Properties, Requirements and Possibilities for Traditional, State-of-the-Art and Future Thermal Building Insulation Materials and Solutions

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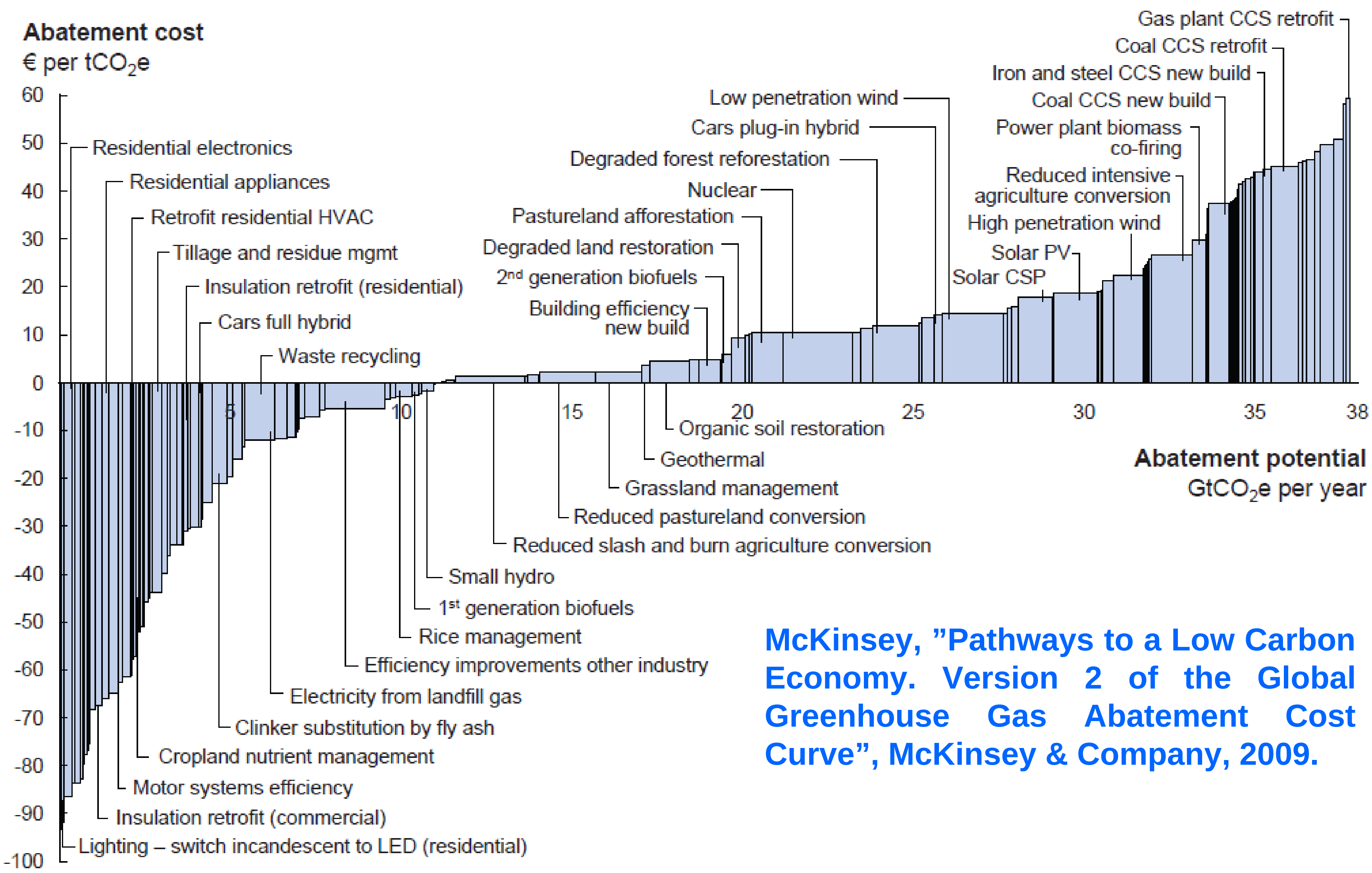
Why is Thermal Insulation Important ?

- What Measures Amounts the Most ?

