

Experimental Pathways for Achieving Superinsulation through Nano Insulation Materials

**Bjørn Petter Jelle ^{ab*}, Tao Gao ^c, Bente Gilbu Tilset ^d,
Linn Ingunn Christie Sandberg ^b, Mathieu Grandcolas ^d,
Christian Simon ^d and Arild Gustavsen ^c**

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

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

^c Norwegian University of Science and Technology (NTNU),
Department of Architectural Design, History and Technology, NO-7491 Trondheim, Norway.

^d SINTEF Materials and Chemistry,
Department of Energy Conversion and Materials, NO-0314 Oslo, Norway.

* Corresponding author, Phone +47 73593377, Fax +47 73593380, bjorn.petter.jelle@sintef.no

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- What Measures Amounts the Most ?

Abatement cost
€ per tCO₂e

Abatement potential
GtCO₂e per year

Residential electronics
Residential appliances
Retrofit residential HVAC
Tillage and residue mgmt
Insulation retrofit (residential)
Cars full hybrid
Waste recycling
Degraded forest reforestation
Pastureland afforestation
Degraded land restoration
2nd generation biofuels
Building efficiency new build
Nuclear
Low penetration wind
Cars plug-in hybrid
Coal CCS retrofit
Iron and steel CCS new build
Coal CCS new build
Power plant biomass co-firing
Reduced intensive agriculture conversion
High penetration wind
Solar PV
Solar CSP
Gas plant CCS retrofit
Organic soil restoration
Geothermal
Grassland management
Reduced pastureland conversion
Reduced slash and burn agriculture conversion
Small hydro
1st generation biofuels
Rice management
Efficiency improvements other industry
Electricity from landfill gas
Clinker substitution by fly ash
Cropland nutrient management
Motor systems efficiency
Insulation retrofit (commercial)
Lighting – switch incandescent to LED (residential)

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 tCO₂e 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

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

λ_{tot} = total overall thermal conductivity

λ_{solid} = solid state thermal conductivity

λ_{gas} = gas thermal conductivity

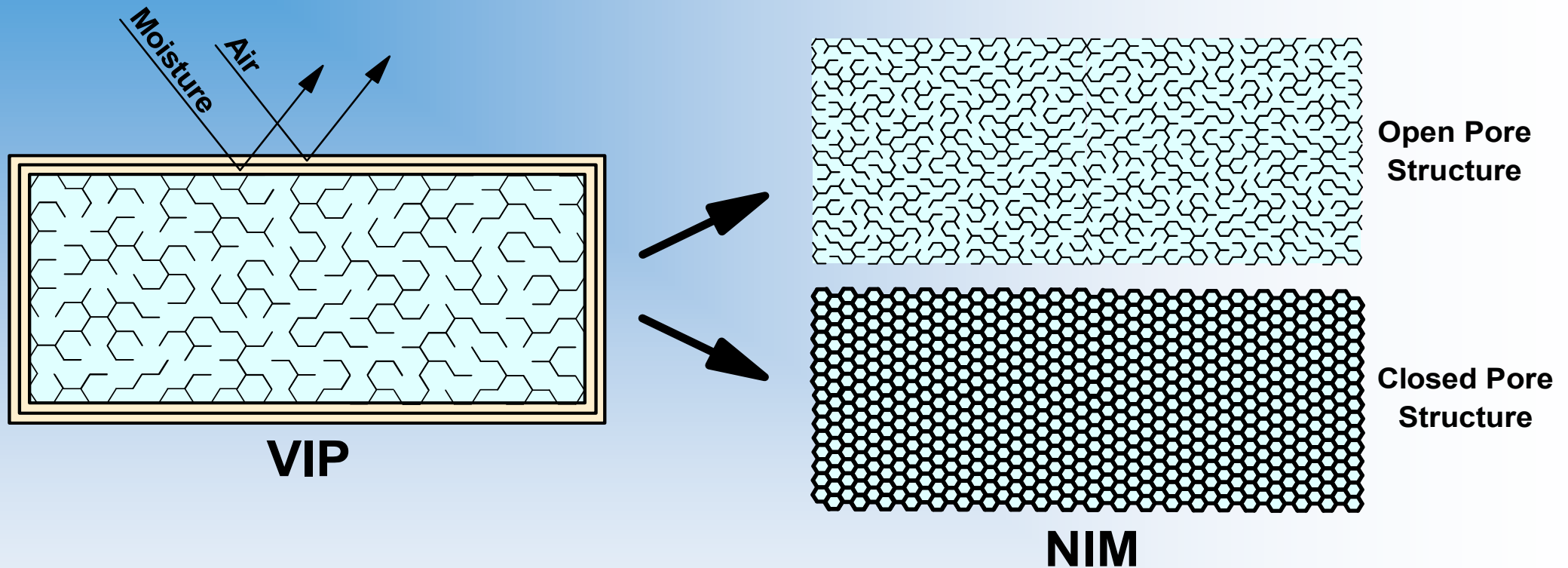
λ_{rad} = radiation thermal conductivity

λ_{conv} = convection thermal conductivity

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

λ_{leak} = leakage thermal conductivity

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}

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

$\sigma_{\text{mean}} > \delta$
 $\Rightarrow \text{LOW } \lambda_{\text{gas}}$

where

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

λ_{gas} = gas thermal conductivity in the pores (W/(mK))

$\lambda_{\text{gas},0}$ = 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)

$\text{Kn} = \sigma_{\text{mean}}/\delta = k_B T / (2^{1/2} \pi d^2 p \delta)$ = the Knudsen number

k_B = Boltzmann's constant $\approx 1.38 \cdot 10^{-23}$ J/K

T = temperature (K)

