Nanotechnology Applied in the Future Thermal Insulation Materials for Buildings

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References:

\begin{itemize}
\item B. P. Jelle, A. Gustavsen and R. Baetens, "The Path to the High Performance Thermal Building Insulation Materials and Solutions of Tomorrow", Accepted for publication in \textit{Journal of Building Physics}, 2010.
\end{itemize}

\textit{Tekna Seminar – Nanotechnology in Buildings, Oslo, 11th of November, 2010.}
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)

- **Gas-Filled Panels (GFP)**

- **Aerogels**

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

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

- Traditional Insulation
  - 36 mW/(mK)

- Vacuum Insulation Panels (VIP)
  - 4 mW/(mK) fresh
  - 8 mW/(mK) 25 years
  - 20 mW/(mK) perforated

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

- Aerogels
  - 13 mW/(mK)

- (Phase Change Materials (PCM))

- Other Materials and Solutions?
Major Disadvantages of VIPs

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

- Vacuum Core
- Air and Moisture Tight Envelope
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 ⇒ Reduced wall thickness ⇒ Large area savings ⇒ Higher value of the real estate

- VIPs - The best solution today and in the near future?

- Beyond VIPs?
## Requirements of the Thermal Insulation of Tomorrow

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

Some key properties of concrete (example values)

<table>
<thead>
<tr>
<th>Property</th>
<th>With Rebars</th>
<th>Without Rebars</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass density (kg/dm³)</td>
<td>2.4</td>
<td>2.2</td>
</tr>
<tr>
<td>Thermal conductivity (mW/mK)</td>
<td>2500</td>
<td>1700</td>
</tr>
<tr>
<td>Specific heat capacity (J/(kgK))</td>
<td>840</td>
<td>880</td>
</tr>
<tr>
<td>Linear thermal expansion coefficient (10⁻⁶/K)</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>Compressive strength (MPa)</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>Tensile strength (MPa)</td>
<td>500</td>
<td>3</td>
</tr>
<tr>
<td>Fire resistance</td>
<td>&gt; 2 h</td>
<td>&gt; 2 h</td>
</tr>
<tr>
<td>Environmental impact (incl. energy and material use in production, emission of polluting agents and recycling issues)</td>
<td>large CO₂ emissions</td>
<td>large CO₂ emissions</td>
</tr>
</tbody>
</table>

*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.*
Environmental Impact of Concrete

Large CO$_2$ emissions from cement production

The cement industry produces 5% of the global man-made CO₂ emissions of which:

- 50% from the chemical process
  - e.g.: \(3\text{CaCO}_3 + \text{SiO}_2 \rightarrow \text{Ca}_3\text{SiO}_5 + 3\text{CO}_2\)
  - \(2\text{CaCO}_3 + \text{SiO}_2 \rightarrow \text{Ca}_2\text{SiO}_4 + 2\text{CO}_2\)

- 40% from burning fossil fuels
  - e.g. coal and oil

- 10% split between electricity and transport uses

Beyond Traditional Thermal Insulation?

"I think you should be more explicit here in step two"
Beyond VIPs – How May It Be Achieved?

"I think you should be more explicit here in step two"
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

Nano Particles

Nano Pores

0.1 nm - 100 nm

0.1 nm - 100 nm
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)
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.
How to Make a VIM?

A solid state material blowing itself up from within during the formation
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 $\lambda_g$

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

where

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

$\lambda_{\text{gas}} = \text{gas thermal conductivity in the pores (W/(mK))}$

$\lambda_{g,0} = \text{gas thermal conductivity in the pores at STP (standard temperature and pressure) (W/(mK))}$

$\beta = \text{coefficient characterizing the molecule - wall collision energy transfer efficiency (between 1.5 - 2.0)}$

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

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

$T = \text{temperature (K)}$

$d = \text{gas molecule collision diameter (m)}$

$p = \text{gas pressure in pores (Pa)}$

$\delta = \text{characteristic pore diameter (m)}$

$\sigma_{\text{mean}} = \text{mean free path of gas molecules (m)}$
Gas Thermal Conductivity

Conductivity vs. Pore Diameter

Various Pore Gases

- Air
- Argon
- Krypton
- Xenon

100 000 Pa
300 K

Gas Thermal Conductivity (mW/(mK))

Characteristic Pore Diameter

10 mm  1 mm  100 µm  10 µm  1 µm  100 nm  10 nm  1 nm
Gas Thermal Conductivity

Conductivity vs. Pore Pressure

Various Pore Gases

10 mm
300 K

- Black: Air
- Yellow: Argon
- Green: Krypton
- Blue: Xenon
- Red: 4 mW/(mK)

Pore Pressure (Pa)

Gas Thermal Conductivity (mW/(mK))

Air
Argon
Krypton
Xenon
Gas Thermal Conductivity

**T = 300 K**
Gas Thermal Conductivity

- **Air**
  - Temperature: $T = 300$ K
  - Pore Diameter (nm) vs. Pore Pressure (Pa) vs. Gas Thermal Conductivity (mW/(mK))

