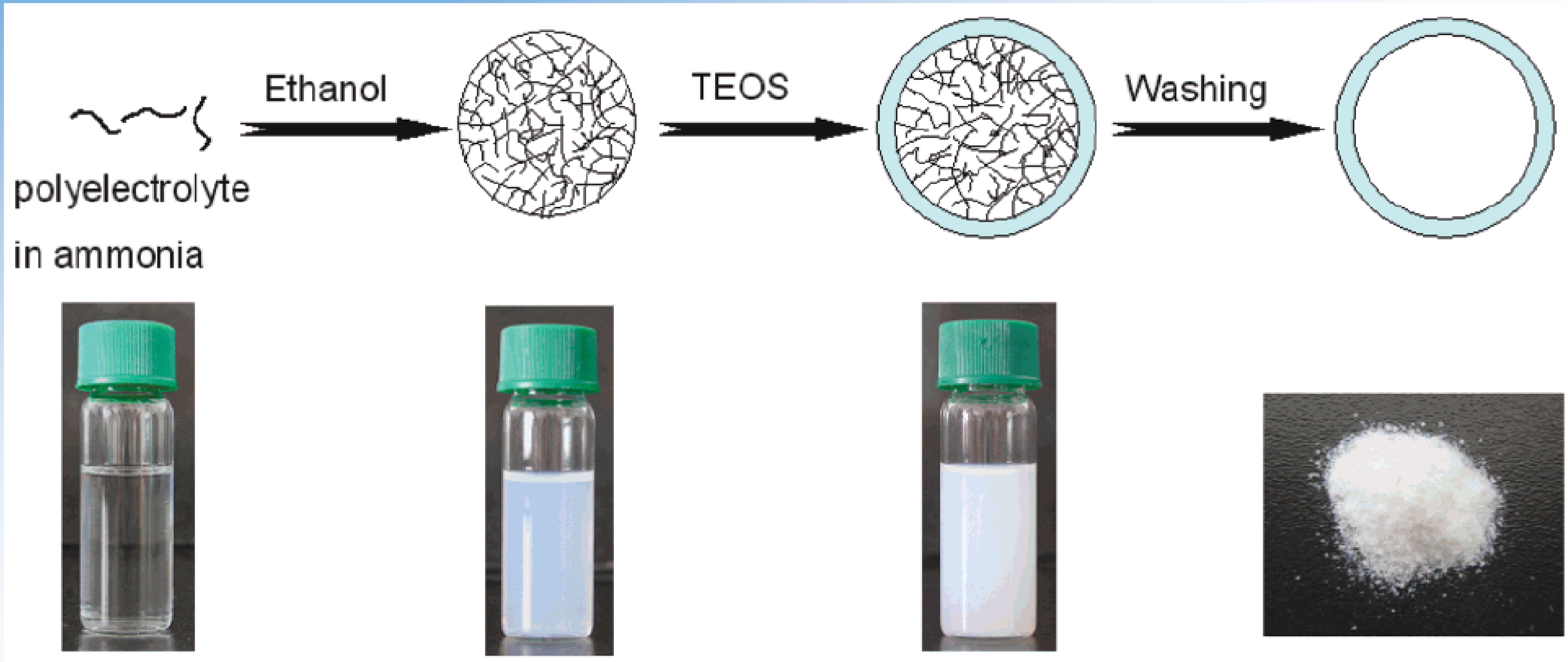
Would Require:

- Simultaneous formation of gas bubbles throughout reaction system.
- Narrow bubble size distribution.
- Very homogeneous system temperature.
- Rapid shell formation (before Ostwald ripening process).
- Extremely reactive chemicals, requiring strict humidity control.

- Very demanding experimental conditions, work terminated.

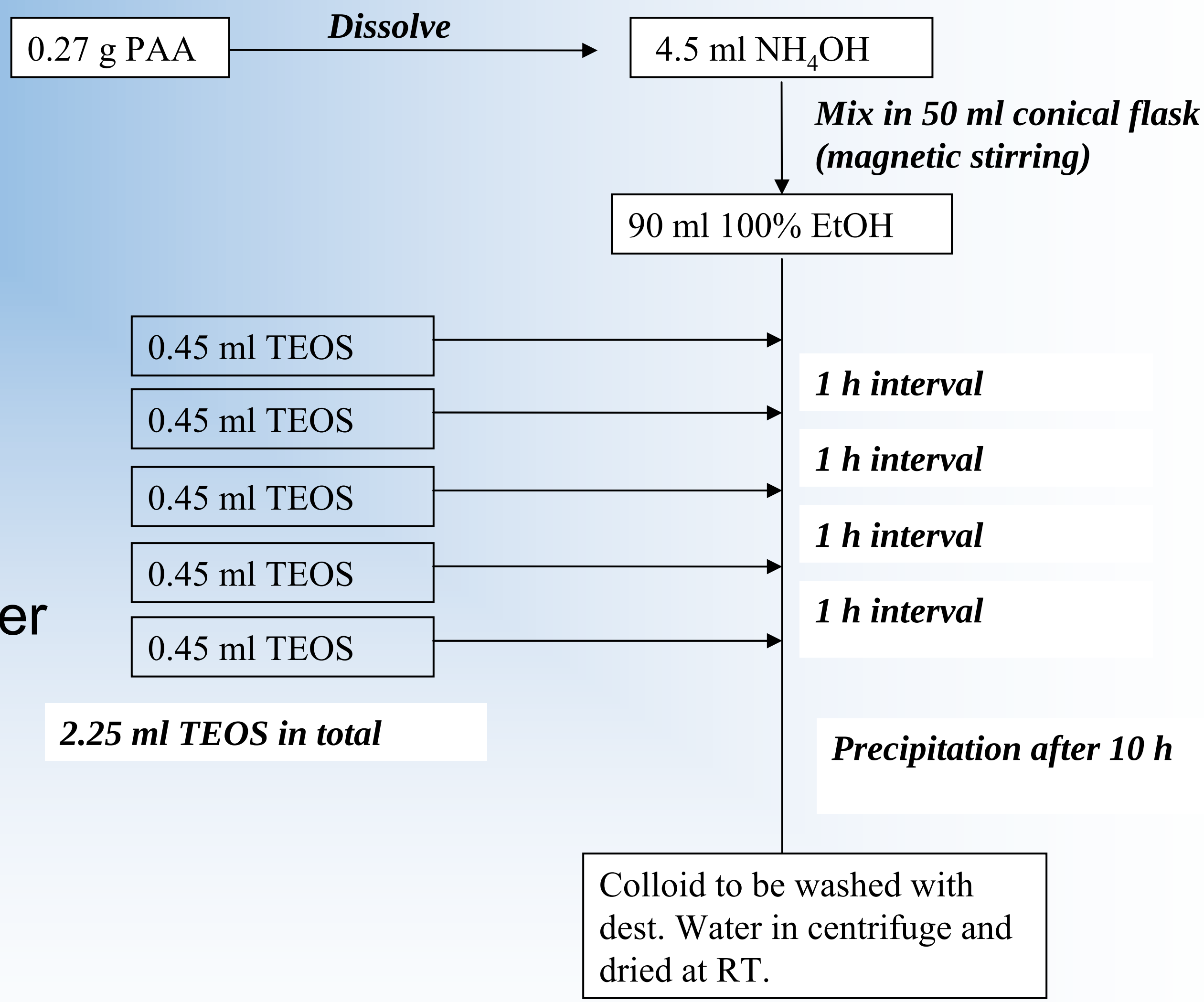
Template-Assisted Systems

Schematic diagram of the formation mechanism of hollow silica spheres, from (Wan and Yu 2008)



Stöber Method for Synthesis of Hollow SiO_2 Nanoparticles (ex.)

- Polyacrylic acid (PAA, MW ≈ 5 000)
- Ammonium hydroxide (25 wt%)
- 100% ethanol
- Tetraethoxysilane (TEOS)
- Ion exchanged destilled water



Same Chemical Reaction as for Aerogel Production:

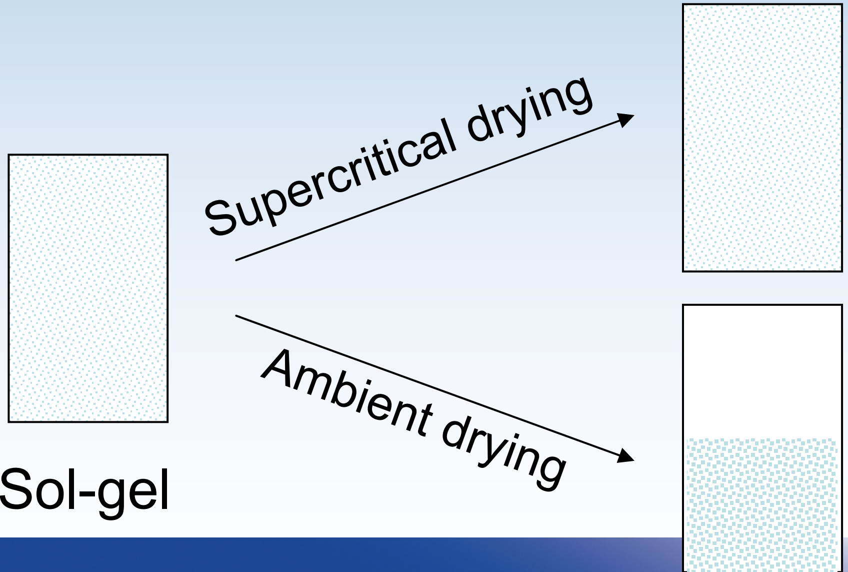
Hydrolysis

R'-Si-OR + H-OH $\rightleftharpoons$ R'-Si-OH + ROH

Condensation

R'-Si-OH + HO-Si-R' $\rightleftharpoons$ R'-Si-O-Si-R' + H_2O

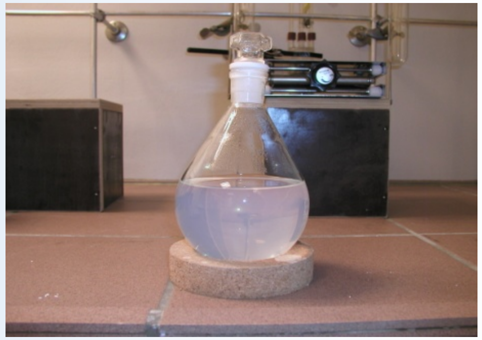
R'-Si-OR + HO-Si-R' $\rightleftharpoons$ R'Si-O-Si-R' + ROH