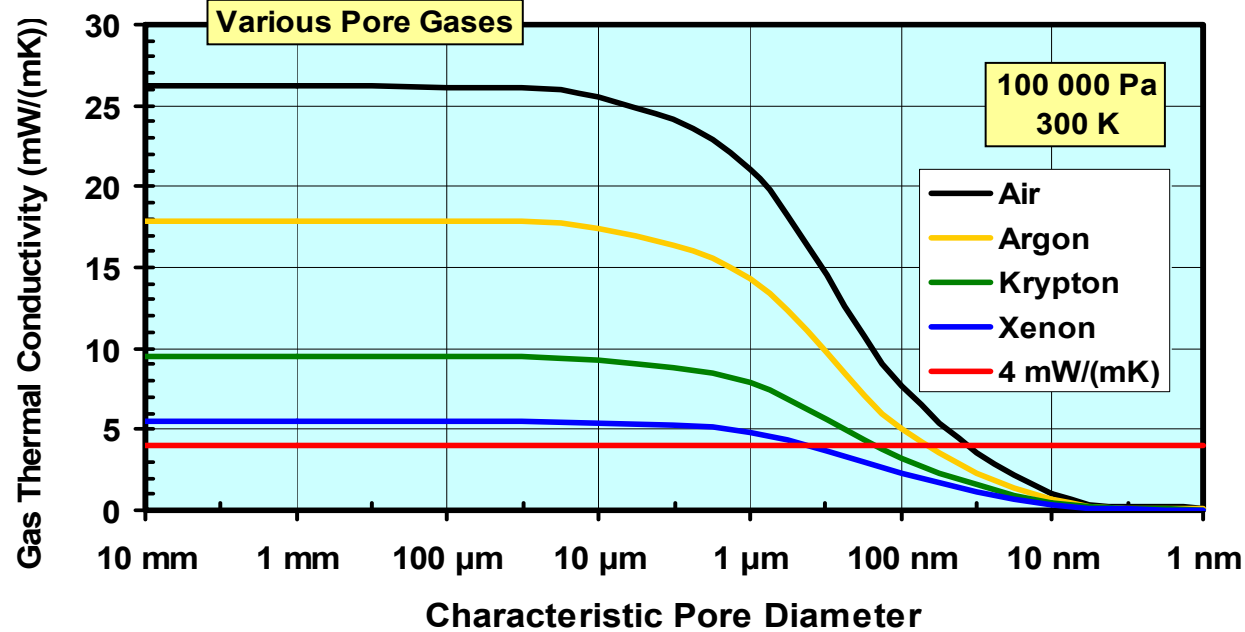
d = gas molecule collision diameter (m)

p = gas pressure in pores (Pa)

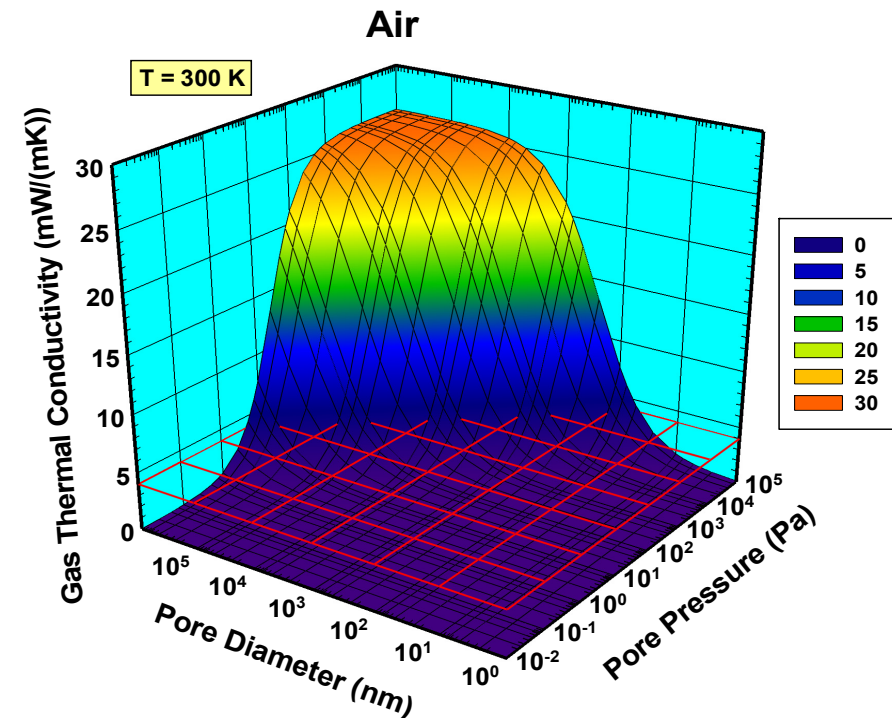
δ = characteristic pore diameter (m)

σ_{mean} = mean free path of gas molecules (m)

Gas Thermal Conductivity



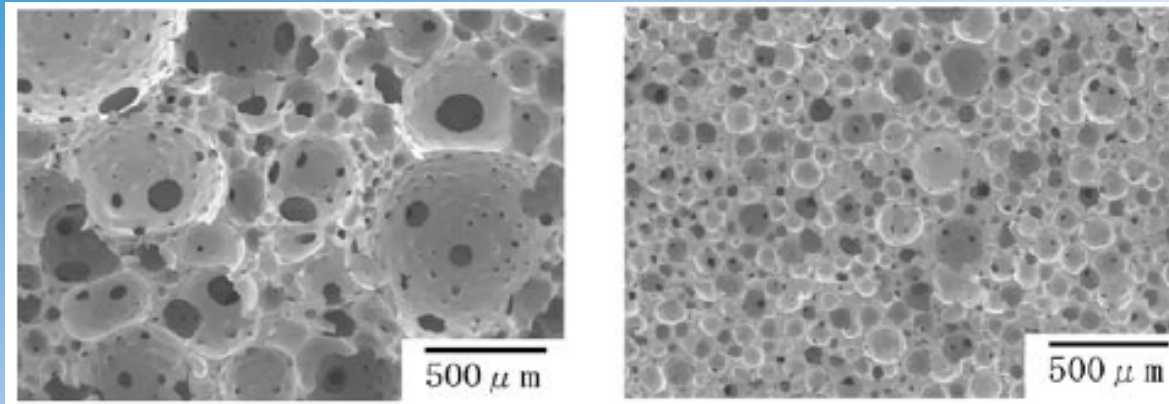
**Conductivity
vs.
Pore Diameter
and
Pore Pressure**



