

# Nanotechnology Applied in the Future Thermal Insulation Materials for Buildings

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#### **References:**

• 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 *Journal of Building Physics*, 2010.

• B. P. Jelle, A. Gustavsen, R. Baetens and S. Grynning, "Nano Insulation Materials Applied in the Buildings of Tomorrow", *Proceedings of COIN Workshop on Concrete Ideas for Passive Houses*, Oslo, Norway, 26-27 January, 2010.

• B. P. Jelle, A. Gustavsen, S. Grynning and R. Baetens, "How Might Nano Technology Improve the Thermal Performance of the Concrete Buildings of Tomorrow?", *Proceedings of COIN Workshop on Concrete Ideas for Passive Houses*, Oslo, Norway, 26-27 January, 2010.

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### **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"

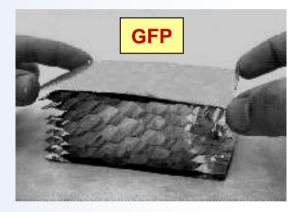
- Core (silica, open porous, vacuum)
- Foil (envelope)
- Gas-Filled Panels (GFP)
- Aerogels

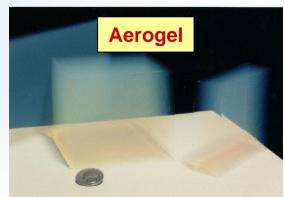
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- Phase Change Materials (PCM)
  - Solid State ↔ Liquid
  - Heat Storage and Release

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











### **Thermal Insulation of Today**

Traditional Insulation

—36 mW/(mK)

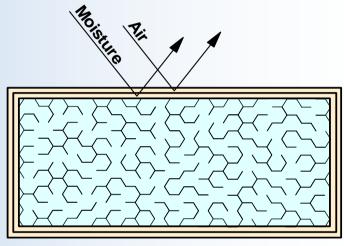
- Vacuum Insulation Panels (VIP)
  - 4 mW/(mK) fresh
    8 mW/(mK) 25 years
    20 mW/(mK) perforated
- Gas-Filled Panels (GFP)
   40 mW/(mK)
- Aerogels

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- —13 mW/(mK)
- (Phase Change Materials (PCM))
- Other Materials and Solutions?

- Vacuum Core
- Air and Moisture Tight Envelope

**RBUST** 



VIP







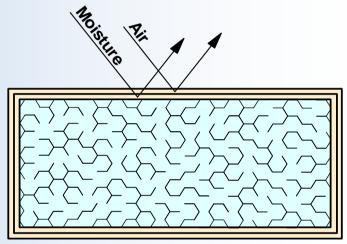
### **Major Disadvantages of VIPs**

- 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?

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- Air and Moisture Tight Envelope



VIP



### COIN

### **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 m<sup>2</sup> ⇒ Reduced wall thickness ⇒ Large area savings ⇒ Higher value of the real estate
- VIPs The best solution today and in the near future?
- Beyond VIPs?







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### 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)







### **Properties of Concrete**

#### **Some key properties of concrete (example values)**

Property	With Rebars	Without Rebars		
Mass density (kg/dm <sup>3</sup> )	2.4	2.2		
Thermal conductivity (mW/mK)	2500	1700		
Specific heat capacity (J/(kgK))	840	880		
Linear thermal expansion coefficient (10 <sup>-6</sup> /K)	12	12		
Compressive strength (MPa)	30	30		
Tensile strength (MPa) <sup>a</sup>	500 <sup>b</sup>	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 <sub>2</sub> emissions	large CO <sub>2</sub> emissions		

<sup>a</sup> 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. <sup>b</sup> Rebars.