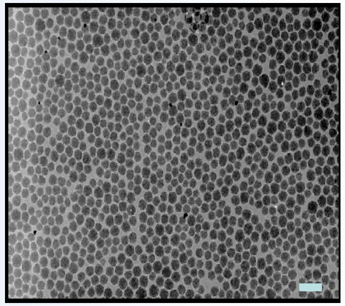
Aerogel

Xerogel

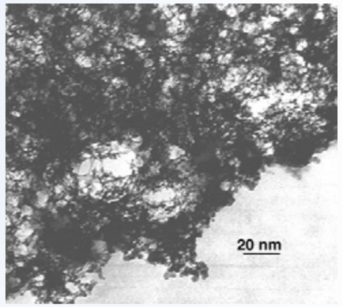
Sol-gel



Sol



TEM of a basic silica sol. Scale bar 20 nm

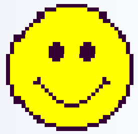


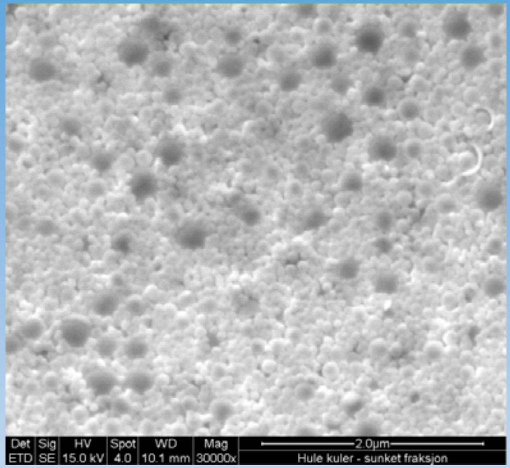
TEM of a base-catalysed silica aerogel Scale bar 20 nm
Lawrence Berkeley National Laboratory

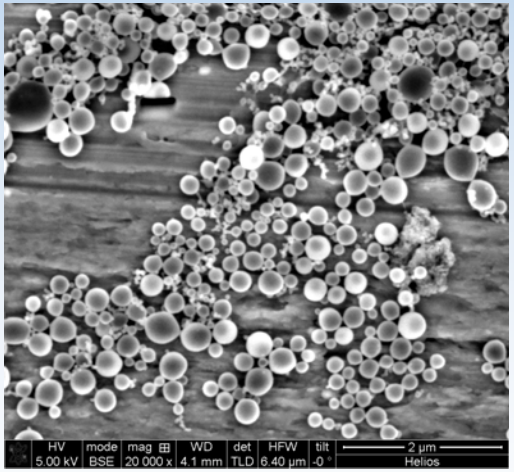
First Attempts to Make the NIMs

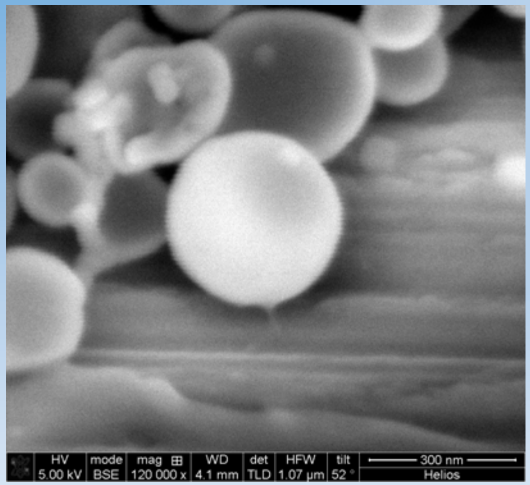
SEM Photos

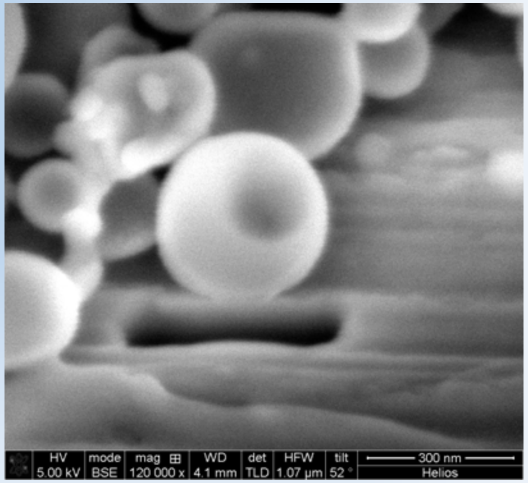
- wish us good luck…!

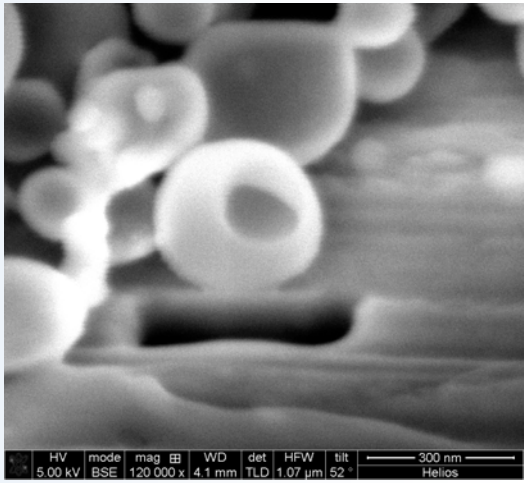












FIB burning... confirming the nanospheres are hollow...

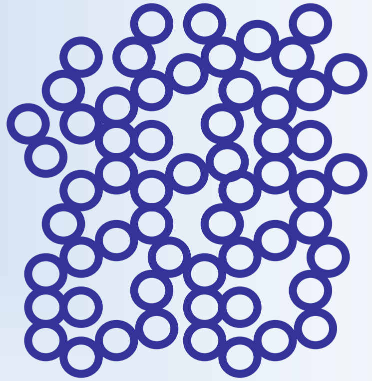
... are we getting the first glimpse at the Holy Grail here...?

Achieved particle size:

90 – 400 nm, most: ~ 200 nm

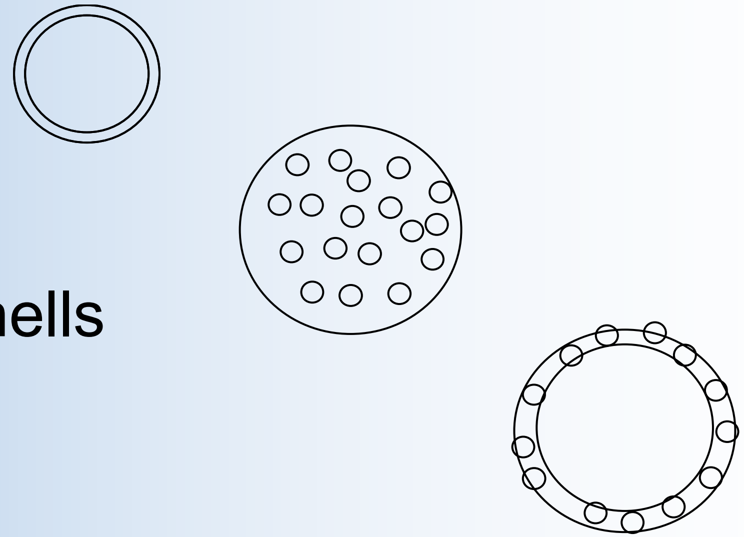
Next:

- Control droplet size
  - Stirring rate
  - Membrane emulsification
  - Ultrasonic treatment
- Control shell thickness
- Drying to obtain powder
- Surface modification: hydrophobic
- Sintering to make NIMs

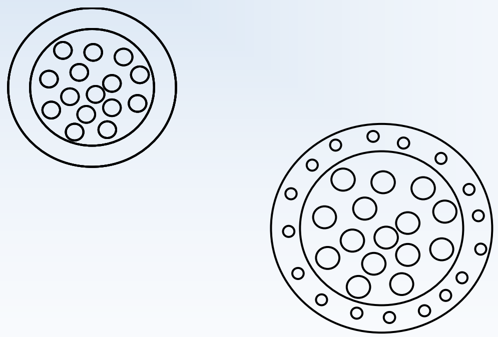


Further Ahead

- **Vary particle morphology**
  - Hollow SiO_2 particles
  - Mesoporous SiO_2 particles
  - Hollow particles with mesoporous shells