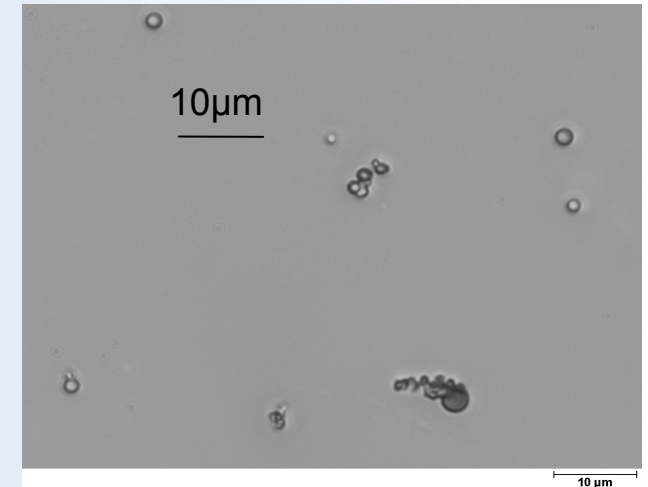
Our First Experimental Attempts towards NIMs as *Hollow Silica Nanospheres* did follow Three Main Preparation Methods:

- 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.

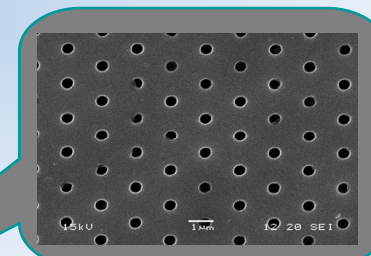
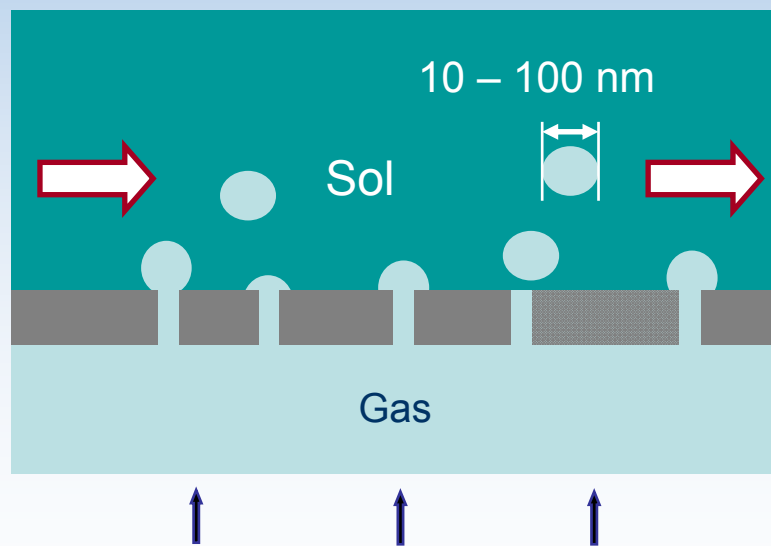
Membrane Foaming



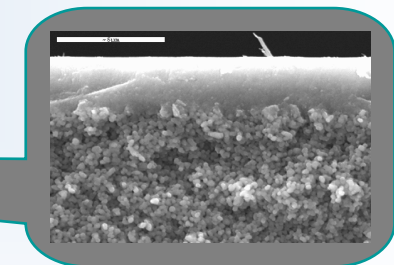
Silica sol stir foamed at 1000 (left) and 2500 (right) mPas
T. Tomita et al. *J. Porous Mater.* **12** (2005) 123.



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

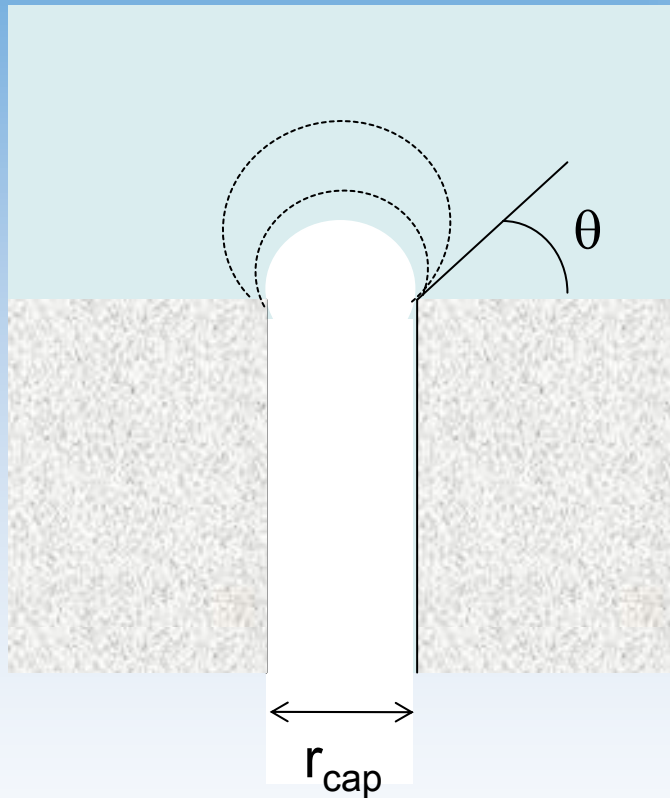


Microconstructed membrane.



Titania
6 nm pores.

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 bilayers.