**Environmental Impact of Concrete** 

#### Large CO<sub>2</sub> emissions from cement production

	1	Carbo	on Dio	xide E r Sourc		ons				
			Othe	rsourc	es					
				immary						
<ul> <li>"Other emissions sources" percent (103.8 MMT) of all</li> </ul>				• Lie	nestone o	consump	tion, esp (15 to 2)	ecially for	r lime m	dioxida
sions in 2008 (Figure 14).	ne enno-	<ul> <li>ture, is the source of 15 to 20 MMT of carbon dioxide emissions per year.</li> </ul>								
. The largest source of U.S. o				<ul> <li>In addition, "other sources" include: soda ash manu-</li> </ul>						
other than fossil fuel consu								arbon d		
facture (Table 15), where m the production of clinker (s								e; flaring le scrubb		
bonate sintered with silica								in the		
duce calcium silicate).				ind	lustrial s	ectors.				
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1990, 2007, and 2008				01	her Sou	rces, 20	08		a de la companya de la	
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(Percent)	4	24.1%	22.0%			{	-		Productik 28.9	×
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		1.07.96	1.1.30		Line			y		
			-1.8		Consu	mption		_	Source	
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(Million Matter: Tonis) present/ Table 15. Life of the Construction Disc manufacture of Disc manufacture of Disc Constructions Matterial trans- Constructions of Disc Constructions of Disc	ide Emis s Carbor 1980 0.1 0.7 12.9 12.4 12.7 0.3 0.1 0.7 0.5 0.5 14.0 14.0 9.7 14.0 9.7 14.0 9.7 14.0 9.5 0.5 0.5 9.5 9	asilons f n Dioxid 36.9 36.1 0.1 0.1 0.2 17.8 15.2 0.5 0.5 0.5 0.2 37.9 16.2 0.2 37.9 16.2 17.2 17.2 17.2 17.2 17.2 17.2 17.2 17	rom Oth 0) 2000 41.3 40.4 0.1 0.8 N8.6 15.4 15.3 15.4 15.3 15.4 15.3 15.4 15.3 15.4 15.3 15.4 15.3 15.3 15.4 15.3 15.3 15.3 15.3 15.3 15.4 15.4 15.3 15.3 15.4 15.4 15.3 15.4 1	2002 43.0 42.0 0.1 0.8 77.0 14.1 0.9 0.5 0.5 0.5 0.5 0.5 0.1 24.4 15.4 60 73.0 74.4 15.0 60 73.0 74.4 15.0 75.0 75.0 75.0 75.0 75.0 75.0 75.0 7	Consu 11 2003 40.2 40.2 40.2 40.2 40.2 40.2 40.2 40.2	0-2008 2004 457 447 0.1 0.9 157 1.6 0.4 0.1 0.4 0.1 0.4 0.1 0.4 0.1 0.4 0.1 0.4 0.1 0.4 0.1 0.4 0.4 0.1 0.4 0.5 0.4 0.5 0.4 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5	46.1 46.1 0.1 16.2 0.3 0.1 15 0.1 15 0.1 15 0.1 15 0.1 15 0.1 15 0.1 25.3 0.1 25.3 0.1 25.3 0.1 25.3 0.1 25.3 0.1 25.3 0.1 25.3 0.1 0.2 0.2 0.2 0.2 0.2 0.2 0.2 0.2 0.2 0.2	46.7 45.7 0.1 16.5 0.9 18.4 16.5 0.4 0.4 0.5 0.4 1.5 0.2 2.8 4.7 7.2 8 1.5 0.2 7.4 9 9.0 6	13 2007 45.4 45.4 45.4 15.9 0.3 0.1 15.9 0.3 0.1 15.9 0.3 0.1 15.9 0.3 0.1 15.9 0.3 0.1 15.9 0.3 0.1 15.9 0.3 0.1 0.2 15.9 0.3 0.1 0.2 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5	41.3 0.1 0.8 16.5 0.3 0.3 15 0.3 15 0.3 15 0.3 28.9 20.8 15 15 0.3 1 28.9 20.8 15 15 0.5 15 15 5 0.5 15 15 5 0.5 15 15 5 0.5 15 15 15 15 15 15 15 15 15 15 15 15 15
Nation Matter: Tong Present/ Table 15. Liferio d'un De ton <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Torien</u> <u>Tor</u>	ide Emili s Carbor 1990 01 33.3 32.6 0.7 15.9 12.4 17 0.5 25.1 24.0 17 0.5 25.1 24.0 8.1 0.7 0.5 25.1 24.0 8.1 8.1 0.7 0.5 25.1 0.7 0.5 0.1 0.7 0.5 0.1 0.7 0.5 0.1 0.7 0.5 0.1 0.7 0.5 0.1 0.7 0.5 0.1 0.7 0.5 0.1 0.7 0.5 0.1 0.7 0.5 0.1 0.7 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5	sisions f 1995 36.1 0.7 77.8 12 0.2 77.8 12 0.2 0.2 0.2 0.2 0.2 0.2 0.2 0.2 0.2 17.2 10.7 10.7 10.7 10.7 10.7 10.7 10.7 10.7	rom Oth e) 2000 41,3 40,4 0,1 15,4 15,4 15,4 15,4 15,4 15,4 15,4 15,4 15,4 16,4 15,4 16,4	2002 43.0 42.0 0.1 0.8 77.0 14.1 0.9 0.5 0.1 10.1 10.1 10.1 24.4 18.4 60 7.2 0.1 15.4 18.4 60 7.2 0.1 15.4 16.4 16.4 16.4 16.4 16.4 16.4 16.4 16	Consu 11 2005 40.2 40.2 40.2 40.2 40.2 40.2 40.2 40.2	0-2008 2004 45.7 45.7 45.7 0.1 0.2 0.1 0.1 0.1 0.2 15.7 15.8	46, f 46, f 0, 1 0, 1 0, 1 15, 7 0, 3 0, 1 0, 2 15, 7 0, 1 0, 2 15, 3 10, 1 25, 10, 10, 10, 10, 10, 10, 10, 10, 10, 10	44.7 45.7 0.1 14.5 0.9 14.6 16.5 0.4 0.1 15 0.2 1.5 0.2 16.7 7.2.4 10.7 7.2.4 10.7 7.2.4 10.7 1.5 0.5 10.5 10.5 10.5 10.5 10.5 10.5 1	112 2007 45,4 0,1 0,8 0,8 0,1 0,1 0,1 0,1 0,1 0,1 0,1 0,1 0,1 0,1	41.3 0.1 0.8 15.5 0.3 0.1 28.9 20.9 1.5 28.9 20.9 1.4 1.5 1.8
Mallion Matter: Tong) Present/ Table 18: Line con Diese Annon Matter Tong Const Marchetter Const Marchetter Const Marchetter Const Marchetter Const Marchetter Const Marchetter Desement IIS Duel Besterfung Desementi	ide Emile 5 Cathor 1980 32.3 32.6 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1	sisions f n Dicoid 1995 36.1 0.7 77.4 12.5 0.2 0.3 0.9 0.2 37.9 0.2 37.9 0.2 37.9 16.7 17.2 4 3.8 0.2 0.3 0.9 0.2 37.9 16.7 17.2 4 5 0.2 0.2 37.9 0 5 0.2 0.3 0.5 0.2 0.5 1905 0 5 0.5 10 0 7 17.4 5 0.5 10 0 7 17.4 5 10 0 7 17.4 5 10 0 7 17.4 5 10 0 7 17.4 5 10 0 7 17.4 5 10 0 7 17.4 5 10 0 7 17.4 5 10 0 7 17.4 5 10 0 7 17.4 5 10 0 7 17.4 5 10 0 7 17.4 5 10 0 7 17.4 5 10 0 7 17.4 5 10 2 10 10 10 10 10 10 10 10 10 10 10 10 10	rom Oth p) 2000 41.3 40.4 10.4	2802 420 420 0.1 0.8 770 14.1 0.5 0.1 1.3 0.1 1.3 0.1 1.3 0.1 1.3 0.1 1.3 0.1 1.3 0.1 1.3 0.1 1.3 0.1 1.3 0.4 4 0.4 4 0.4 4 0.5 0.1 1.3 0.5 0.1 1.3 0.1 0.5 0.1 0.5 0.1 0.5 0.1 0.5 0.1 0.5 0.1 0.5 0.1 0.5 0.1 0.5 0.1 0.5 0.1 0.5 0.1 0.5 0.1 0.5 0.1 0.5 0.1 0.5 0.1 0.5 0.5 0.1 0.5 0.5 0.1 0.5 0.5 0.1 0.5 0.5 0.1 0.5 0.5 0.1 0.5 0.5 0.1 0.5 0.5 0.1 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5	Consu 11 2005, 1990 2005 40.2 40.2 40.2 40.2 40.2 40.2 40.2 40.2	0-2008 2004 45.7 45.7 45.7 0.1 0.2 16.9 15.0 0.4 0.1 0.2 16.9 15.0 0.4 0.1 0.2 16.9	48.5 48.1 0.1 15.7 0.3 0.1 0.2 1.5 0.1 1.5 0.1 1.5 1.5 1.5 1.5 1.5 1.5 1.5 1.5 1.5 1	44.7 45.7 0.9 19.6 0.9 0.4 0.9 0.4 0.9 0.4 0.2 1.5 2 20.6 7 10.7 7 20.6 15 0.2 20.6 7 15 7 0.9 0.4 15 0.9 0.4 15 0.9 0.4 15 0.9 0.9 19.6 0.9 19.6 0.9 19.6 0.9 19.6 0.9 19.6 0.9 19.6 0.9 19.6 0.9 19.6 0.9 19.6 0.9 19.6 0.9 10.9 10.9 10.9 10.9 10.9 10.9 10.9	13 2007 45.4 0.1 0.9 15.9 0.8 0.3 0.1 0.2 1.5 0.1 20.9 1.5 0.1 20.9 0.8 0.1 0.2 0.1 0.1 20.7 0.1 0.1 0.1 0.2 0.2 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1	41.3 0.1 0.8 15.5 0.3 0.1 28.9 20.9 1.5 28.9 20.9 1.4 1.5 1.8
Name Marce Tool ( Proceed) Table 11: Like or Solon Da For- <u>Bare and Solon Da For- Bare and Bardener Constrations ( Constrations) Constrations Const</u>	ide Emile 5 Carbor 1980 332.6 0.1 32.6 0.2 15.9 12.9 12.9 12.9 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1	soloms f 1995 36.9 36.9 36.9 36.9 36.9 36.9 36.9 16.2 17.7 17.2 14.5 14.5 14.5 14.5 14.5 14.5 14.5 14.5	rom Oth c) 2030 41.3 41.4 0.1 0.1 0.1 0.1 0.2 0.1 0.1 0.2 0.2 0.2 0.1 0.2 0.2 0.2 0.2 0.2 0.2 0.2 0.2	2802 4320 0.1 0.5 77.0 14.1 0.9 0.5 0.5 0.1 0.1 24.4 18.4 620 7.3 5 0.4 18.4 620 7.3 5 0.4 14.4 620 7.4 0 14.4 620 7.5 0 14.4 620 7.5 0 14.5 15.5 0 14.5 15.5 15.5 15.5 15.5 15.5 15.5 15.5	Consu 11 2005, 1990 2023 40.2 40.2 40.2 40.2 40.2 40.2 40.2 40.2	450 2004 447 0.2008 447 0.1 0.2 169 169 169 169 169 169 169 169	48, f 48, f 9, f 0, g 18, g 0, g 0, g 0, g 0, g 1, g 1, g 1, g 1, g 1, g 1, g 1, g 1	46.7 45.7 0.9 18.5 0.9 0.4 0.1 0.2 28.6 1.5 0.2 28.6 1.5 3.3 3.5 106.0	13 2007 48.4 48.4 48.4 10.9 10.9 10.9 10.1 10.1 10.1 10.2 10.1 10.2 10	41.3 0.1 0.8 16.5 0.3 0.1 0.2 1.5 0.1 0.2 20.9 0.1 6.1 28.9 0.1 0.5 0.5 1.8 0.5 1.8 0.5 1.8 0.5 1.8 0.5 1.4 0.5 0.5 0.1 0.2 0.1 0.2 0.1 0.2 0.1 0.2 0.1 0.2 0.5 0.1 0.2 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5
Mann Marte toop Proventy Table TR - Marco Martin Marten TR - Marco Marten Marten Constant Marten Consta	ide Emile s Carbor 1980 326 0.1 326 0.1 326 0.7 1529 1529 1529 1529 1529 1529 1529 1529	1995 36.9 36.9 36.9 36.9 36.9 36.9 36.9 36.9	rom Oth c) 2030 41.3 41.4 0.1 0.1 0.1 0.1 0.2 0.1 0.1 0.2 0.2 0.2 0.1 0.2 0.2 0.2 0.2 0.2 0.2 0.2 0.2	2802 430 420 0.1 0.1 770 141 0.5 0.1 0.1 0.1 0.1 244 184 55 0.4 184 184 184 184 184 184 184 184 184 18	Consul 11 2003 402 0.3 10.4 10.3 10.4 0.4 0.4 0.4 0.4 0.4 0.4 0.4	447 447 447 447 01 02 167 167 167 167 167 167 167 167	46.1 46.1 0.9 16.7 0.8 0.1 0.2 15.7 0.1 0.2 10.2 10.2 10.2 10.2 10.5 100.5	46.7 45.7 0.1 0.9 18.6 0.9 0.4 0.5 0.2 15 0.2 15 0.2 15 0.2 15 0.2 15 0.2 15 0.2 15 0.2 15 0.2 15 0.2 15 0.2 15 0.2 15 0.2 15 0.5 18.6 10 15 0.5 0.5 10 15 0.5 0.5 10 15 0.5 0.5 10 15 0.5 0.5 10 15 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.	13 2007 48.4 48.4 48.4 10.9 10.9 10.9 10.1 10.1 10.1 10.2 10.1 10.2 10	41.3 0.1 0.8 16.5 16.5 0.3 0.3 0.3 0.2 1.5 0.1 22.9 20.9 20.9 20.9 20.9 20.9 20.9 20.9

Table 15. U.S. Carbon Dioxide Emissions from Other Sources, 1990-2008										
(Million Metric Tons Carbon Dioxide)										
Source	1990	1995	2000	2002	2003	2004	2005	2006	2007	2008
Cement Manufacture	33.3	36.9	41.3	43.0	43.2	45.7	46.1	46.7	45.4	42.2
Clinker Production	32.6	36.1	40.4	42.0	42.2	44.7	45.1	45.7	44.4	41.3
Masonry Cement	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Cement Kiin Dust	0.7	0.7	0.8	0.8	0.8	0.9	0.9	0.9	0.9	0.8
Limestone Consumption	15.9	17.8	18.6	17.0	18.0	18.9	18.8	19.6	18.9	18.5
Lime Manufacture	12.4	14.5	15.4	14.1	15.1	15.7	15.7	16.5	15.9	15.5
Iron Smelting	1.7	1.2	1.1	0.9	0.9	1.0	8.0	0.9	8.0	0.8
Steelmaking	0.3	0.5	0.5	0.5	0.4	0.4	0.3	0.4	0.3	0.3
Copper Refining	0.1	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Glass Manufacture	0.1	0.3	0.2	0.1	0.2	0.2	0.2	0.2	0.2	0.2
Flue Gas Desulfurization	0.7	0.9	1.2	1.3	1.3	1.4	1.5	1.5	1.5	1.5
Dolomite Manufacture	0.5	0.2	0.1	0.1	0.1	0.1	0.1	0.2	0.1	0.1
Natural Gas Production	23.1	33.9	23.8	24.4	24.5	24.3	25.3	26.6	28.5	29.9
Carbon Dioxide in Natural Gas	14.0	16.7	18.3	18.4	18.6	18.4	18.1	18.7	19.3	20.8
Natural Gas Flaring	9.1	17.2	5.5	6.0	5.9	5.8	7.2	7.8	9.1	9.1
Other	12.7	13.8	14.1	13.3	13.2	13.1	13.2	13.0	12.9	13.1
Soda Ash Manufacture	3.4	3.8	3.6	3.5	3.6	3.8	3.9	3.9	4.0	4.1
Soda Ash Consumption	0.5	8.0	0.6	0.4	0.6	0.6	0.6	0.6	0.6	0.5
Carbon Dioxide Manufacture	0.9	1.0	1.3	1.4	1.5	1.5	1.6	1.6	1.7	1.8
Aluminum Manufacture	5.9	4.9	5.4	4.0	4.0	3.7	3.6	3.3	3.7	3.9
Shale Oil Production	0.2									
Waste Combustion	1.9	3.2	3.2	4.0	3.6	3.5	3.6	3.6	2.8	2.8
Total	85.1	102.3	97.8	97.7	98.9	102.0	103.5	106.0	105.6	103.8

\*Less than 0.05 million metric tons.