- **Particle synthesis – Optimization**
  - Particle size
  - Bulk mesoporosity
  - Shell thickness
  - Shell mesoporosity



ZEB-1SK (60 mg PAA, 2 ml NH_4OH (28%), 20 ml EtOH)

Preparation of Silica Capsules

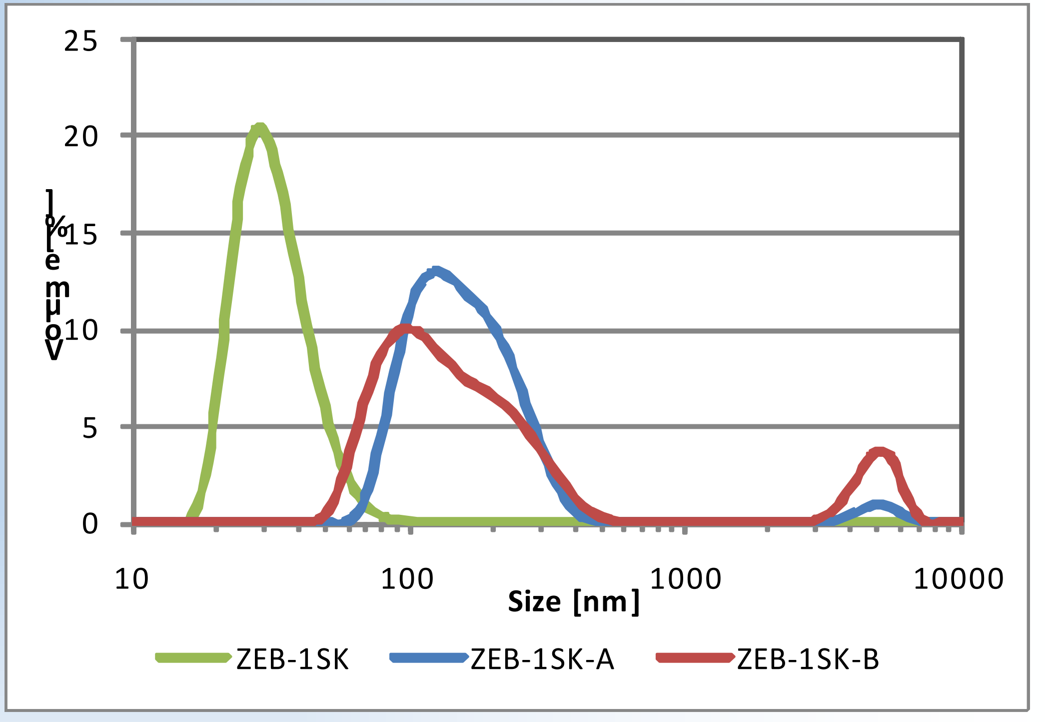
ZEB-1SK

10 ml → ZEB-1SK-A → 5x100µl TEOS, 1h in between

- Partly precipitation
- Washed with water
- single capsules difficult to sediment in EtOH

10 ml → ZEB-1SK-B → 5x50µl TEOS, 0.5h in between

- Less precipitation
- EtOH evaporated first
- Washed with water
- Capsules sediment a bit better w/o EtOH



Sample	d_z [nm]	PDI
ZEB-1SK	38.2	0.11
ZEB-1SK-A	155.5	0.16
ZEB-1SK-B	144.5	0.18

ZEB-6SK (60 mg PAA, 2 ml NH_4OH (14%), 20 ml EtOH)

Preparation of Silica Capsules

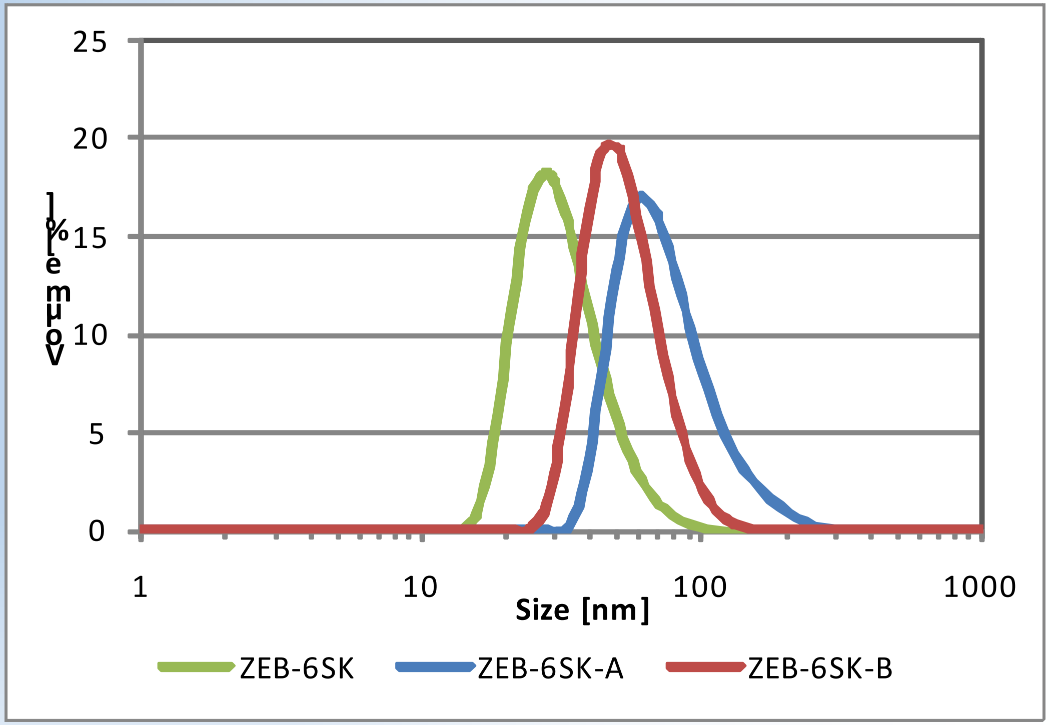
ZEB-6SK

10 ml → ZEB-6SK-A → 5x100µl TEOS, 1h in between

- Slight precipitation
- Washed with water
- single capsules difficult to sediment in EtOH

10 ml → ZEB-6SK-B → 5x50µl TEOS, 0.5h in between

- No precipitation
- EtOH evaporated first
- Washed with water
- Capsules sediment a bit better w/o EtOH



Sample	d_z [nm]	PDI
ZEB-6SK	41.2	0.12
ZEB-6SK-A	89.9	0.12
ZEB-6SK-B	61.6	0.08

ZEB-13SK (300 mg PAA, 10 ml NH_4OH (14%), 100 ml EtOH)