Membrane Foaming Attempts not Successful:

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

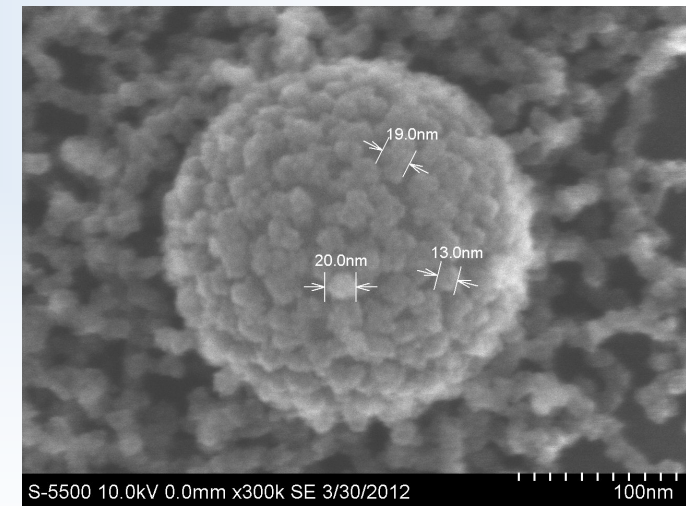
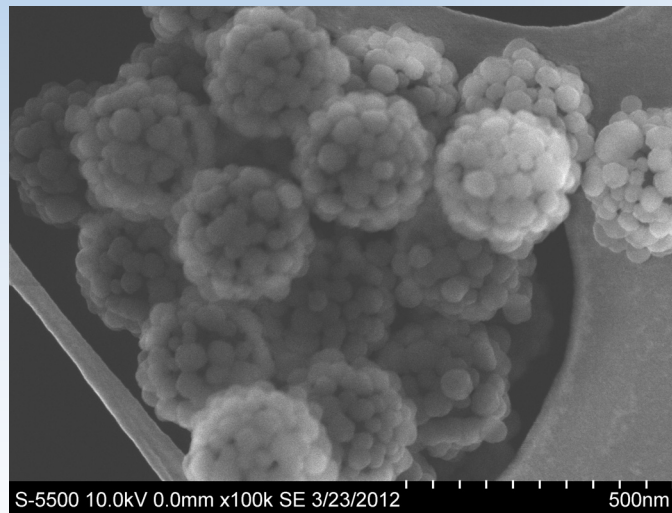
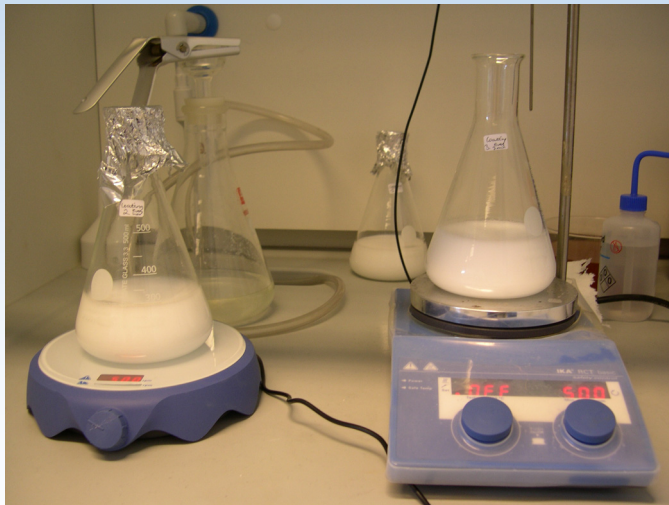
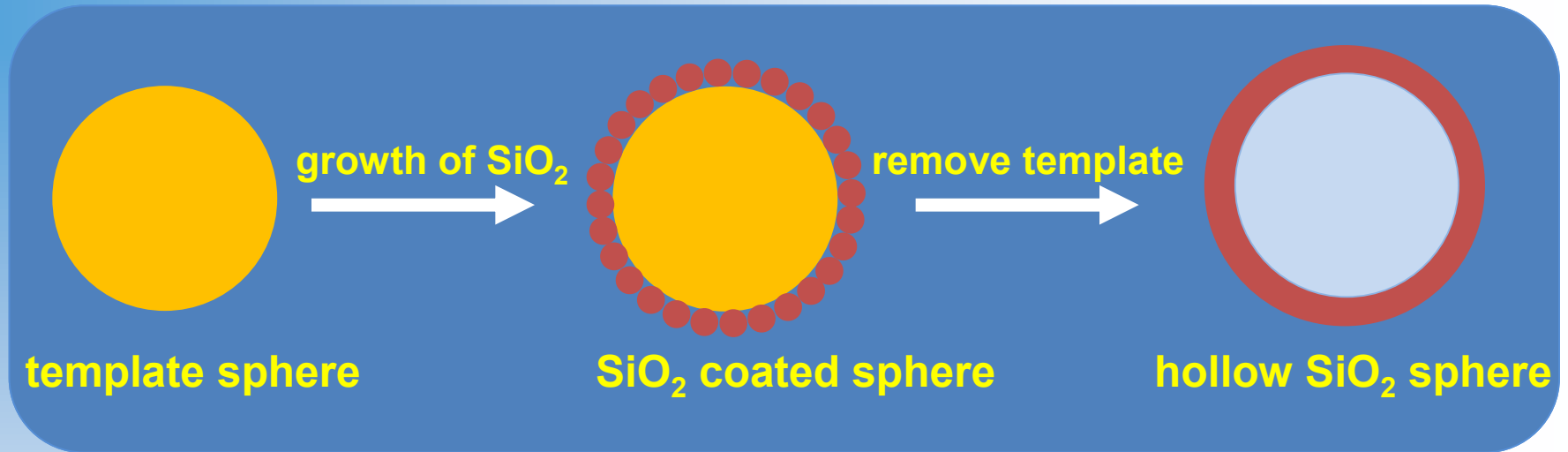
Internal Gas Release Attempts Terminated:

- Very demanding experimental conditions, work terminated.