Notes: Data in this table are revised from the data contained in the previous EIA report, Emissions of Greenhouse Gases in the United States 2007, DOE/EIA-0573(2007) (Washington, DC, December 2008). Totals may not equal sum of components due to independent rounding. Source: EIA estimates.

P. McArdle and P. Lindstrom, "Emissions of greenhouse gases in the United States 2008", U.S. Energy Information Administration, DOE/EIA-0573(2008), December 2009.









### Large CO<sub>2</sub> Emissions from Cement Production



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- The cement industry produces 5 % of the global man-made CO<sub>2</sub> 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

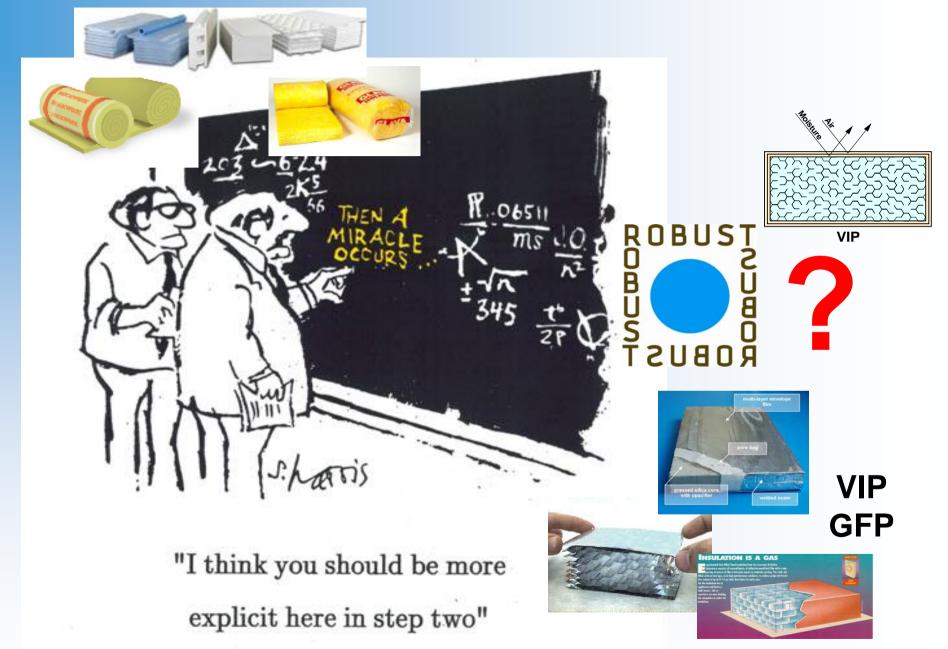
World Business Council for Sustainable Development, "The cement sustainability initiative – Our agenda for action", July 2002.





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### **Beyond Traditional Thermal Insulation?**



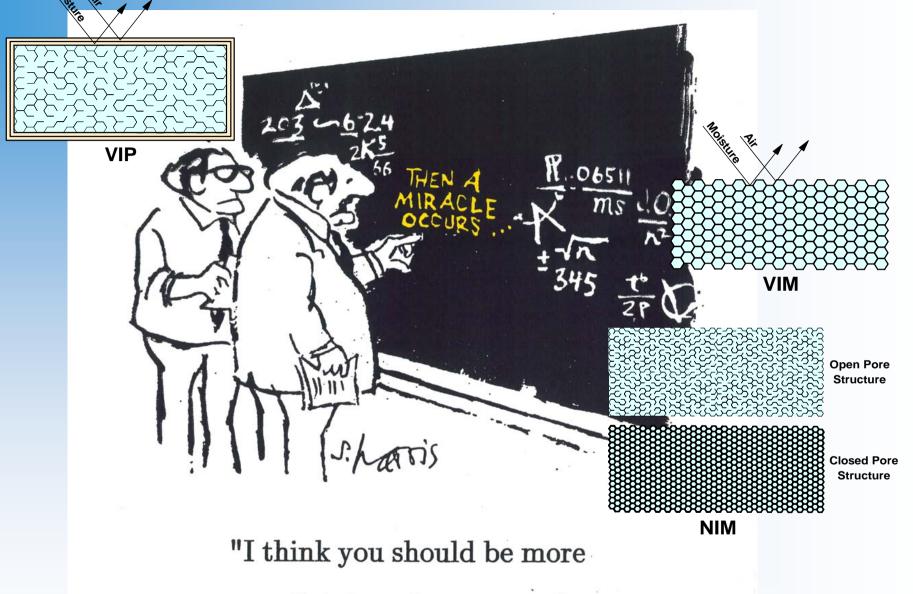


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### **Beyond VIPs – How May It Be Achieved?**



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explicit here in step two"

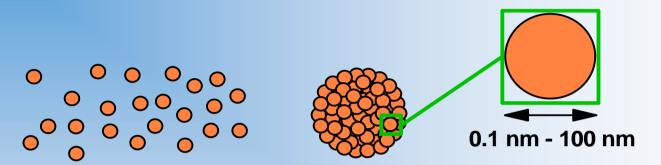
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### Nano Technology

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<sub>17</sub>H<sub>35</sub>COOH)

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

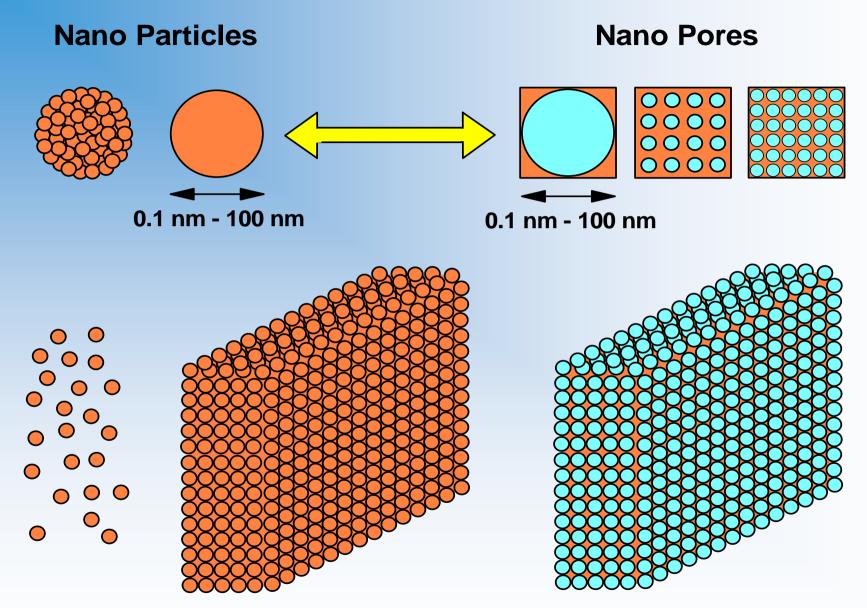




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### **Nano Technology and Thermal Insulation**









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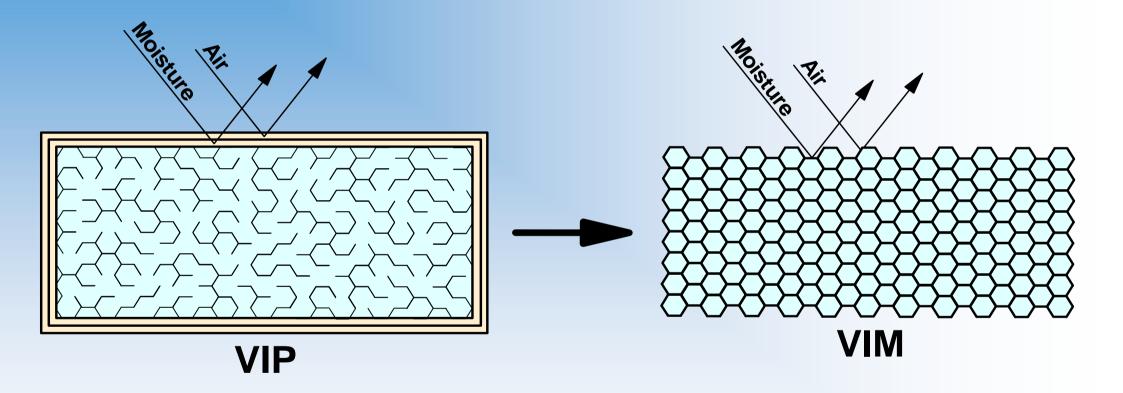