Preparation of Silica Capsules

ZEB-13SK

↓

5x500µl TEOS
0.5h in between

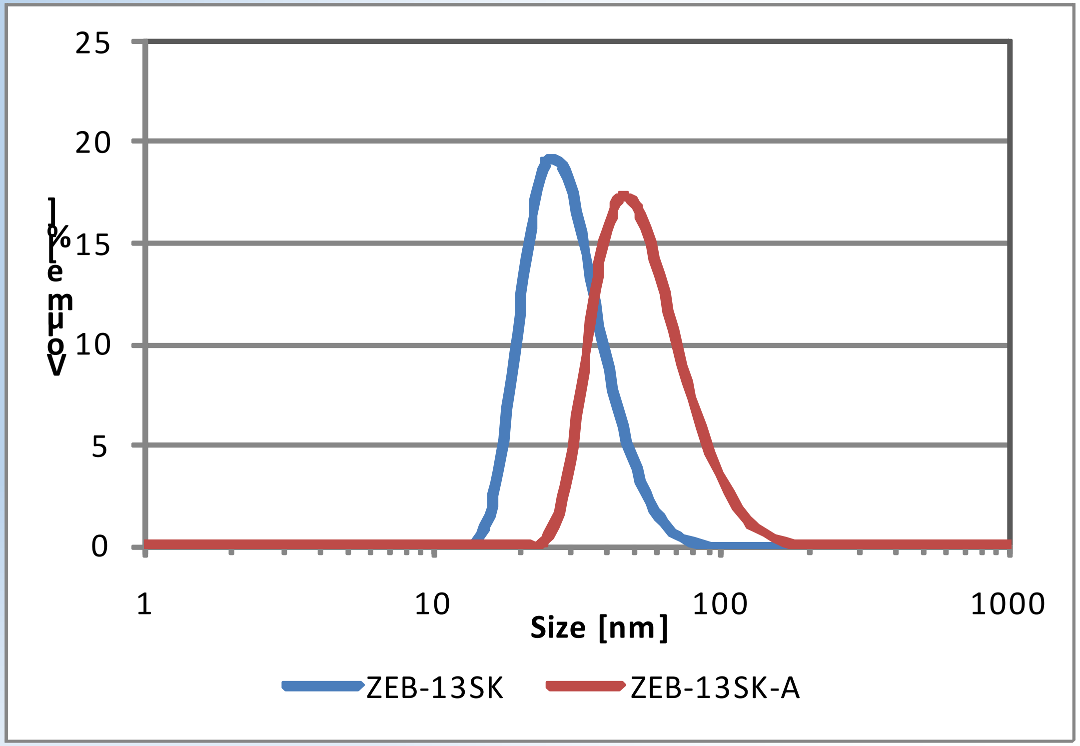
↓

- No precipitation

↓

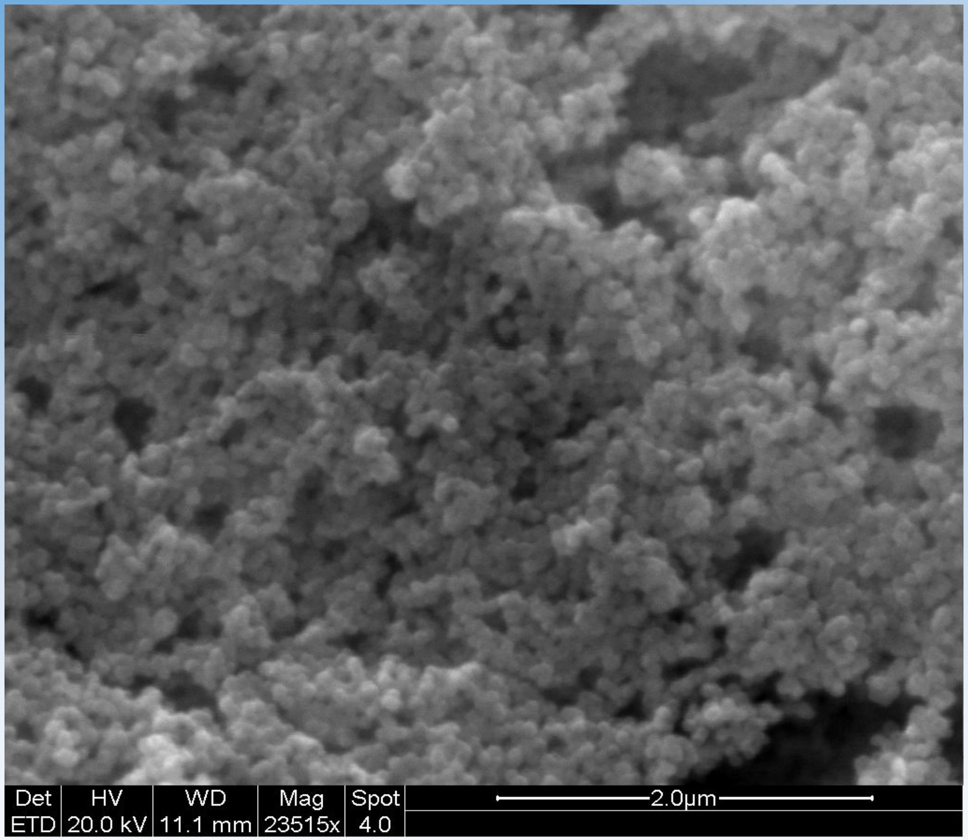
ZEB-13SK-A

- → ZEB-13SK-A1
- → EtOH evaporated
  - → ZEB-13SK-A2 → Tempered at 550°C
  - → ZEB-13SK-A3 → Washed with water