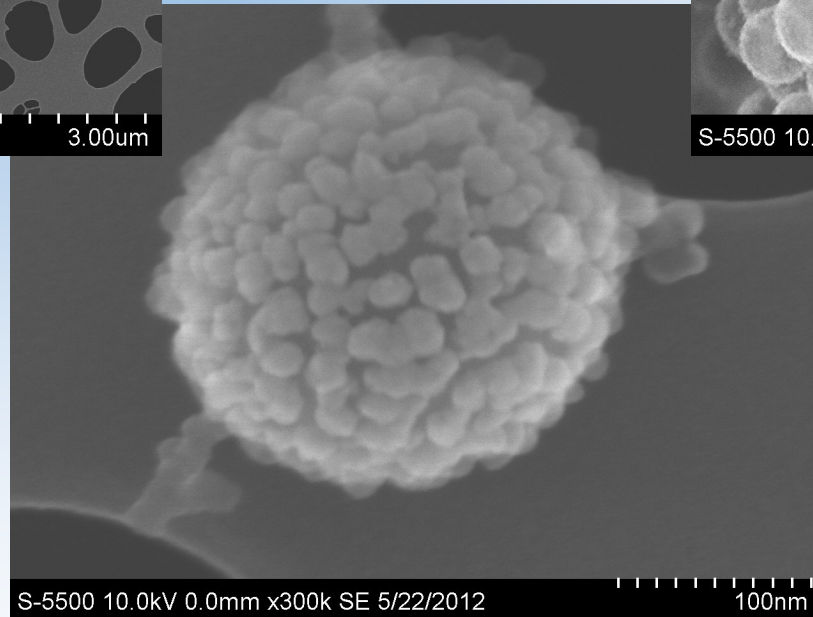
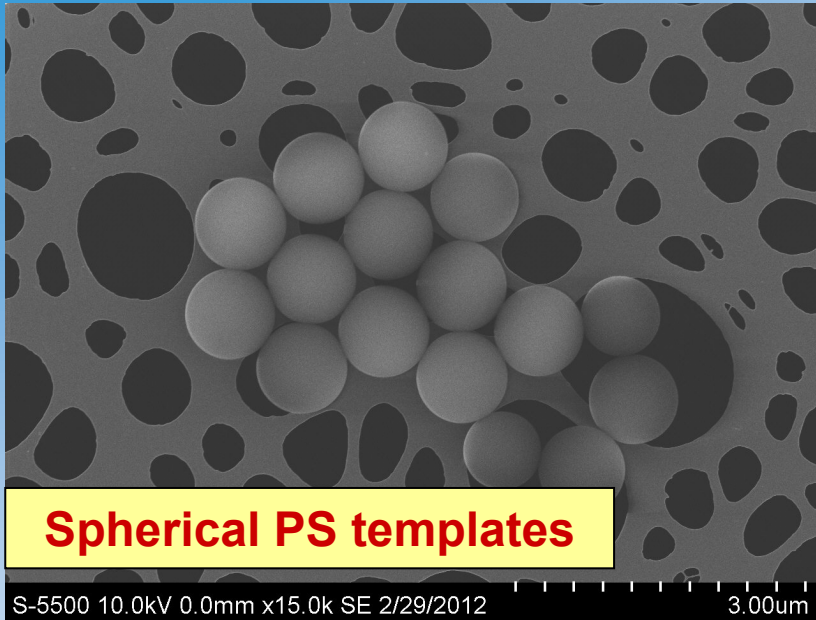
Future experiments may prove different, though.