### **Vacuum Insulation Material (VIM)**



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

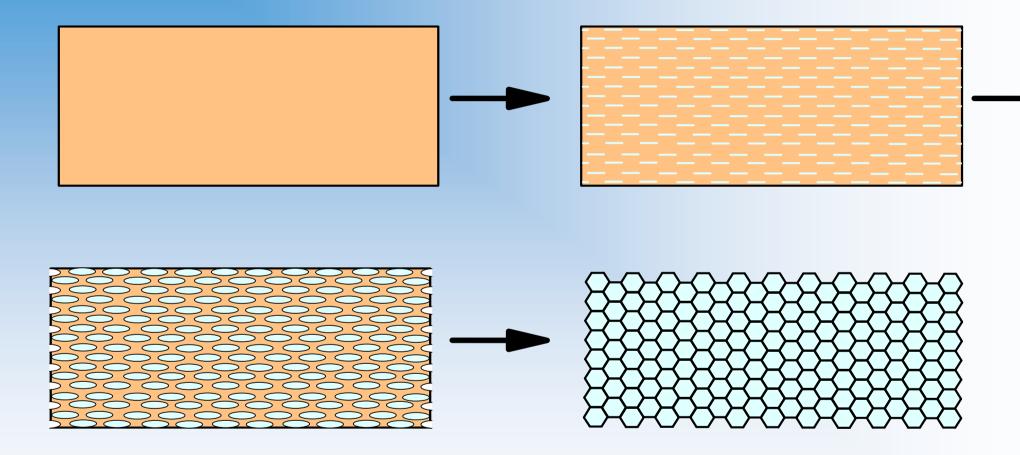








### How to Make a VIM ?



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



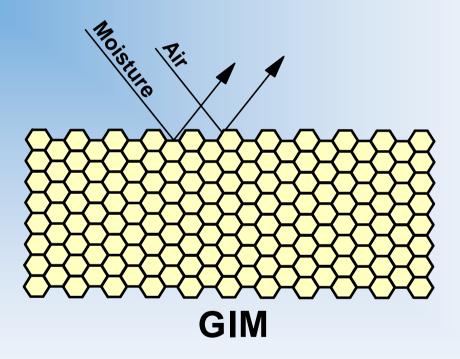






### **Gas Insulation Material (GIM)**

... 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

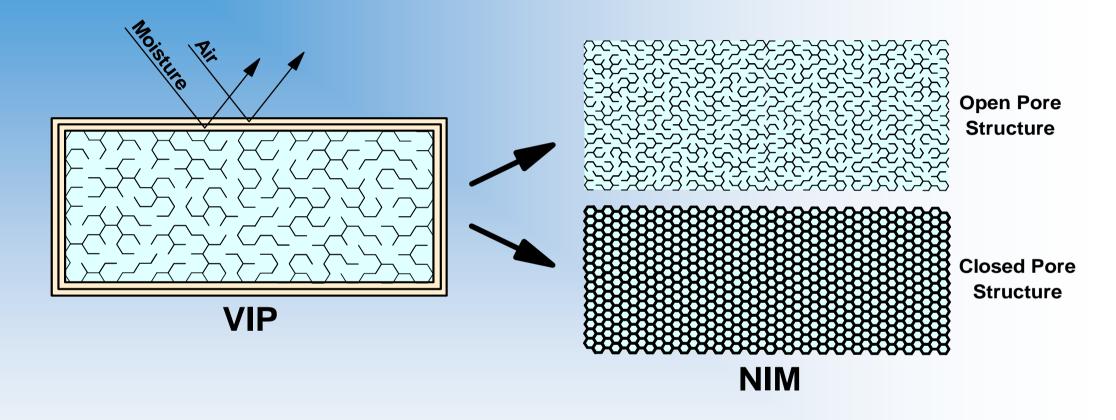








### **Nano Insulation Material (NIM)**



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



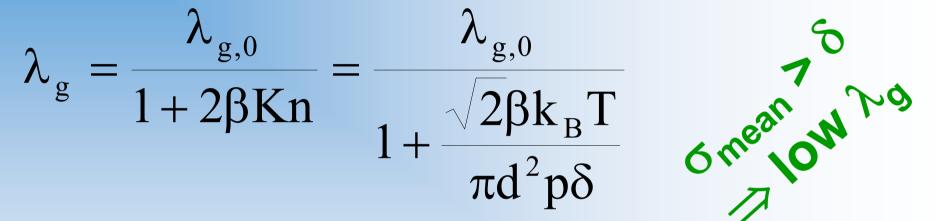






### **The Knudsen Effect – Nano Pores**

#### Gas Thermal Conductivity $\lambda_{a}$



#### where

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

 $λ_{gas}$  = gas thermal conductivity in the pores (W/(mK))  $λ_{gas,0}$  = 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 = σ<sub>mean</sub>/δ = k<sub>B</sub>T/(2<sup>1/2</sup>πd<sup>2</sup>pδ) = the Knudsen number k<sub>B</sub> = Boltzmann's constant ≈ 1.38 · 10<sup>-23</sup> J/K T = temperature (K) d = gas molecule collision diameter (m) p = gas pressure in pores (Pa) S = characterizitic pare diameter (m)

 $\delta$  = characteristic pore diameter (m)

 $\sigma_{mean}$  = mean free path of gas molecules (m)

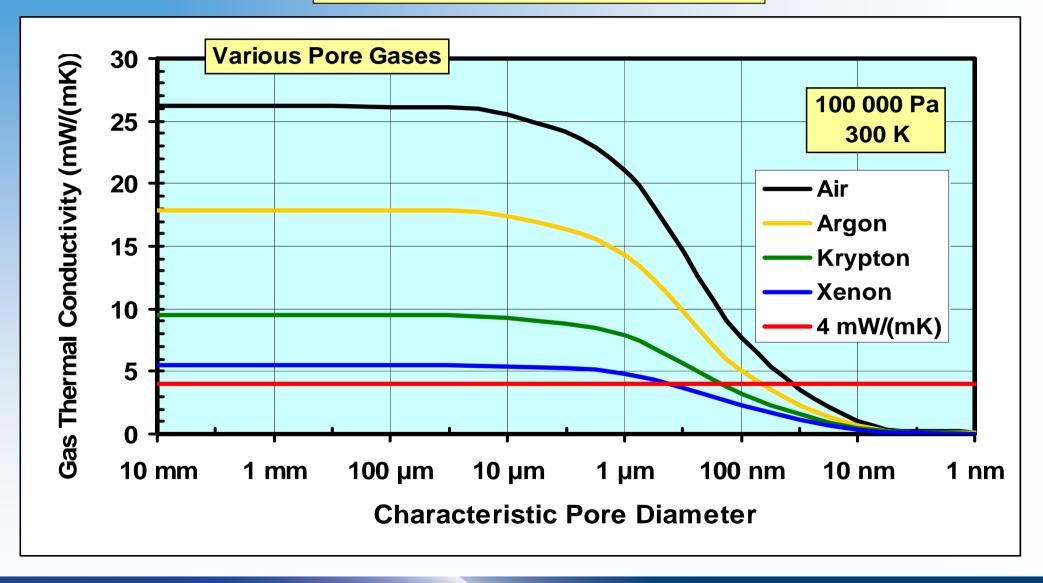




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# **Gas Thermal Conductivity**

#### **Conductivity vs. Pore Diameter**





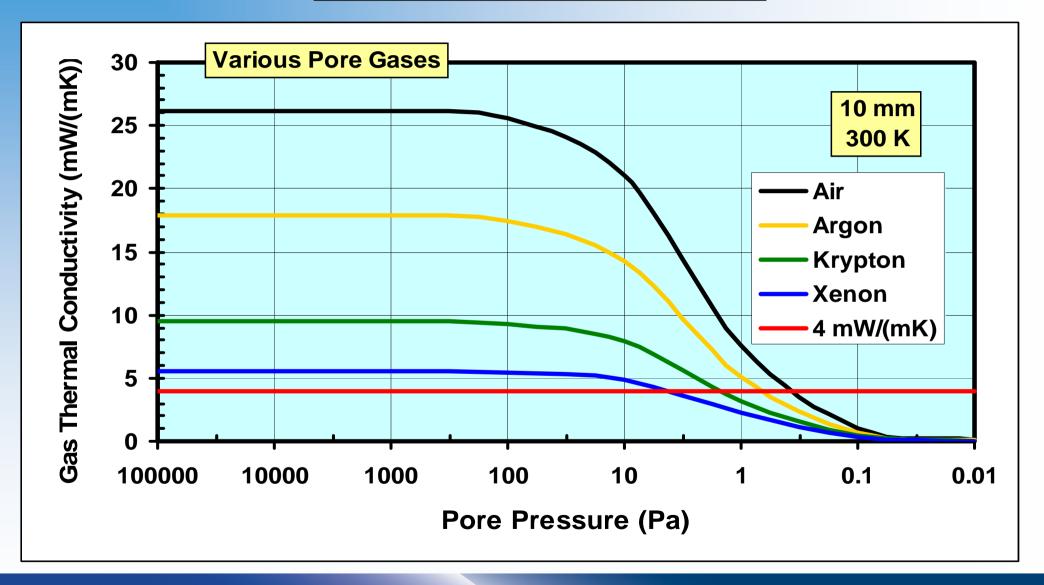


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# **Gas Thermal Conductivity**