- **Argon**
  - Temperature: $T = 300$ K
  - Pore Diameter (nm) vs. Pore Pressure (Pa) vs. Gas Thermal Conductivity (mW/(mK))

- **Krypton**
  - Temperature: $T = 300$ K
  - Pore Diameter (nm) vs. Pore Pressure (Pa) vs. Gas Thermal Conductivity (mW/(mK))

- **Xenon**
  - Temperature: $T = 300$ K
  - Pore Diameter (nm) vs. Pore Pressure (Pa) vs. Gas Thermal Conductivity (mW/(mK))
Nano Pores – Thermal Radiation

- Knudsen effect ⇒ \( \sigma_{\text{mean}} > \delta \) ⇒ low gas thermal conductivity \( \lambda_g \)
- What about the thermal radiation in the pores?
- "Classical" – from Stefan-Boltzmann’s law:

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

- Pore diameter \( \delta \) small ⇒ low thermal radiation conductivity \( \lambda_r \)
- But what happens when \( \xi_{ir} > \delta \) (IR wavelength > pore diameter)
- \( \xi_{ir} > \delta \) ⇒ high thermal radiation conductivity \( \lambda_r \) ?
- Evanescent waves… tunneling… etc. …
- Currently looking into these matters…

\( \lambda_r = \) thermal radiation conductivity in the pores \((W/(mK))\)
\( \sigma = = \pi^2 k_B^4/(60\hbar^3 c^2) = \) Stefan-Boltzmann’s constant \( \approx 5.67 \cdot 10^{-8} W/(m^2K^4) \)
\( k_B = \) Boltzmann’s constant \( \approx 1.38 \cdot 10^{-23} \) J/K
\( \hbar = h/(2\pi) \approx 1.05 \cdot 10^{-34} \) Js \( (h = \) Planck’s constant)
\( c = \) light velocity \( \approx 3.00 \cdot 10^8 \) m/s
\( \delta = \) pore diameter \((m)\)
\( \varepsilon = \) emissivity of pore walls
\( T_i = \) interior temperature \((K)\)
\( T_e = \) exterior temperature \((K)\)
\( \xi_{ir} = \) infrared radiation wavelength \((m)\)
Thermal Radiation in Nano Pores

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

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

Stefan-Boltzmann’s Law

Radiation Thermal Conductivity $\lambda_{rad}$

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

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

Radiation Thermal Conductivity $\lambda_{\text{rad}}$

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

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

$\lambda_{\text{rad}}$ = radiation thermal conductivity in the pores (W/(mK))

$\sigma = \pi^2 k_B^4/(60\hbar^3 c^2) = $ Stefan-Boltzmann’s constant $\approx 5.67 \times 10^{-8}$ W/(m$^2$K$^4$)

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

$\hbar = h/(2\pi) \approx 1.05 \times 10^{-34}$ Js = reduced Planck’s constant ($h = $ Planck’s constant)

$c = $ velocity of light $\approx 3.00 \times 10^8$ m/s

$\delta = $ pore diameter (m)

$\varepsilon = $ emissivity of inner pore walls (assumed all identical)

$T_i = $ interior (indoor) temperature (K)

$T_e = $ exterior (outdoor) temperature (K)

$J_{\text{rad,tot}} = $ total radiation heat flux (W/m$^2$)

$n = $ number of pores along a given horizontal line in the material
Radiation Thermal Conductivity

Conductivity vs. Pore Diameter

Emissivity

Indoor 20°C
Outdoor 0°C

Increasing Emissivity
Radiation Thermal Conductivity

Conductivity vs. Pore Diameter

Indoor 20°C
Outdoor 0°C

Increasing Emissivity

Emissivity

- 1
- 0.9
- 0.8
- 0.7
- 0.6
- 0.5
- 0.4
- 0.3
- 0.2
- 0.1
- 0.05
- 0.02
- 4 mW/(mK)

Radiation Thermal Conductivity (mW/(mK))

Characteristic Pore Diameter (mm)
Radiation Thermal Conductivity

- Stefan-Boltzmann’s law $\Rightarrow$ Linear $\lambda_{\text{rad}}$ vs. $\delta$ relationship $\Rightarrow$
- Pore diameter $\delta$ small $\Rightarrow$ low radiation thermal conductivity $\lambda_{\text{rad}}$
- But what happens when $\xi_{ir} > \delta$? (IR wavelength > pore diameter)
- $\xi_{ir} > \delta$ $\Rightarrow$ high radiation thermal conductivity $\lambda_{\text{rad}}$?
- Tunneling of evanescent waves
- Indications that the large thermal radiation is only centered around a specific wavelength (or a few) $\Rightarrow$
- The total thermal radiation integrated over all wavelengths is not that large (?)
- Currently looking into these matters…
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?
The Triangle and The Square

Triangle: Make 4 identical equilateral triangles as the one above (same size also!) out of a total of 6 matches.