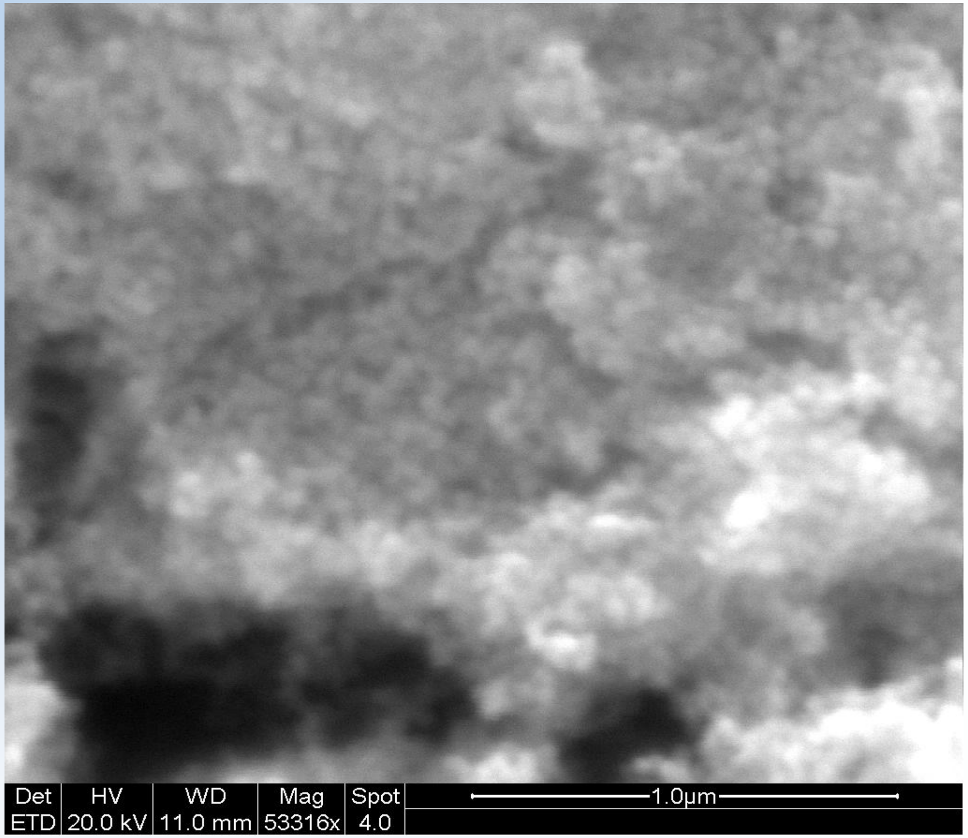


Sample	d_z [nm]	PDI
ZEB-13SK	36.1	0.10
ZEB-13SK-A	67.1	0.10

SEM Photos



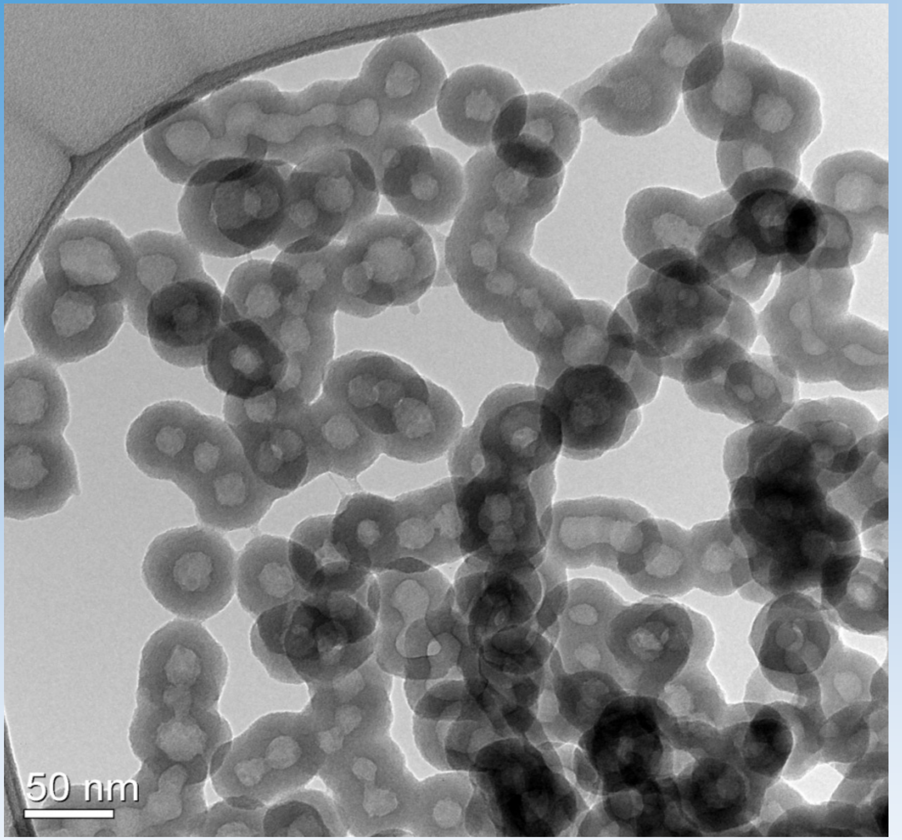
ZEB-1SK-A



ZEB-6SK-A

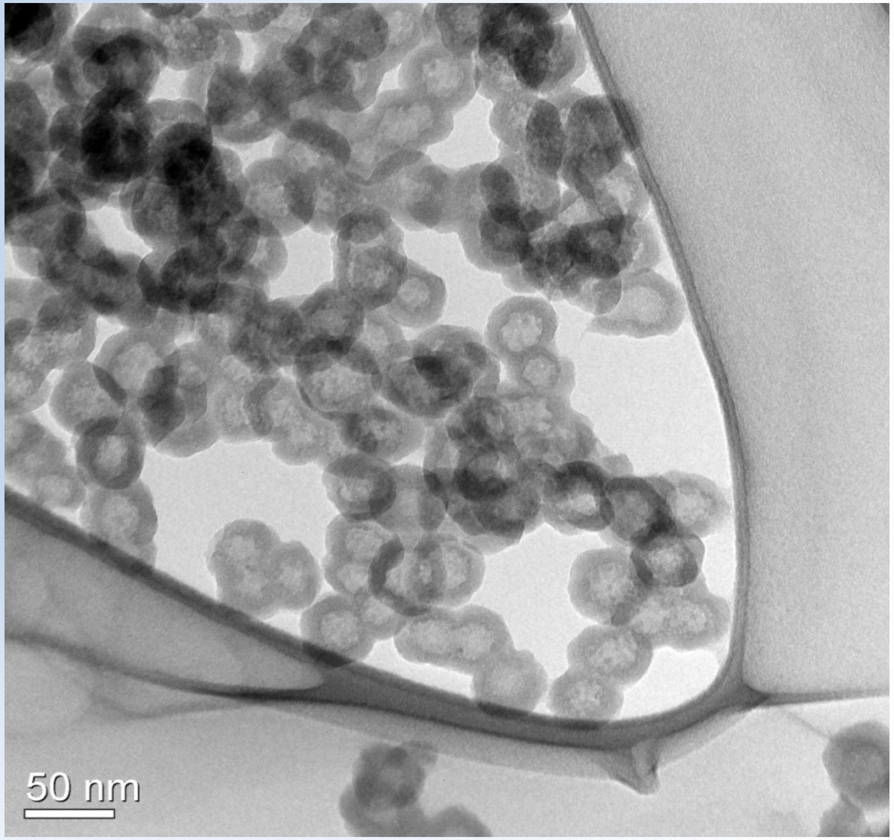
TEM Photos

Different amount of silicon



ZEB-1SK-A
5x100µl TEOS
1h in between
2ml NH_4OH (28%)

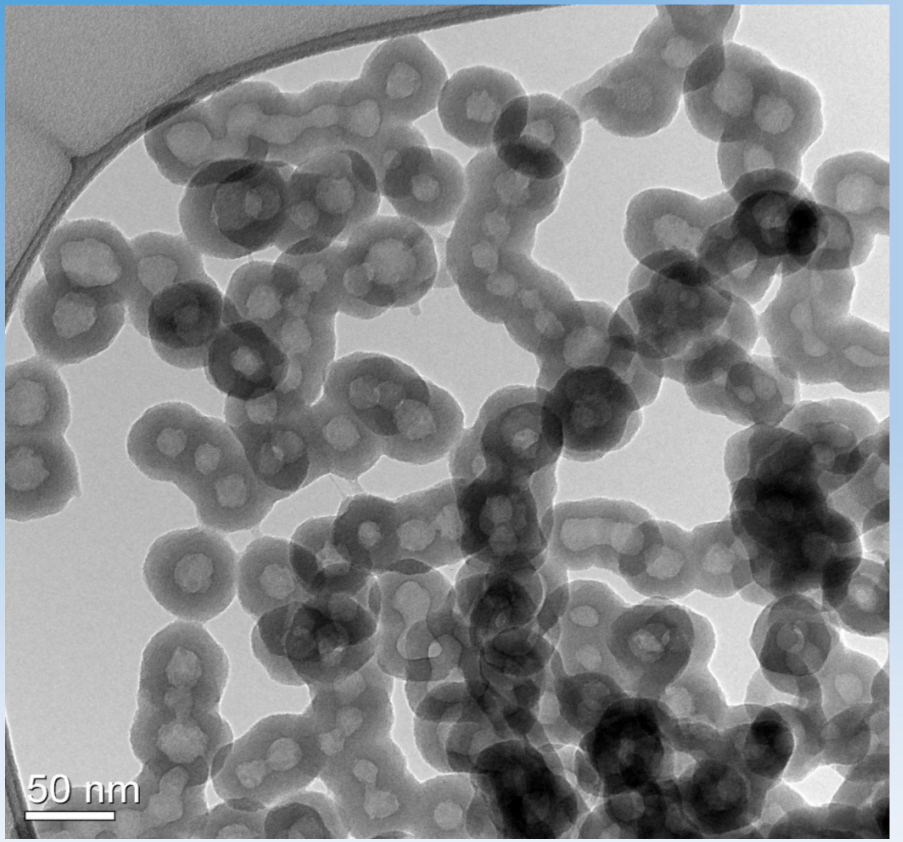
Size: 50-60 nm
Cavity: 20-25 nm
Wall: 30-35 nm

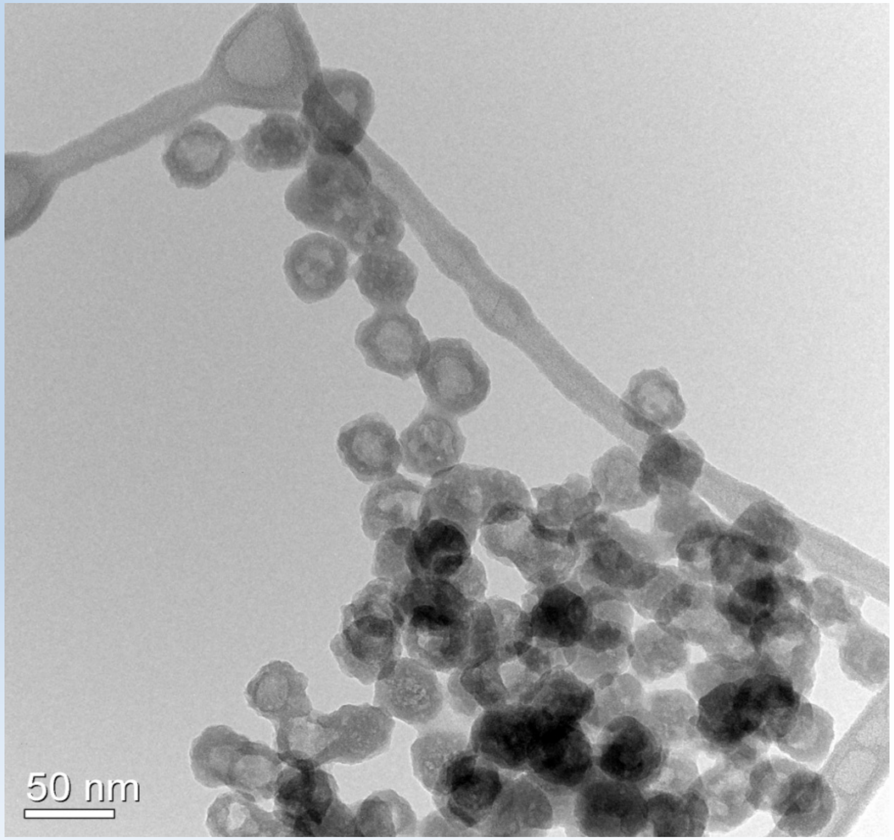


ZEB-1SK-B
5x50µl TEOS
0.5h in between
2ml NH_4OH (28%)

Size: 40-45 nm
Cavity: 20-25 nm
Wall: 20-25 nm

TEM Photos Different amount of NH_4OH





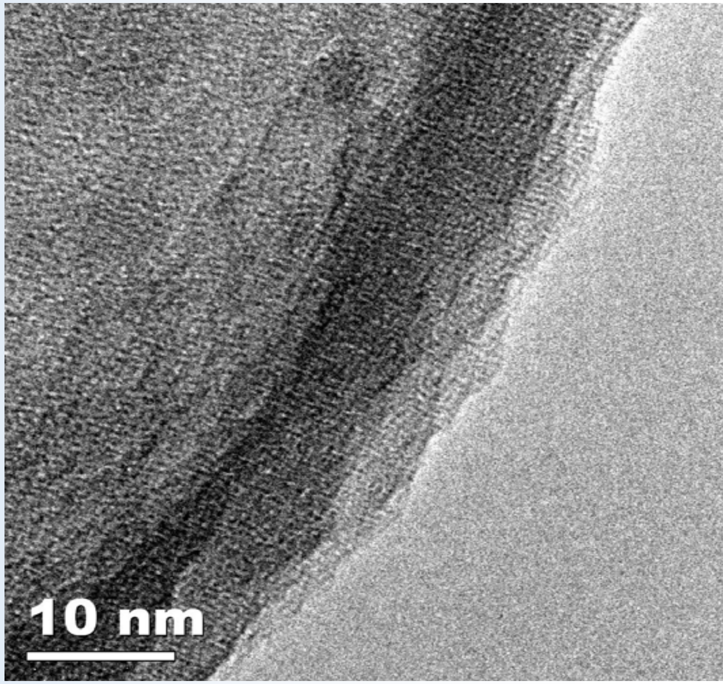
ZEB-1SK-A
5x100µl TEOS
1h in between
2ml NH_4OH (28%)