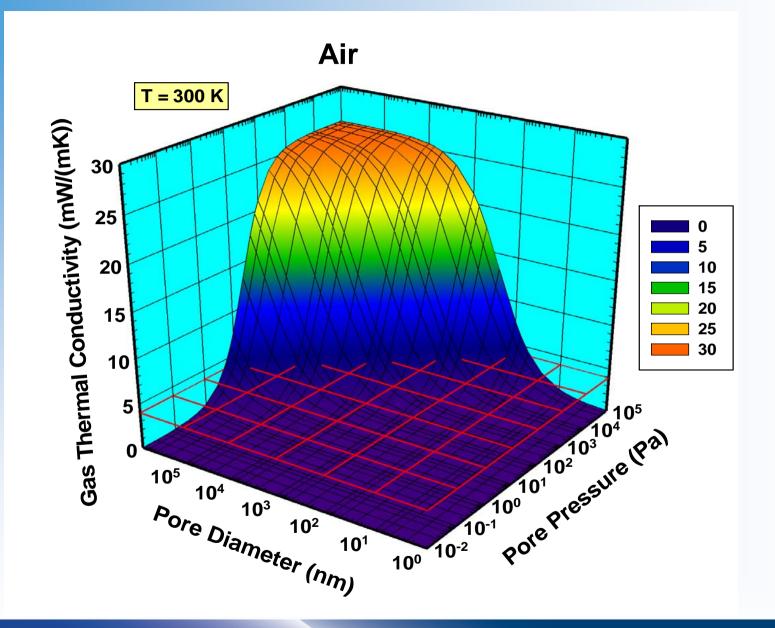
**Conductivity vs. Pore Pressure** 







### **Gas Thermal Conductivity**





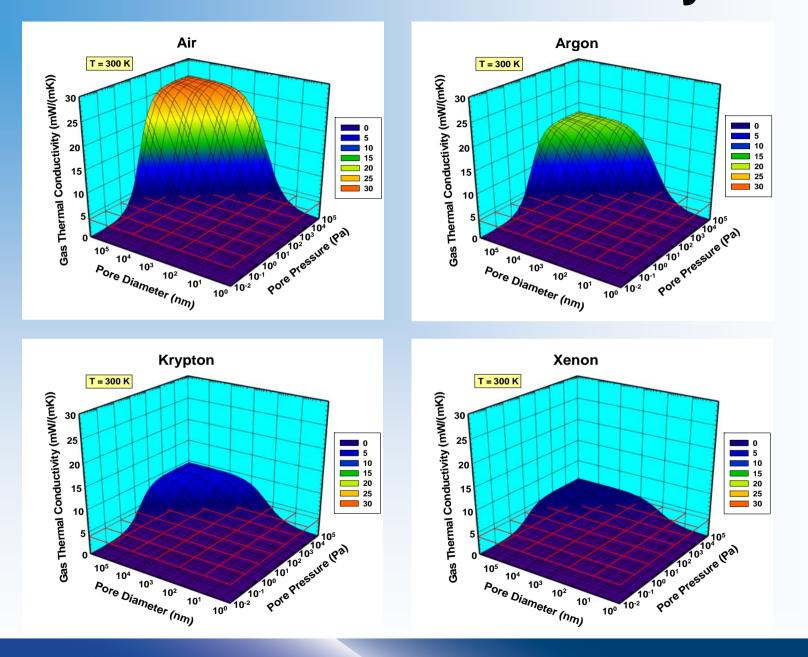
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# **Gas Thermal Conductivity**











# **Nano Pores – Thermal Radiation**

- Knudsen effect  $\Rightarrow \sigma_{mean} > \delta \Rightarrow$  low gas thermal conductivity  $\lambda_{g}$
- What about the thermal radiation in the pores?
- "Classical" from Stefan-Boltzmann's law:

$$\lambda_{r} = \frac{\pi^{2}k_{B}^{4}\delta}{60\hbar^{3}c^{2}\left[\frac{2}{\epsilon}-1\right]} \frac{(T_{i}^{4}-T_{e}^{4})}{(T_{i}-T_{e})}$$

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

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

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### **Thermal Radiation in Nano Pores**

**Total Radiation Heat Flux J**rad,tot

$$J_{rad,tot} = \frac{\sigma}{n\left[\frac{2}{\epsilon}-1\right]} \left(T_i^4 - T_e^4\right)$$
Stefan-Boltzmann's Law
$$\lambda_{rad} = J_{rad,tot} \delta/(T_{k-1} - T_k) \text{ is found by applying}$$
the approximation  $(T_{k-1} - T_k) = (T_k - T_k)/n$ 

Radiation Thermal Conductivity  $\lambda_{rad}$ 

$$\lambda_{\text{rad}} = \frac{\sigma\delta}{\left[\frac{2}{\epsilon} - 1\right]} \frac{(T_{i}^{4} - T_{e}^{4})}{(T_{i} - T_{e})} = \frac{\pi^{2}k_{B}^{4}\delta}{60\hbar^{3}c^{2}\left[\frac{2}{\epsilon} - 1\right]} \frac{(T_{i}^{4} - T_{e}^{4})}{(T_{i} - T_{e})}$$







### **Thermal Radiation in Nano Pores**

Radiation Thermal Conductivity  $\lambda_{rad}$ 

$$\lambda_{\text{rad}} = \frac{\sigma\delta}{\left[\frac{2}{\epsilon}-1\right]} \frac{(T_i^4 - T_e^4)}{(T_i - T_e)} = \frac{\pi^2 k_B^4 \delta}{60\hbar^3 c^2 \left[\frac{2}{\epsilon}-1\right]} \frac{(T_i^4 - T_e^4)}{(T_i - T_e)} \qquad J_{\text{rad,tot}} = \frac{\sigma}{n \left[\frac{2}{\epsilon}-1\right]} (T_i^4 - T_e^4)$$

$$\begin{split} \lambda_{\text{rad}} &= \text{radiation thermal conductivity in the pores (W/(mK))} \\ \sigma &= \pi^2 k_B^4 / (60\hbar^3 c^2) = \text{Stefan-Boltzmann's constant} \approx 5.67 \cdot 10^{-8} \text{ W/(m}^2 \text{K}^4) \\ k_B &= \text{Boltzmann's constant} \approx 1.38 \cdot 10^{-23} \text{ J/K} \\ \hbar &= h / (2\pi) \approx 1.05 \cdot 10^{-34} \text{ Js} = \text{reduced Planck's constant} (h = \text{Planck's constant}) \\ c &= \text{velocity of light} \approx 3.00 \cdot 10^8 \text{ m/s} \\ \delta &= \text{pore diameter (m)} \\ \epsilon &= \text{emissivity of inner pore walls (assumed all identical)} \\ T_i &= \text{interior (indoor) temperature (K)} \\ T_e &= \text{exterior (outdoor) temperature (K)} \\ J_{\text{rad,tot}} &= \text{total radiation heat flux (W/m^2)} \\ n &= \text{number of pores along a given horizontal line in the material} \end{split}$$

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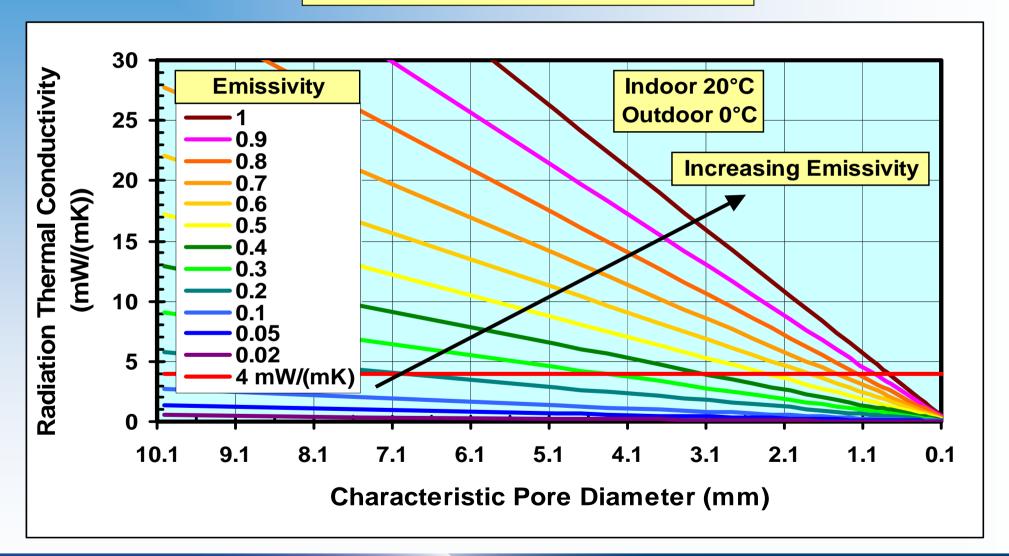




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### **Radiation Thermal Conductivity**

**Conductivity vs. Pore Diameter** 



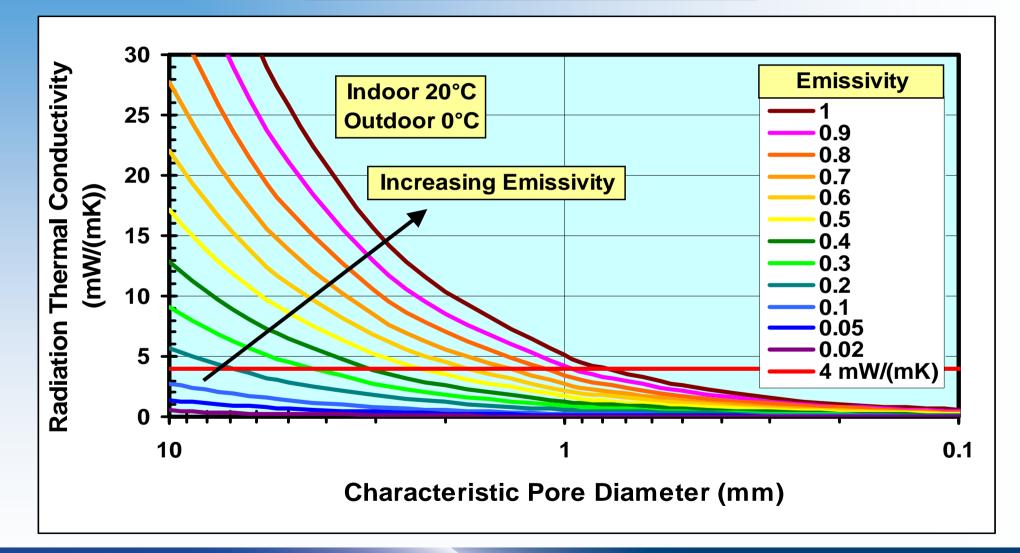




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### **Radiation Thermal Conductivity**

#### **Conductivity vs. Pore Diameter**









### **Radiation Thermal Conductivity**

- Stefan-Boltzmann's law  $\Rightarrow$  Linear  $\lambda_{rad}$  vs.  $\delta$  relationship  $\Rightarrow$
- Pore diameter  $\delta$  small  $\Rightarrow$  low radiation thermal conductivity  $\lambda_{rad}$
- But what happens when  $\xi_{ir} > \delta$ ? (IR wavelength > pore diameter)
- $\xi_{ir} > \delta \Rightarrow$  high radiation thermal conductivity  $\lambda_{rad}$  ?
- Tunneling of evanescent waves