Templating Process: Hollow Silica Nanospheres

Hollow silica
nanospheres
by making
and applying
equal-sized
templates

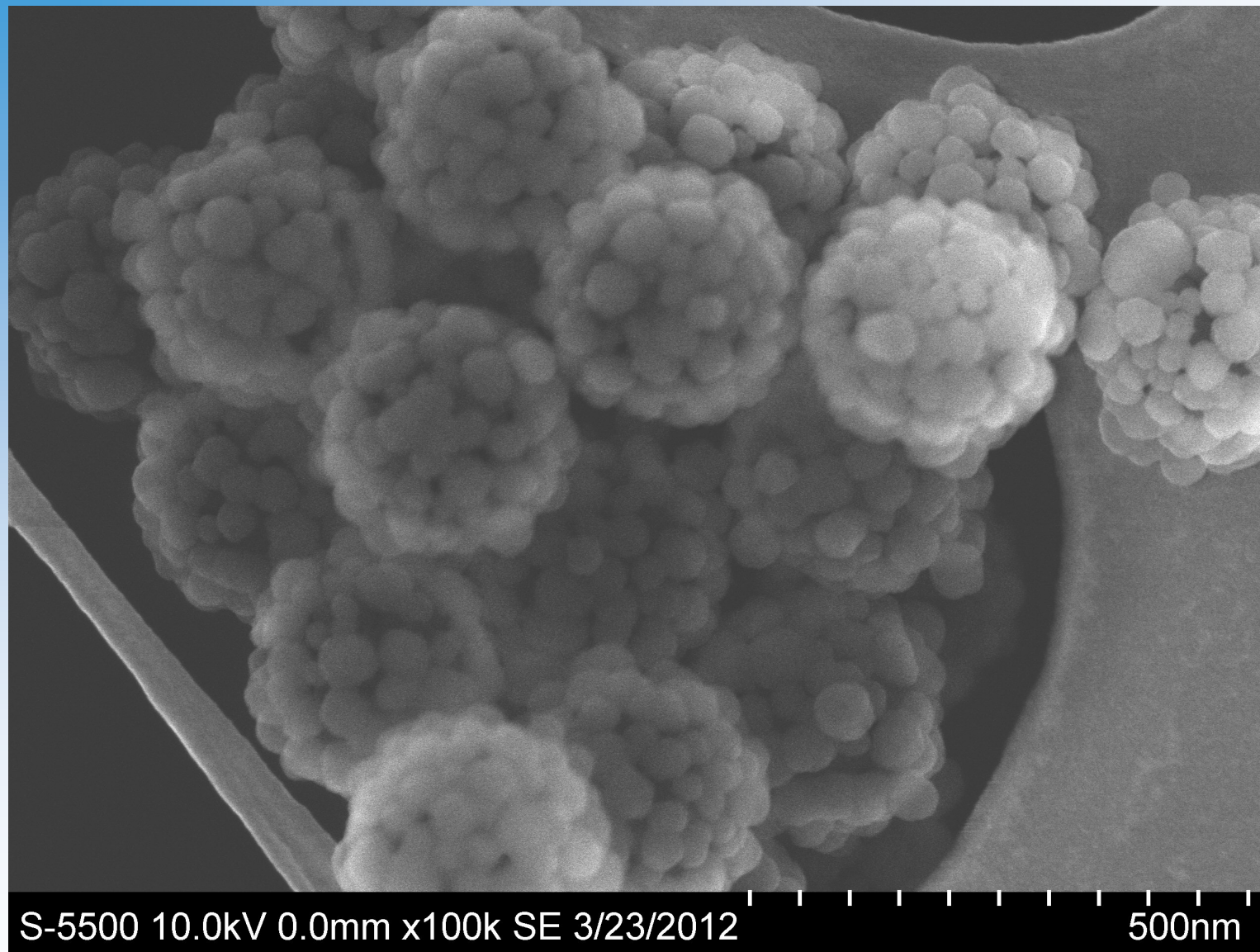


SEM Photos



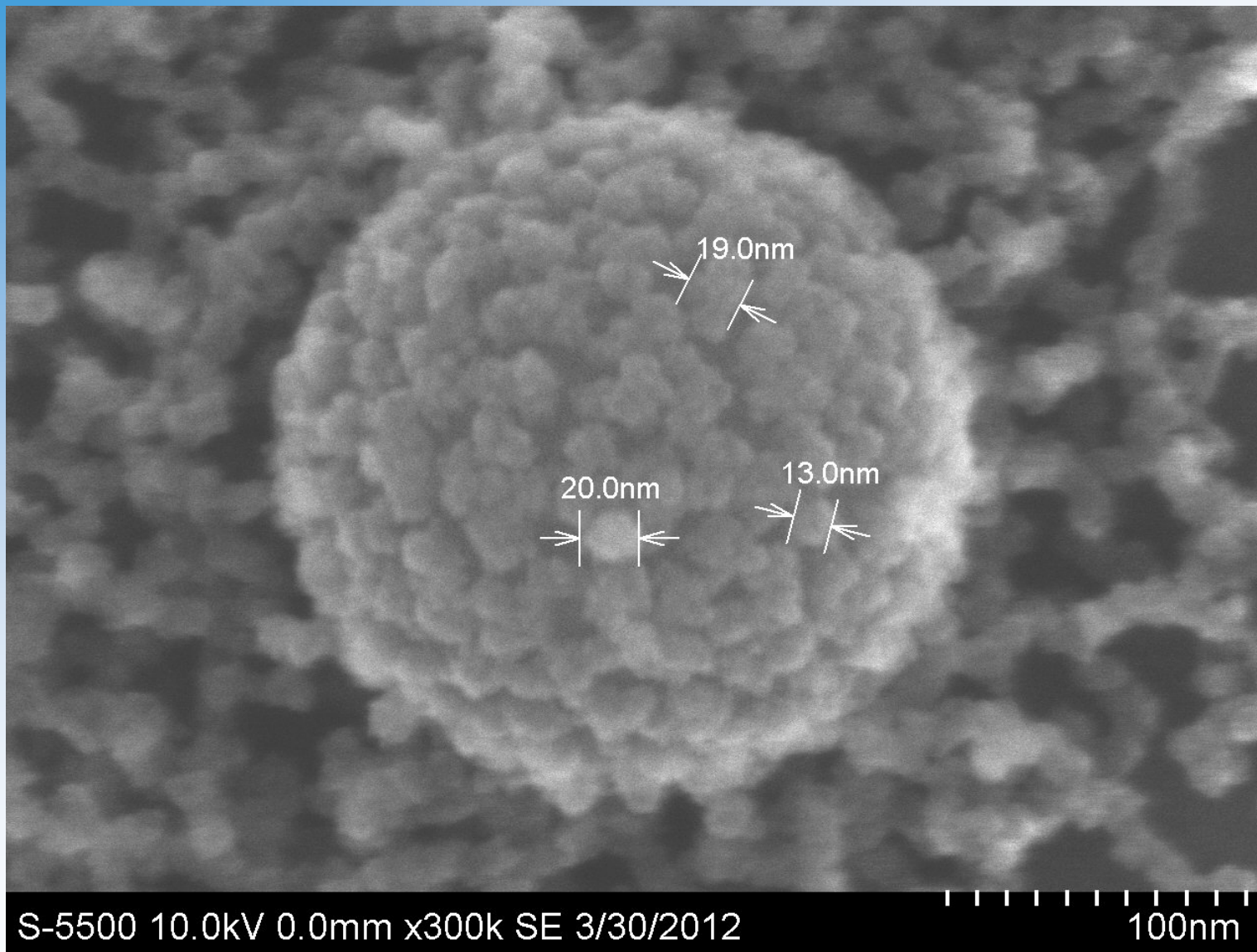
PS = Polystyrene
HSNS = Hollow Silica Nanospheres