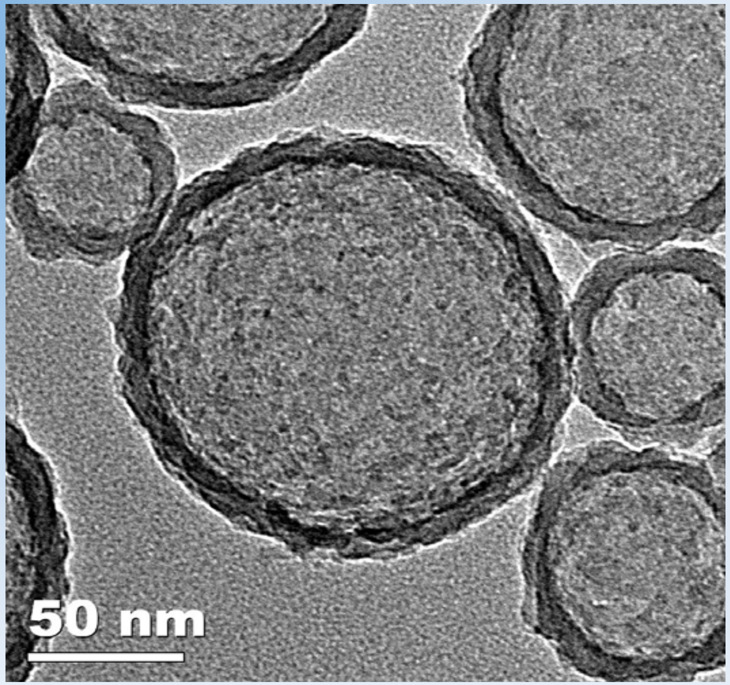
Size: 50-60 nm
Cavity: 20-25 nm
Wall: 30-35 nm

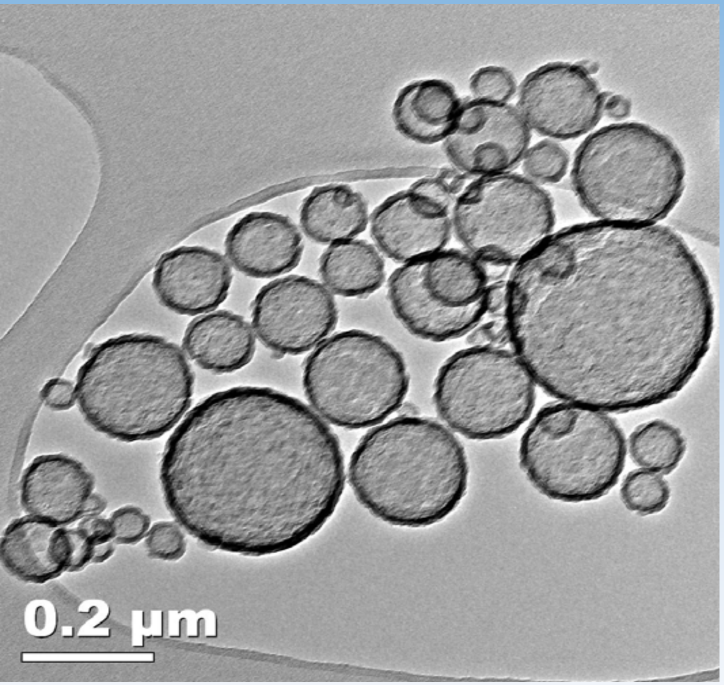
ZEB-6SK-A
5x100µl TEOS
1h in between
2ml NH_4OH (14%)

Size: 40-45 nm
Cavity: 18-22 nm
Wall: 20-25 nm

Hollow silica nanospheres by templating

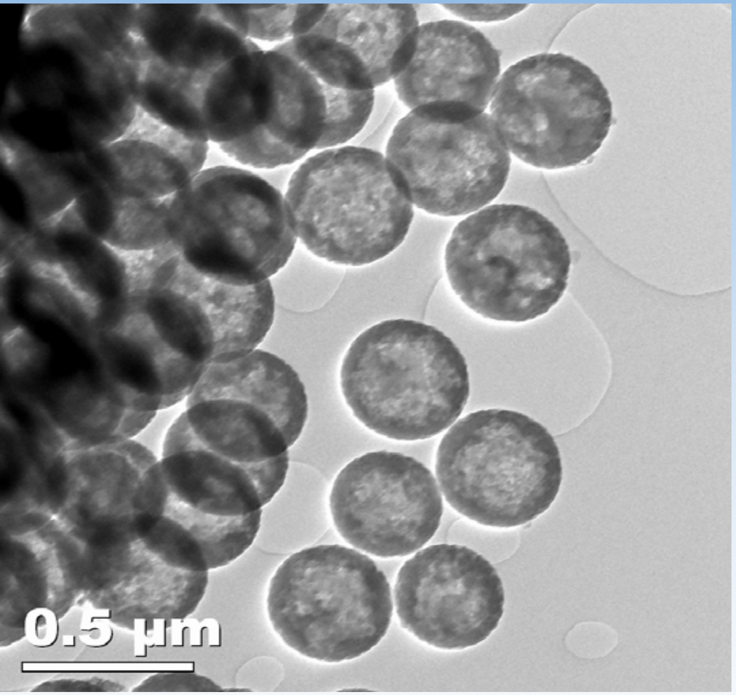


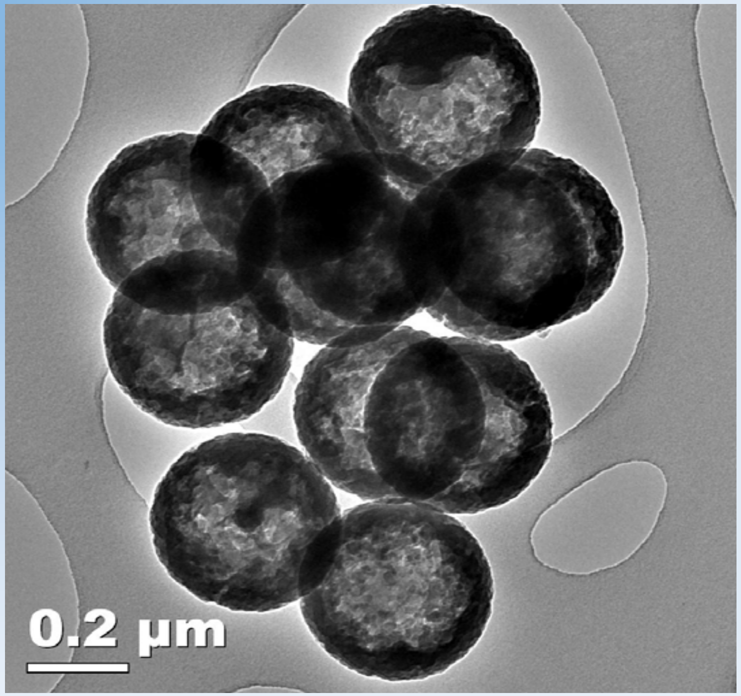


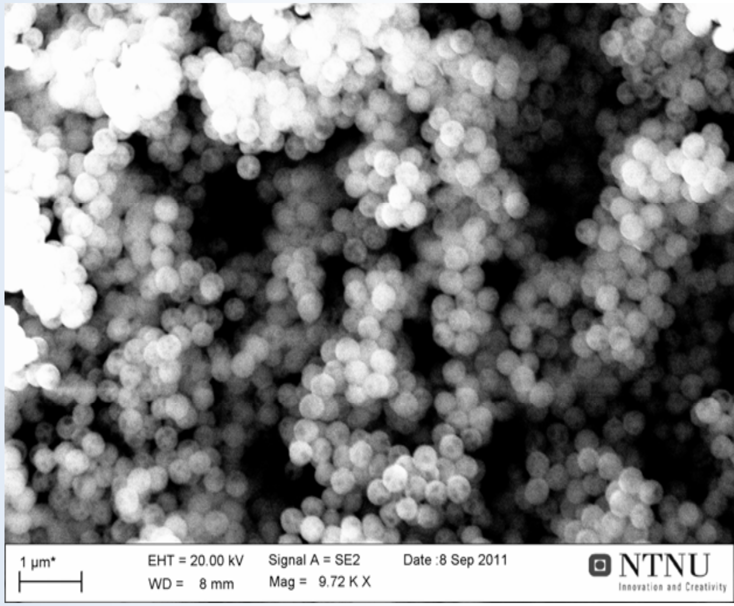


Sizes of the hollow silica nanospheres range from 50 to 250 nm; while the thickness is fairly uniform, about 10 nm, which can be tuned by varying the silica source materials.

Hollow silica nanospheres by etching







Sizes of the hollow silica nanospheres are fairly uniform, about 300 nm in diameter; the thickness of the shell is about 20 nm, which can be tuned by varying the etching time.