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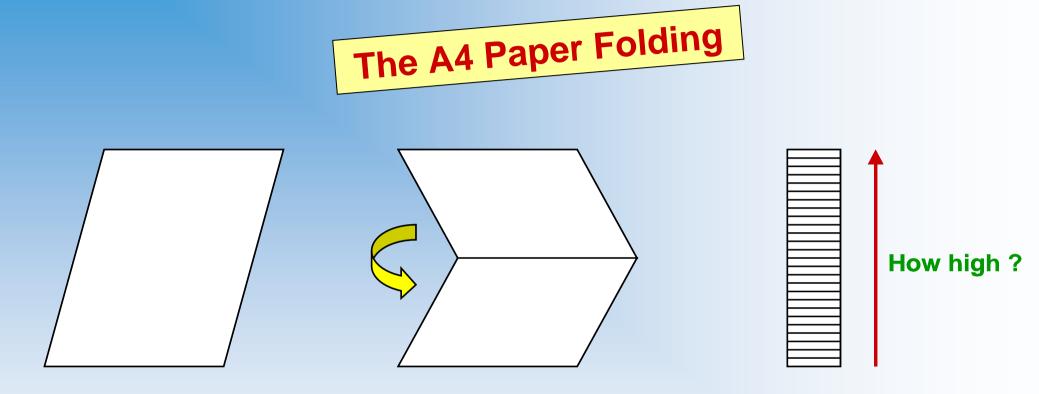
- Indications that the large thermal radiation is only centered around a specific wavelength (or a few) ⇒
- The total thermal radiation integrated over all wavelengths is not that large (?)
- Currently looking into these matters...







### **How Good are You at Guessing?**



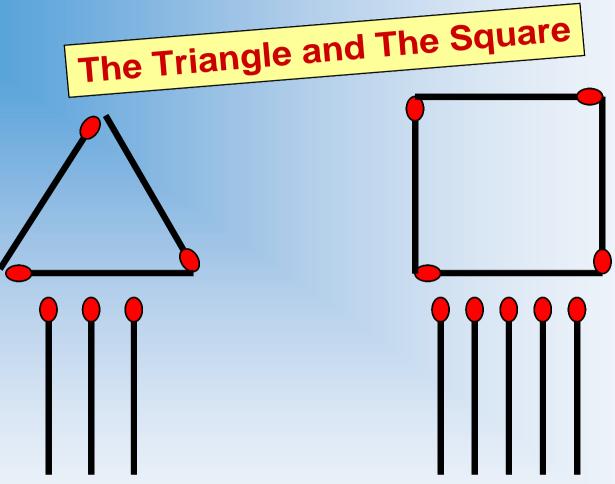
- Fold an A4 paper 100 times.
- Press out all air between the paper sheets.
- Put the paper pile on the table in front of you.
- Guess how far above the table does the paper pile reach ?







# **Today's Second Nut**



**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.





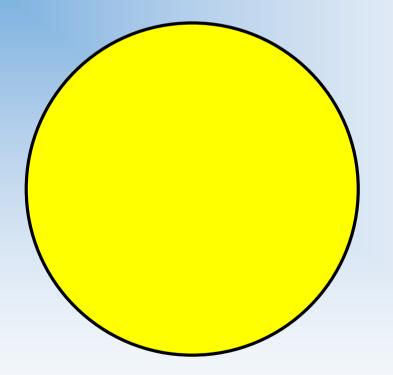




# **Today's Third Nut**

# **The Cake Division**

The Cake Nut - A Nut Cake ?









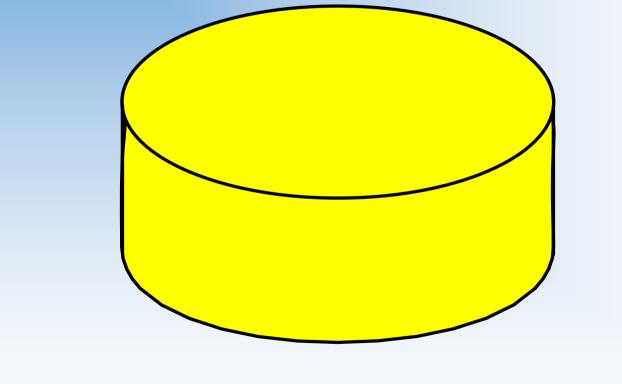




# **Today's Third Nut**

# **The Cake Division**

### The Cake Nut - A Nut Cake ?



x 3 = 8 identical cake pieces





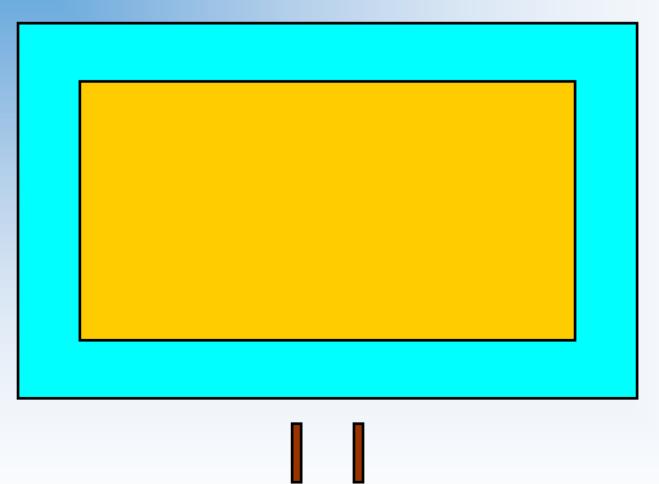




# **Today's Fourth Nut**

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:

 $(x-a)(x-b)(x-c)\cdots(x-z) = ?$ 



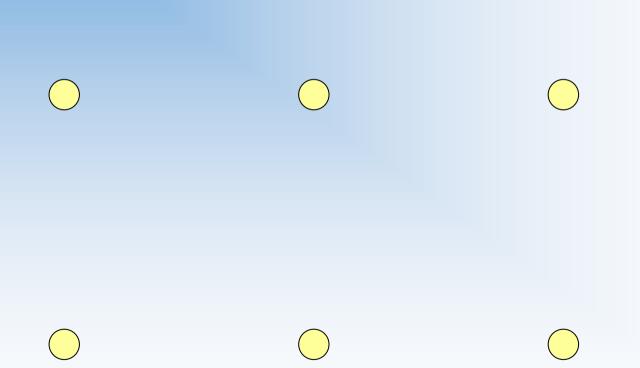


## **Today's Seventh Nut**

(

Draw 4 straight lines without lifting the pencil where you are striking all the 9 dots in the figure.

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## **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

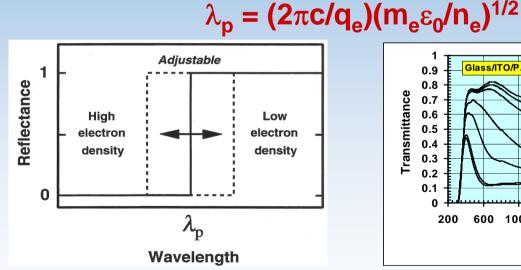
#### Dynamic Solid Core Thermal Conductivity

- Is it possible?

**Other?** 

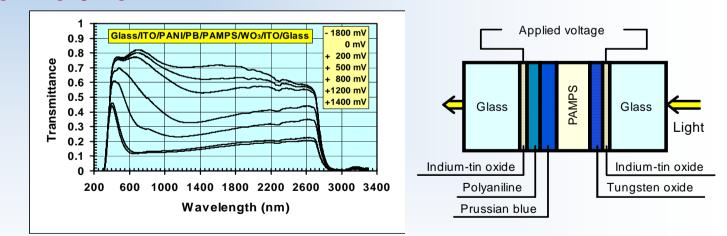
- Fundamental understanding of the thermal conductance?

Learning from Electrochromic Materials?:





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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?







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#### **Example of Application of Nano Technology with Concrete**

#### Hielscher - Ultrasound Technology

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#### Ultrasonic Mixing For High-Performance Concrete

The use of micro- and nanosilica or nanotubes leads to improvements in the compressive strength of high -performance concrete. Ultrasonication is an effective means for the mixing, wetting and dispersing of nanomaterials in cement or concrete.



Micro silica is widely used in concrete today, leading to higher compressive strength or water and chemical resistant concretes. That can reduce material costs and energy usage. New nanomaterials,

such as nano silica or nanotubes lead to further improvements in resistance and strength.

#### Concrete Background Information

Concrete is composed of cement, e.g. Portland cement and other cementitious materials, such as fly ash and slag cement, aggregate (gravel, limestone, granite, sand), water and chemical admixtures. Typical admixtures include accelerators or retarders, plasticizers, pigments, silica fume or High Reactivity Metakaolin (HRM). Micro silica is a typical admixture in concrete. Its disadvantage is its relatively high cost and contamination affecting operatore heatin.

#### Concrete Research And Development

Concrete research looks for materials and processes to:

- reduce material costs and energy costs
- obtain high initial and final resistance
- improve density and compressive strength
   improve workability, pumpability and finishability
- Improve workability, pumpability and inishability
   improve durability and reduce permeability







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#### Concrete Research And Development

Concrete research looks for materials and processes to:

- reduce material costs and energy costs
- obtain high initial and final resistance
- · improve density and compressive strength
- · improve workability, pumpability and finishability
- improve durability and reduce permeability
- reduce shrinkage cracks, dusting and delamination problems
- chemical resistance, e.g. sulfate resistance

#### ... by the way...

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

... yes, exactly...:

Thermal performance, e.g. thermal conductivity.