Square: Make 6 identical squares as the one above (same size also!) out of a total of 9 matches.
Today’s Third Nut

The Cake Division

The Cake Nut - A Nut Cake?

\[ \times 3 = 8 \text{ identical cake pieces} \]
Today’s Third Nut

The Cake Division

The Cake Nut - A Nut Cake?

x 3 = 8 identical cake pieces
Today’s Fourth Nut

The Moat

Get over the moat in a safe way – each log is just too short!
Today’s Fifth and Sixth Nut

The Hole

Digging a hole:

5 men digs 4 holes in 3 days. How long time does one man use to dig half a hole?

The Expression

Solve the expression:

\((x-a)(x-b)(x-c)\cdots(x-z) = ?\)
The 9 Dots

Draw 4 straight lines without lifting the pencil where you are striking all the 9 dots in the figure.
Dynamic Insulation Material (DIM)

- 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?:

$$\lambda_p = (2\pi c/q_e)(m_e\epsilon_0/n_e)^{1/2}$$


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?
Example of Application of Nano Technology with Concrete

http://www.hielscher.com/ultrasonics/nano_cement_concrete_01.htm

… by the way…

What research and property of concrete is "missing" here?

… yes, exactly…:

- Thermal performance, e.g. thermal conductivity.
Example of Application of Nano Technology with Concrete

Ultrasonic Mixing Of Nanomaterials

Ultrasonication is a very effective means for the mixing, dispersing and deagglomeration. The picture below shows a typical result of ultrasonic dispersing of fumed silica in water.

Starting (green curve) at an agglomerate particle size of more than 200 micron (D50) most of the particles were reduced to less than 200 nanometers.

http://www.hielscher.com/ultrasonics/nano_cement_concrete_01.htm
Concrete with NIM Outdoor Retrofitting

Outdoor Thermal Insulation Retrofitting

NIM

Concrete
Concrete with NIM Indoor Retrofitting
Concrete with NIM Indoor and Outdoor

Both Indoor and Outdoor Thermal Insulation Retrofitting
NIM in the Midst of Concrete
NIM and Concrete Mixture

NIM Mixed in the Concrete

NIM and Concrete Mixture
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

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

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 CO₂ 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 CO₂ emissions.
- Envisioned with or without reinforcement or rebars.
NanoCon – Introducing a New Material

Making a New Material: NanoCon
NanoCon – Introducing a New Material

- Defining a new material on a conceptual basis:

  *NanoCon* is basically a homogeneous material with a closed or open small nano pore structure with an overall thermal conductivity of less than 4 mW/(mK) (or another low value to be determined) and exhibits the crucial construction properties that are as good as or better than concrete.

- Note that the term "Con" in NanoCon is meant to illustrate the *construction* properties and abilities of this material, with historical homage to concrete.
NanoCon – Introducing a New Material

- NanoCon
- 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.

Essentially, NanoCon is a NIM with construction properties matching or surpassing those of concrete.
NanoCon – Introducing a New Material

Dependent on the mechanical or construction properties of NanoCon, it may be envisioned both with or without rebars.
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...!*
## The Thermal Insulation Potential

<table>
<thead>
<tr>
<th>Thermal Insulation Materials and Solutions</th>
<th>Low Pristine Thermal Conductivity</th>
<th>Low Long-Term Thermal Conductivity</th>
<th>Perforation Robustness</th>
<th>Possible Building Site Adaptation Cutting</th>
<th>Load-Bearing Capabilities</th>
<th>A Thermal Insulation Material and Solution of Tomorrow?</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Traditional</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mineral Wool and Polystyrene</td>
<td>no</td>
<td>no</td>
<td>yes</td>
<td>yes</td>
<td>no</td>
<td>no</td>
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<tr>
<td><strong>Today's State-of-the-Art</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Vacuum Insulation Panels (VIP)</td>
<td>yes</td>
<td>maybe</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>today and near future</td>
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<tr>
<td>Gas-Filled Panels (GFP)</td>
<td>maybe</td>
<td>maybe</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>probably not</td>
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<td>Aerogels</td>
<td>maybe</td>
<td>maybe</td>
<td>yes</td>
<td>yes</td>
<td>no</td>
<td>maybe</td>
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<td>Phase Change Materials (PCM)</td>
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<td>-</td>
<td>-</td>
<td>-</td>
<td>no</td>
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<tr>
<td><strong>Beyond State-of-the-Art – Advanced Insulation Materials (AIM)</strong></td>
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<td>yes</td>
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<td>yes</td>
<td>no/maybe</td>
<td>maybe</td>
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<td>Others ?</td>
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<td>maybe</td>
</tr>
</tbody>
</table>
Conclusions

- Several possibilities of applying nano technology and nano insulation materials (NIM) in order to improve the thermal performance of the future concrete buildings have been presented.

- NanoCon as essentially a NIM with construction properties matching or surpassing those of concrete has been introduced and defined.
Sorry folks…

… we simply couldn’t resist the two following slides…(!)


… though… with Concrete and NanoCon it might take several years…(!)
Sunset...

R.I.P.
VIP
IVIS
2009?

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

R.I.P. CONCRETE
COIN 2010
?
Sunrise...
and the Phoenix rises again...!