The Path Ahead

- At the moment following various paths to make hollow nanospheres
- First thermal conductivity measurements on the powder … no optimization yet… measured yesterday…
- ~ 37 mW/(mK) … we intend to go further down yes…
- … then to piece the nanospheres together to form a bulk insulation material…

Dynamic Insulation Material (DIM)

DIM – A material where the thermal conductivity can be controlled within a desirable range

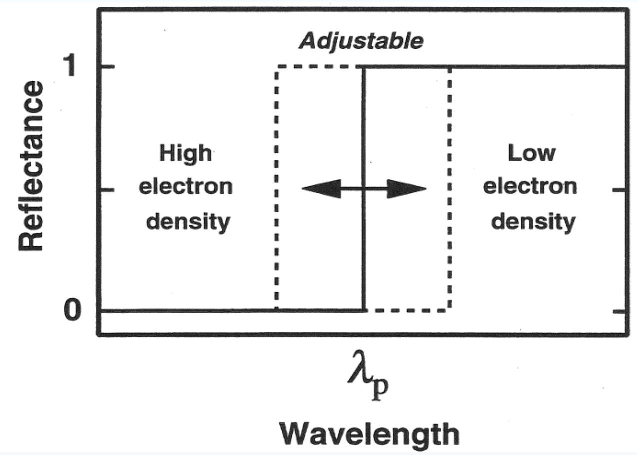
- **Thermal conductivity control may be achieved by:**
  - **Inner pore gas content or concentration including the mean free path of the gas molecules and the gas-surface interaction**
  - **The emissivity of the inner surfaces of the pores**
  - **The solid state thermal conductivity of the lattice**
- **What is really solid state thermal conductivity? Two models:**
  - **Phonon thermal conductivity - atom lattice vibrations**
  - **Free electron thermal conductivity**
- ***What kind of physical model could describe and explain thermal conductivity?***
- ***Could it be possible to dynamically change the thermal conductivity from very low to very high, i.e. making a DIM?***

Dynamic Insulation Material (DIM)

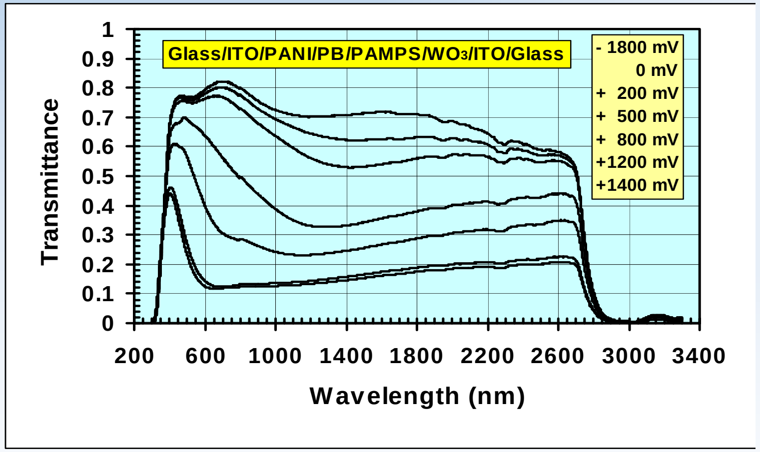
- **Dynamic Vacuum**
- **Dynamic Emissivity of Inner Pore Surfaces**
- **Dynamic Solid Core Thermal Conductivity**
  - Is it possible?
  - Fundamental understanding of the thermal conductance?
- **Other?**

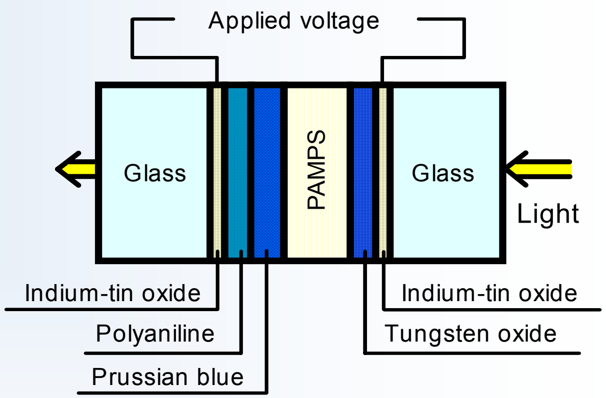
Learning from Electrochromic Materials?:

$$\lambda_p = (2\pi c/q_e)(m_e\varepsilon_0/n_e)^{1/2}$$



B. P. Jelle, "Electrochemical and Spectroscopic Studies of Electrochromic Materials", *Ph.D. thesis*, 1993:131, Department of Applied Electrochemistry, The Norwegian Institute of Technology, Trondheim, Norway, 1993.





B. P. Jelle, A. Gustavsen, T.-N. Nilsen and T. Jacobsen, "Solar Material Protection Factor (SMPF) and Solar Skin Protection Factor (SSPF) for Window Panes and other Glass Structures in Buildings", *Solar Energy Materials & Solar Cells*, 91, 342-354 (2007).

Inspiration and Ideas

Could other fields of science and technology inspire and give ideas about how to be able to make DIMs, e.g. from the fields?:

- **Electrochromic Materials**
- **Quantum Mechanics**
- **Electrical Superconductivity**
- **Other?**

Aerogels – Approaching the NIMs

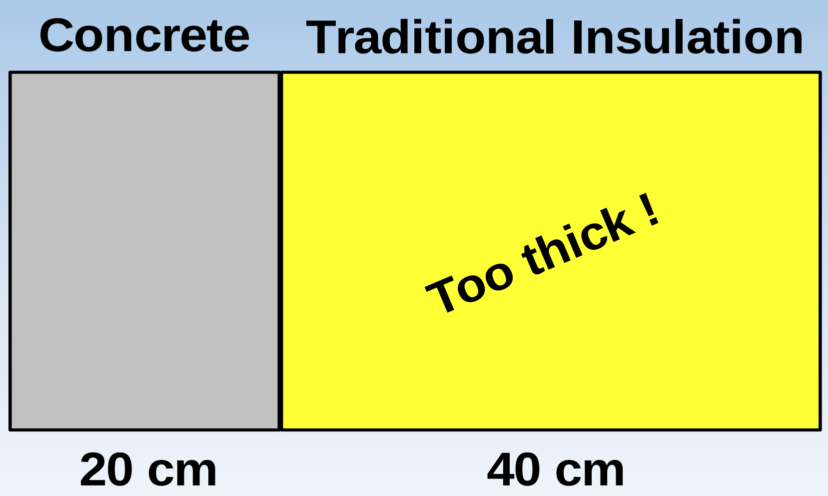
- Aerogels – At the moment the closest commercial approach to NIMs
- 12 – 14 mW/(mK)
- Aspen Aerogels
  - Spaceloft
- Cabot Aerogel
  - Nanogel

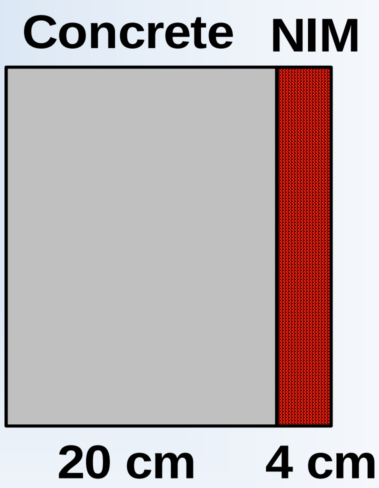
- Production costs still high
- Relatively high compression strength
- Very fragile due to very low tensile strength
- Tensile strength may be increased by incorporation of a carbon fibre matrix
- May be produced as either opaque, translucent or transparent materials
  - ➔ Thus enabling a wide range of possible building applications

Thinner Concrete Buildings with NIMs

- Mineral Wool or Polystyrene
- 36 mW/(mK)
- 40 cm traditional thermal insulation retrofitting

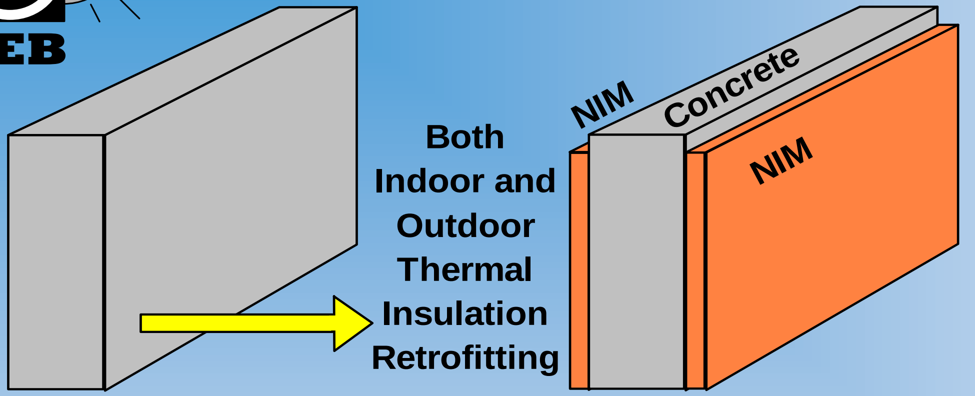
- NIM
- 3.6 mW/(mK)
- 4 cm NIM thermal insulation retrofitting



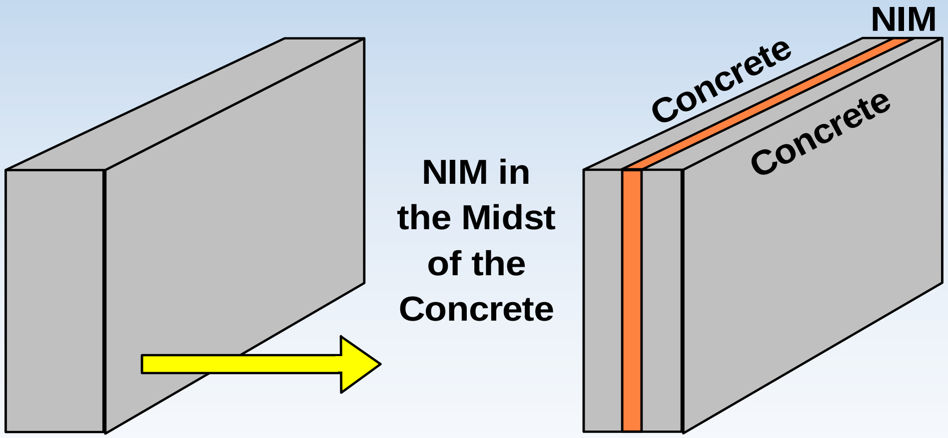


- A vast reduction – factor 10 – of the thermal insulation layer and thereby the total building envelope thickness.