#### http://www.hielscher.com/ultrasonics/nano\_cement\_concrete\_01.htm



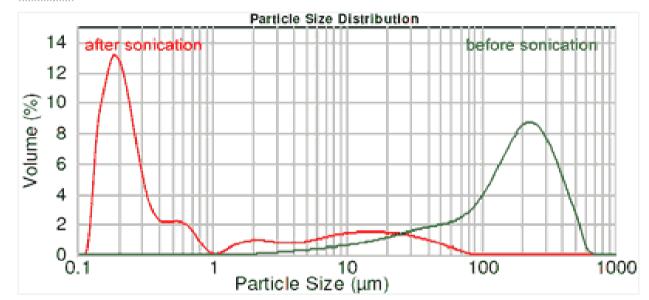


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#### **Example of Application of Nano Technology with Concrete**

#### 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



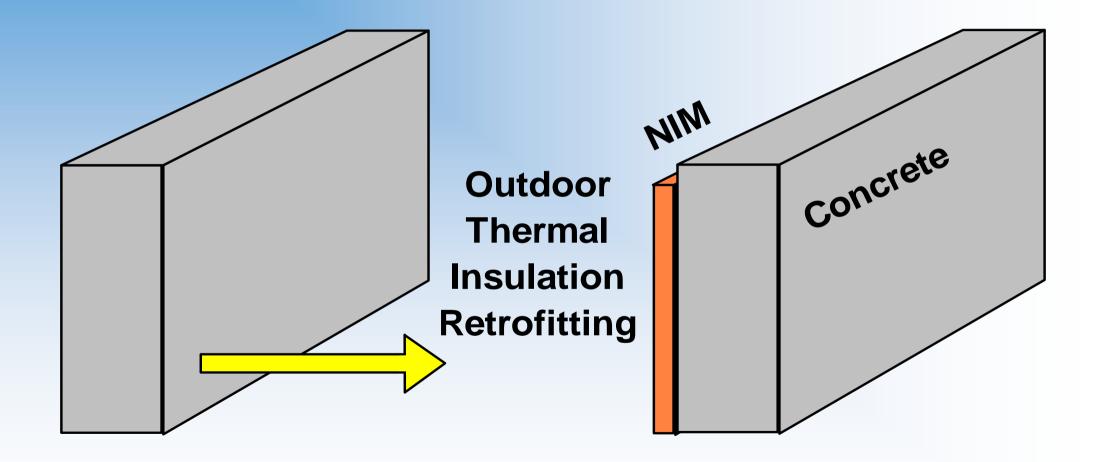




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### **Concrete with NIM Outdoor Retrofitting**





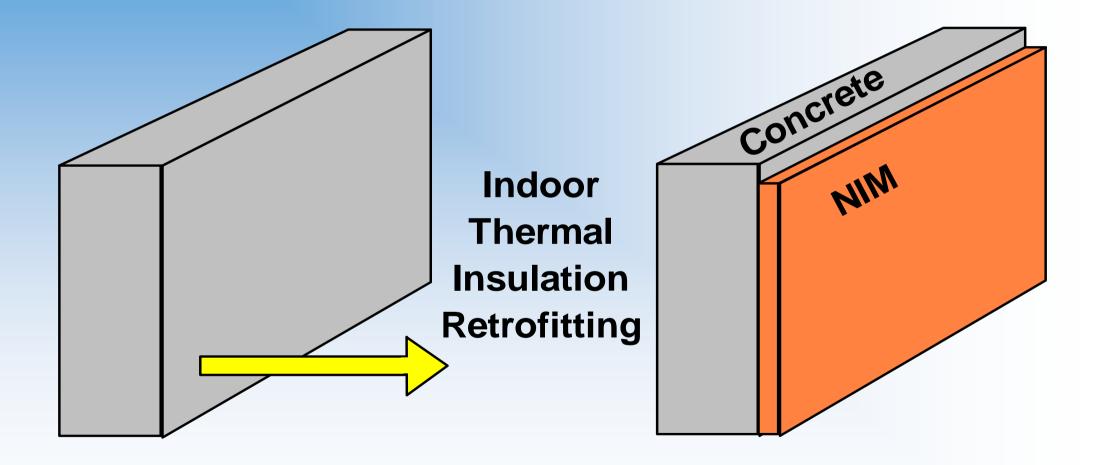




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### **Concrete with NIM Indoor Retrofitting**



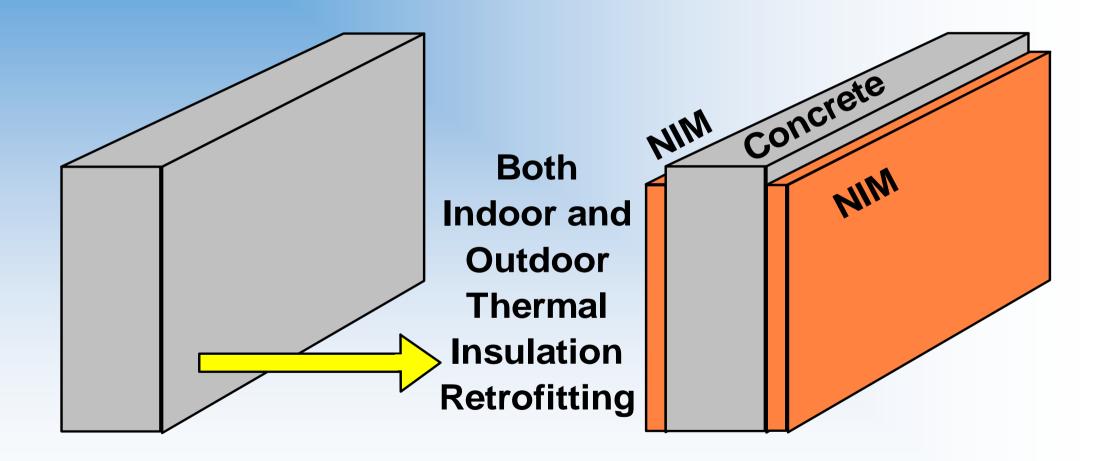




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#### **Concrete with NIM Indoor and Outdoor**



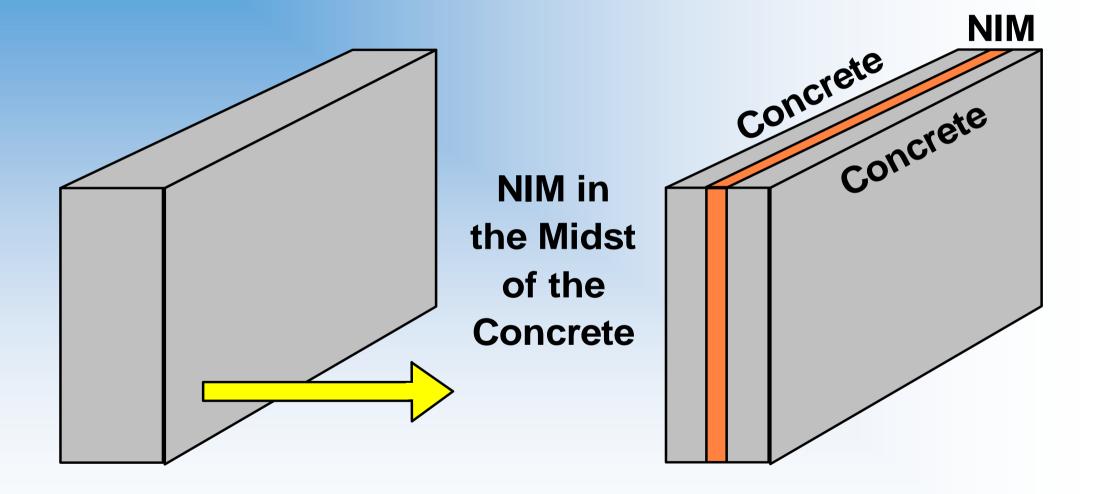




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### **NIM in the Midst of Concrete**



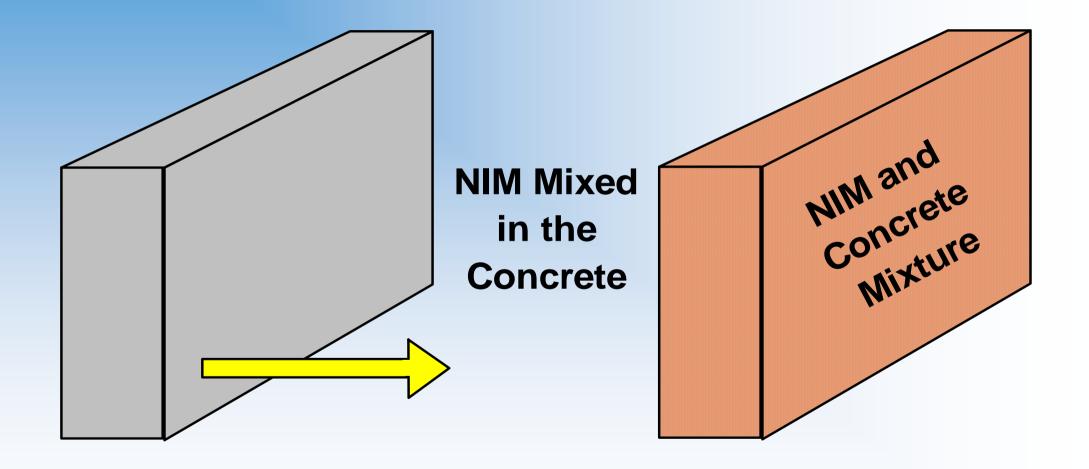




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### **NIM and Concrete Mixture**



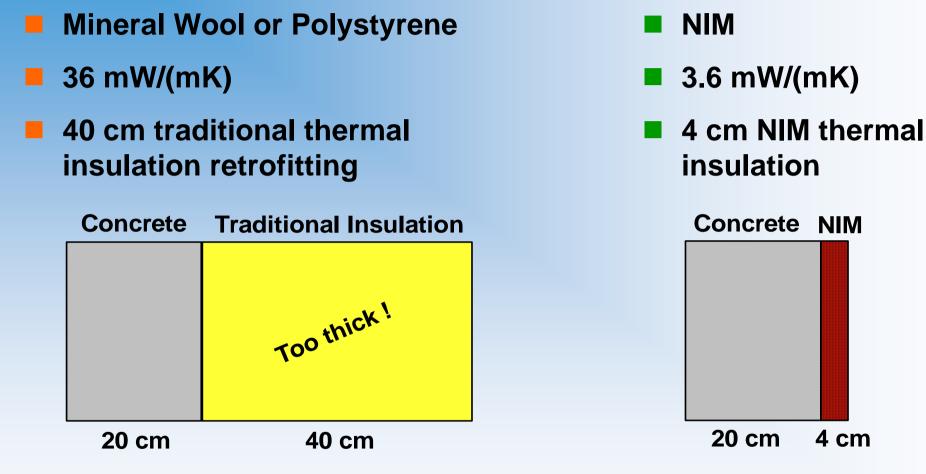




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## **Thinner Concrete Buildings with NIMs**



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

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- 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 ?**

- 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<sub>2</sub> 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<sub>2</sub> emissions.
- Envisioned with or without reinforcement or rebars.