SEM Photos



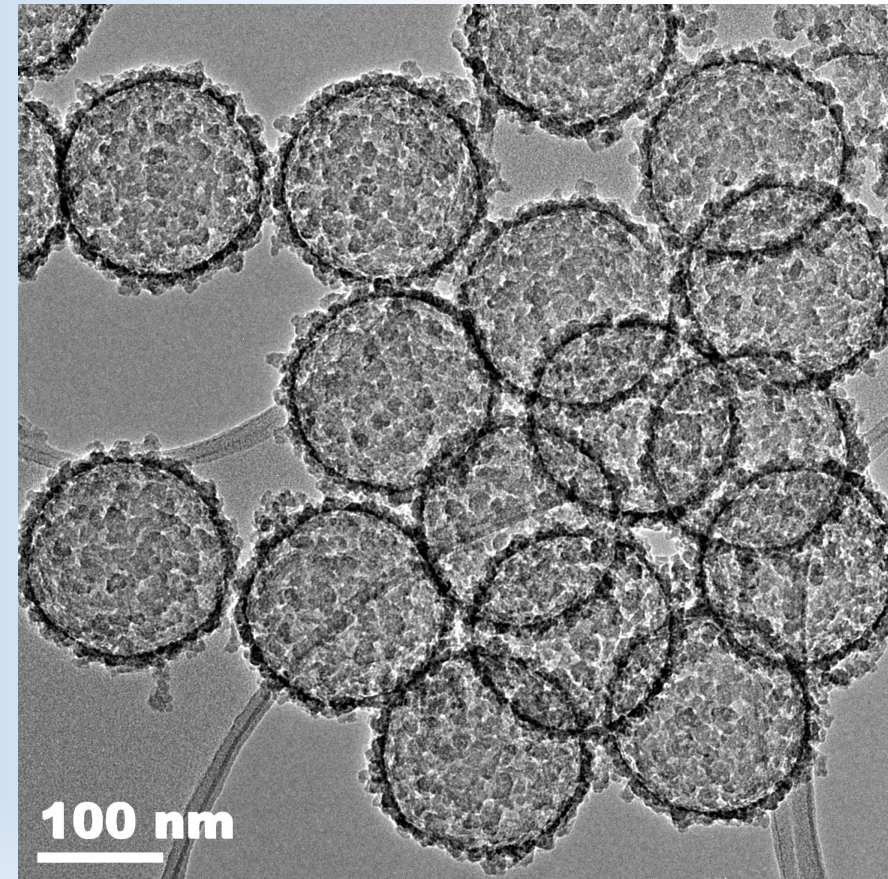
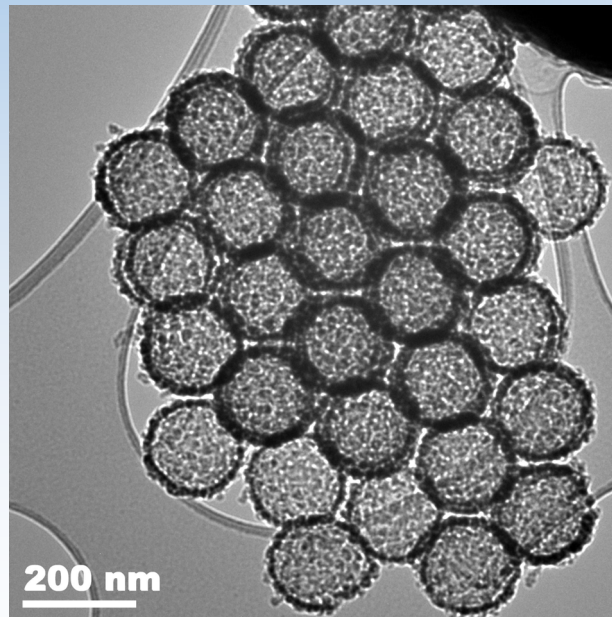
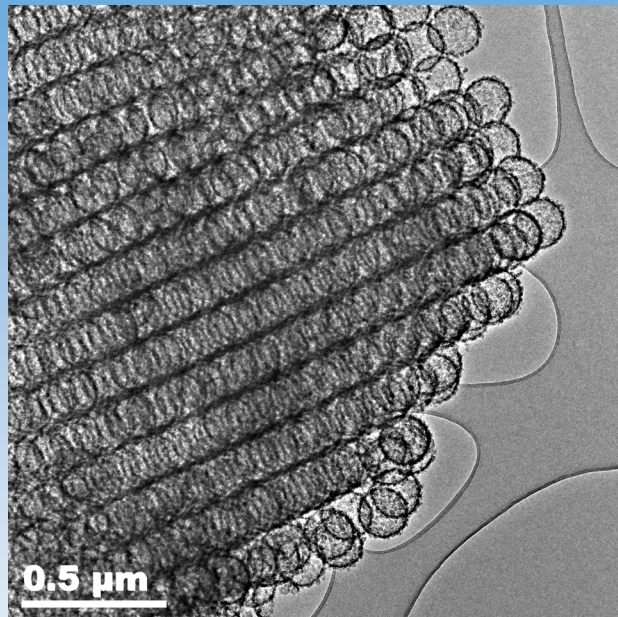
**Hollow silica
nanospheres
by making
and applying
equal-sized
templates**