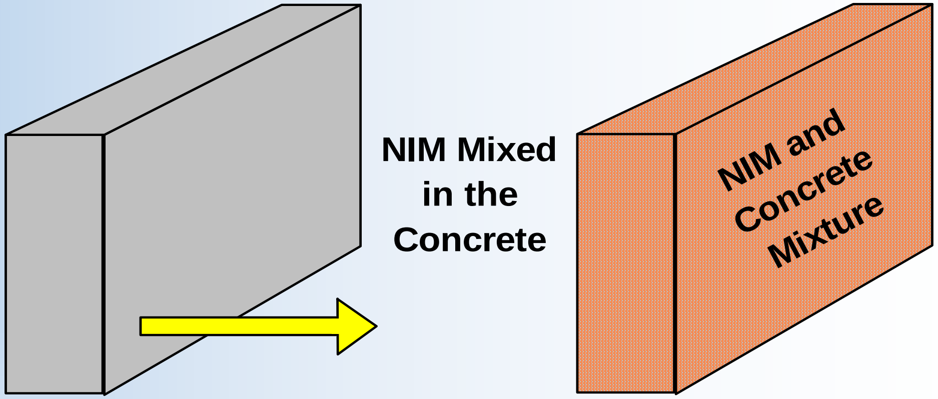
Concrete with NIMs



Concrete with NIM Indoor and Outdoor
- Retrofitting



NIM in the Midst of Concrete



NIM and Concrete Mixture

… or going beyond these…?

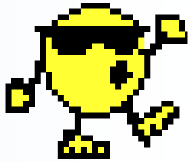
To Envision Beyond Concrete ?

- *In the community of concrete it might be compared to using profane language in the church and close to blasphemy to suggest that maybe the answer is not concrete after all…* 👍☺

Emphasis on Properties and Functional Requirements

- Concrete:
- High thermal conductivity.
- Total thickness of the building envelope will often become unnecessary large (passive house, zero energy building or zero emission building).
- Large CO_2 emissions connected to the production of cement.
- Prone to cracking induced by corrosion of the reinforcement steel.
- Easy accessible and workable, low cost and local production.
- High fire resistance.

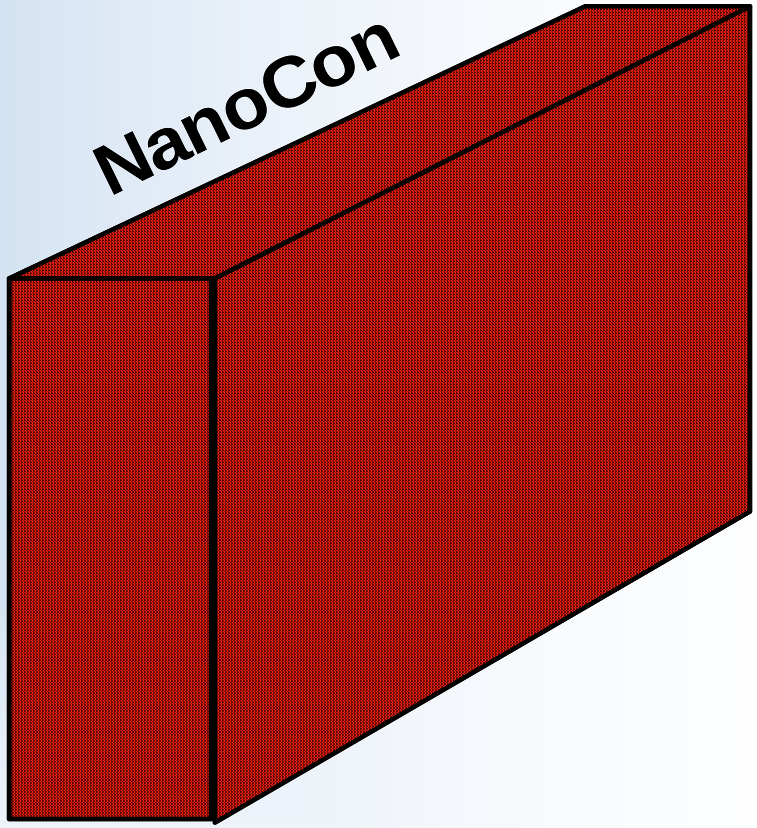
- Is it possible to envision a building and infrastructure industry without an extensive usage of concrete?



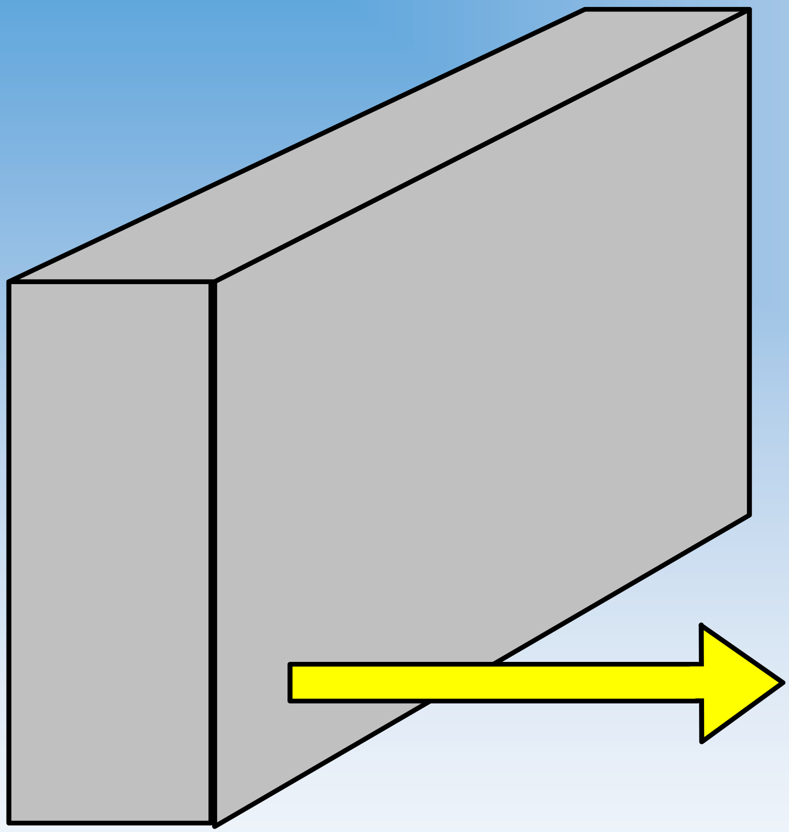
Emphasis on Functional Requirements

- Not the building material itself which is important.
- Property or functional requirements are crucial.
- Possible to invent and manufacture a material with the essential structural or construction properties of concrete intact or better, but with substantially lower thermal conductivity?
- Beneficial with a much lower negative environmental impact than concrete with respect to CO_2 emissions.
- Envisioned with or without reinforcement or rebars.

NanoCon – Introducing a New Material



Making a New Material: NanoCon

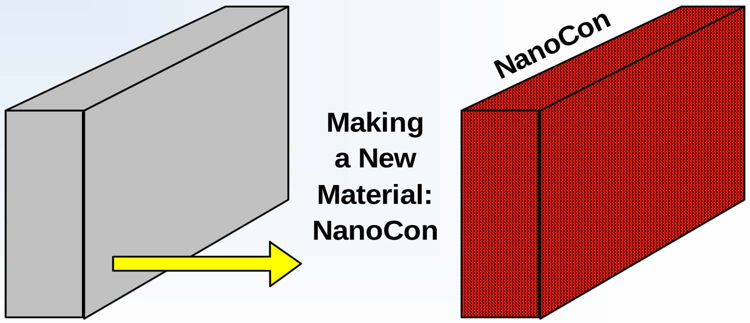


B. P. Jelle, A. Gustavsen and R. Baetens, "The High Performance Thermal Building Insulation Materials and Solutions of Tomorrow", *Proceedings of the Thermal Performance of the Exterior Envelopes of Whole Buildings XI International Conference (Buildings XI)*, Clearwater Beach, Florida, U.S.A., 5-9 December, 2010.

NanoCon – Introducing a New Material

- NanoCon
- Basically a homogeneous material
- Closed or open small nano pore structure
- Overall thermal conductivity < 4 mW/(mK) (or another low value to be determined)
- Exhibits the crucial construction properties that are as good as or better than concrete.
  - Utilize carbon nanotubes (CNT)? Tensile strengths of 63 GPa (measured) and 300 GPa (theoretical). (Steel rebars 500 MPa and concrete 3 MPa.)

- Essentially, NanoCon is a NIM with construction properties matching or surpassing those of concrete.



Materials and Solutions Not Yet Thought Of ?

- *The more we know the more we know we don't know…!*
  - *… and the more we want to know…!*
  - *… and that's the whole fun of it…!*
- *Think thoughts not yet thought of…!*

Conclusions

- **The Thermal Insulation Materials of Beyond Tomorrow ? :**
- **Theoretical concepts established – Others?**
- **Nano Insulation Materials (NIM)**
- **Dynamic Insulation Materials (DIM)**
- **NanoCon**
- **Others?**
- **First experimental attempts towards NIMs**

Sunrise...
and the Phoenix rises again...!