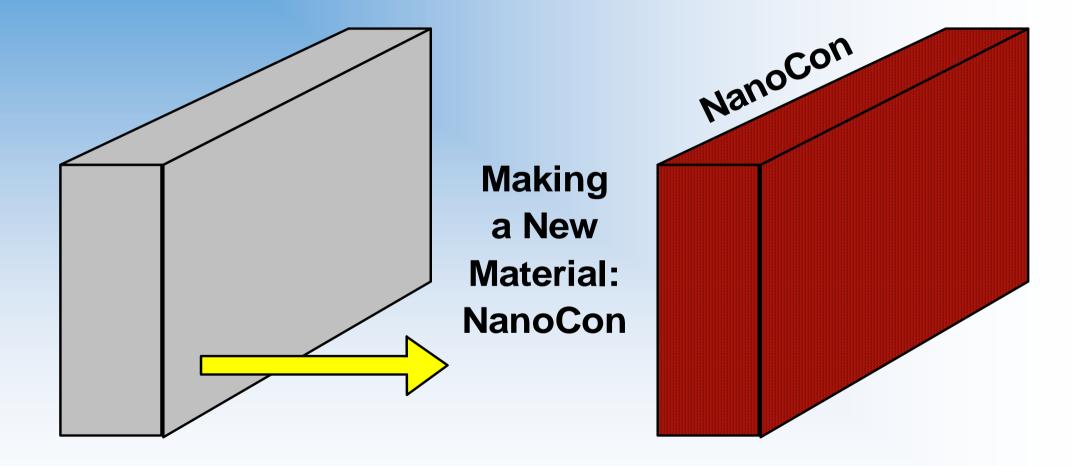




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### **NanoCon – Introducing a New Material**







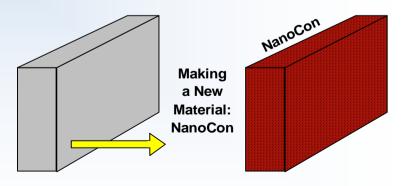




### **NanoCon – Introducing a New Material**

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.







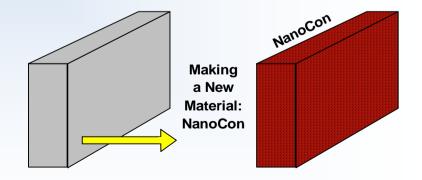


## **NanoCon – Introducing a New Material**

#### NanoCon

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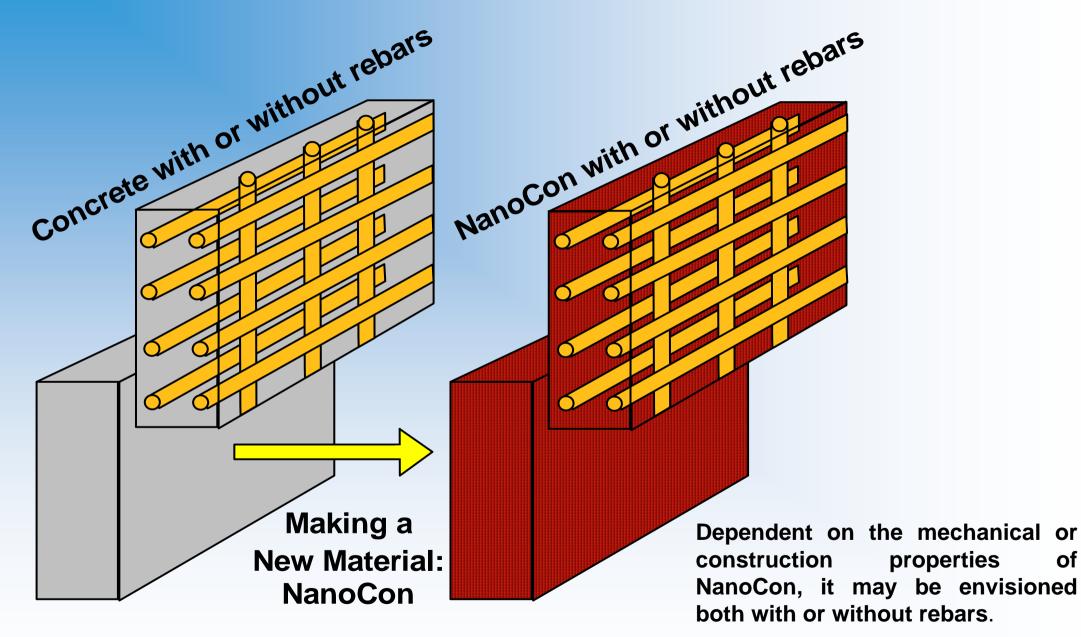
- Homogeneous material
- Closed or open small nano pore structure
- Overall thermal conductivity < 4 mW/(mK) (or another low value to be determined)
- Exhibits the crucial construction properties that are as good as or better than concrete.
- Essentially, NanoCon is a NIM with construction properties matching or surpassing those of concrete.







#### **NanoCon – Introducing a New Material**



SINTEF

of

**RBUST** 







#### **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...!







**D**NTNU

#### **The Thermal Insulation Potential**

**RBUST** 

Thermal Insulation Materials and Solutions	Low Pristine Thermal Conductivity	Low Long-Term Thermal Conductivity	Perforation Robustness	Possible Building Site Adaption Cutting	Load-Bearing Capabilities	A Thermal Insulation Material and Solution of Tomorrow ?
Traditional						
Mineral Wool and Polystyrene	no	no	yes	yes	no	no
Todays State-of-the-Art						
Vacuum Insulation Panels (VIP)	yes	maybe	no	no	no	today and near future
Gas-Filled Panels (GFP)	maybe	maybe	no	no	no	probably not
Aerogels	maybe	maybe	yes	yes	no	maybe
Phase Change Materials (PCM)	-	-	-	-	no	heat storage and release
Beyond State-of-the-Art – Advanced Insulation Materials (AIM)						
Vacuum Insulation Materials (VIM)	yes	maybe	yes	yes	no/maybe	yes
Gas Insulation Materials (GIM)	yes	maybe	yes	yes	no/maybe	maybe
Nano Insulation Materials (NIM)	yes	yes	yes, excellent	yes, excellent	no/maybe	yes, excellent
Dynamic Insulation Materials (DIM)	maybe	maybe	not known	not known	no/maybe	yes, excellent
NanoCon	yes	yes	yes	yes	yes	yes, excellent
Others ?	-	-	-	-	-	maybe





## 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.





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## Sorry folks... ... we simply couldn't resist the two following slides...(!)



Analogously to the VIP-NIM originally presented at the 9th International Vacuum Insulation Symposium, London, September 17-18, 2009.

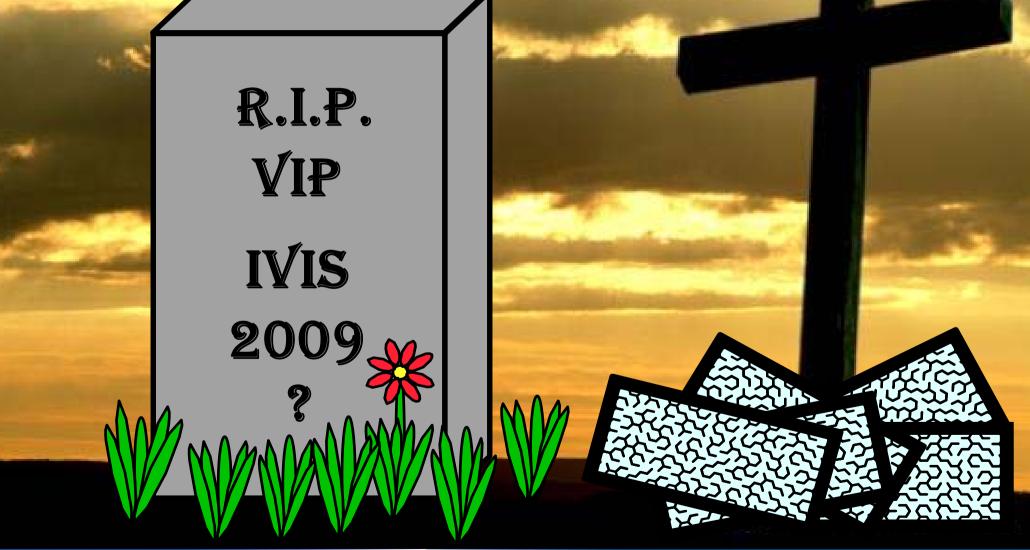
... though... with Concrete and NanoCon it might take several years...(!)







### Sunset...







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

 $\Box$  NTNU





#### Sunset...

## **R.I.P.** CONCRETE

# COIN 2010





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

 $\Box$  NTNU

#### NanoCon

COIN

2014