SEM Photos



**Hollow silica
nanospheres
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TEM Photos

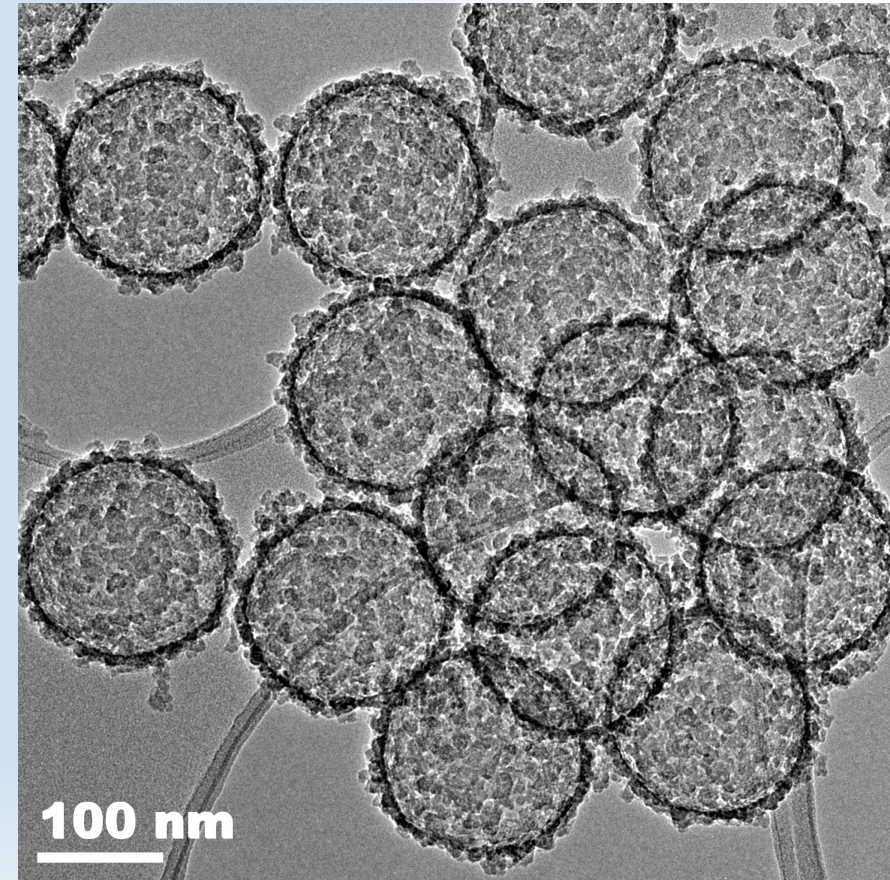
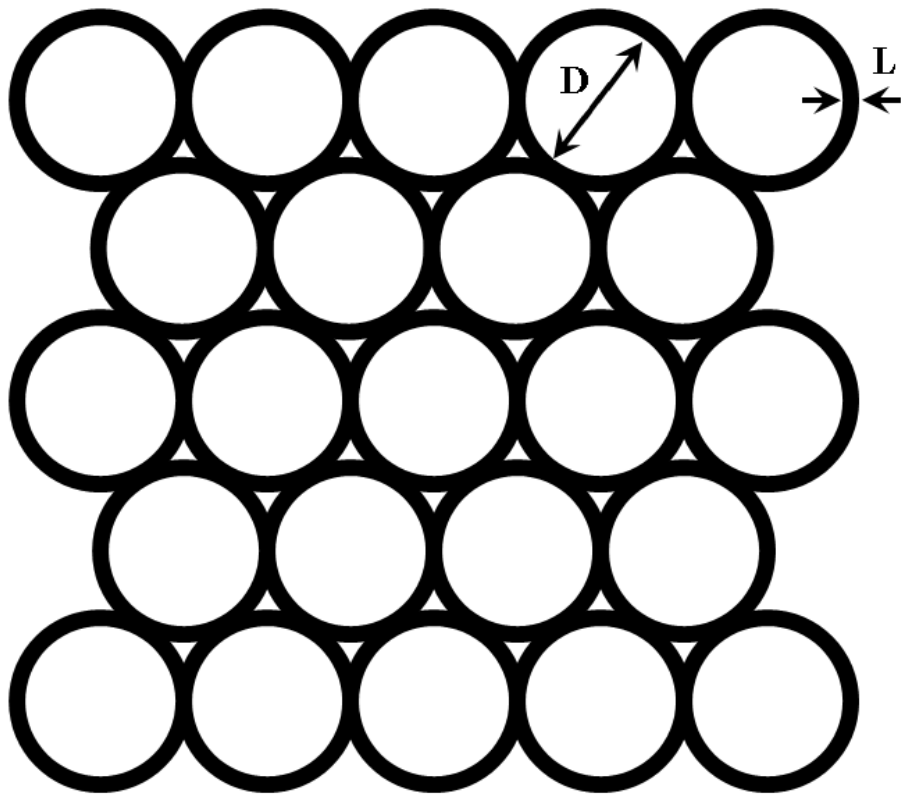


**Hollow silica nanospheres
by making and applying
equal-sized templates**

Hollow Silica Nanospheres

Hollow silica nanospheres
by making and applying
equal-sized templates

NIM

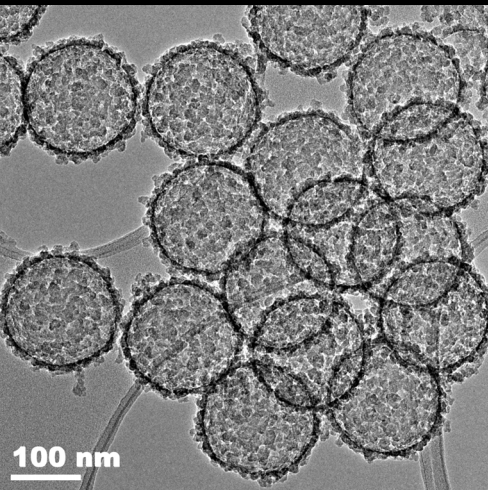
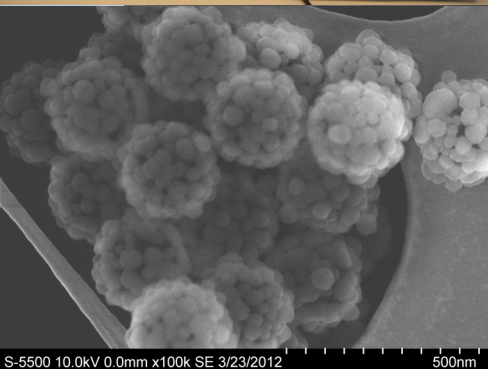


- Controlling:
- Sphere inner diameter
- Sphere wall thickness

Looking into the Crystal Ball and Seeing ... the Building Envelopes of Tomorrow...

Developing NIMs
– Nano Insulation Materials

On the path
to NIMs:
Hollow silica
nanospheres



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

19.0nm
20.0nm
13.0nm

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

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

NIM

From theory and experimental nanotechnology to...



kV 0.0mm x300k SE 3/30/2012

100nm

Conclusions and The Path Ahead

- Various paths to make nano insulation materials (NIM) as hollow silica nanospheres (HSNS).
- Future NIMs may not necessarily be based on HSNS.
- Investigations on HSNS represent a possible stepping-stone towards achieving high performance thermal insulation materials.
- Powder samples of HSNS have measured thermal conductivity values $\sim 20\text{-}90 \text{ mW}/(\text{mK})$, though some uncertainties in the Hot Disk apparatus measurement method have to be further clarified.
- Further optimization.
- Then to piece HSNS together to form a bulk material.
- Other paths...?