Global GHG abatement cost curve beyond business-as-usual – 2030



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)

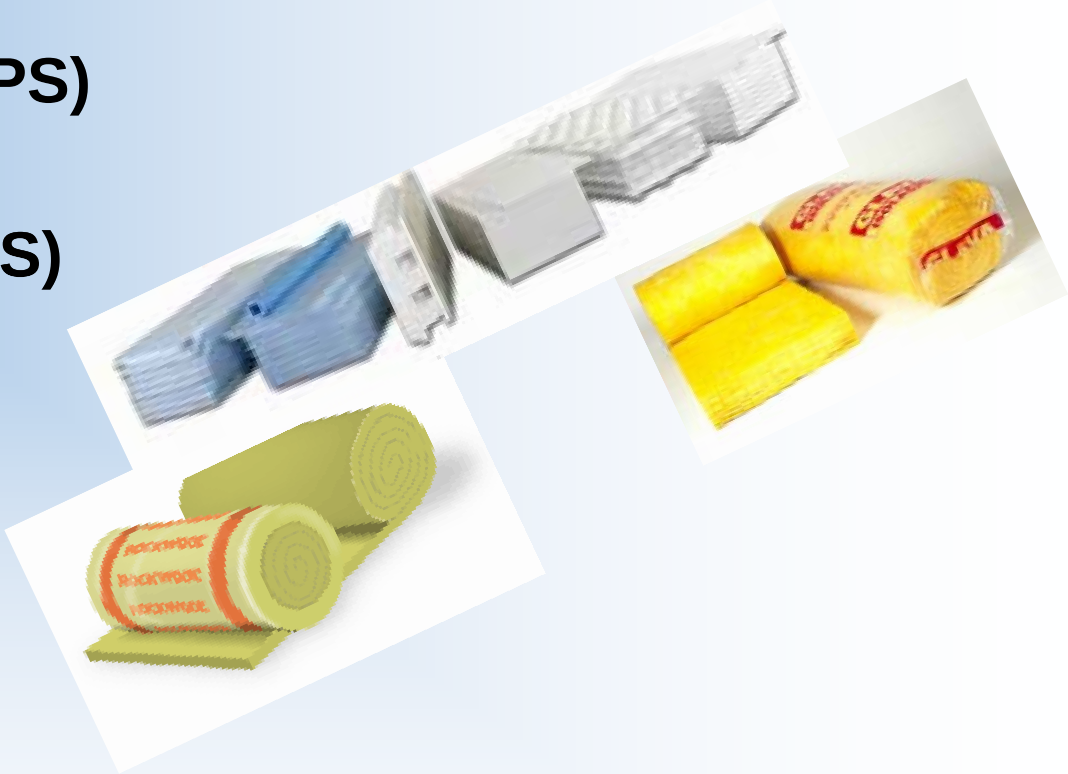
- **Expanded Polystyrene (EPS)**
  - 30-40 mW/(mK)

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

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

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

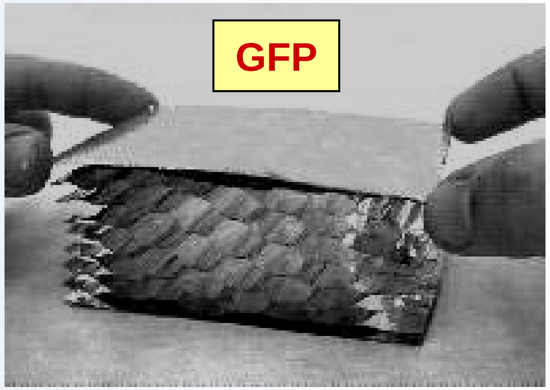
- **Polyurethane (PUR)**
  - Toxic gases (e.g. HCN) released during fire
  - 20-30 mW/(mK)

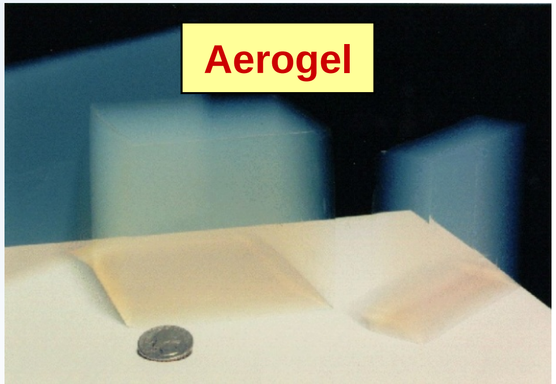


State-of-the-Art Thermal Insulation of Today

- 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)
- **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 ?**

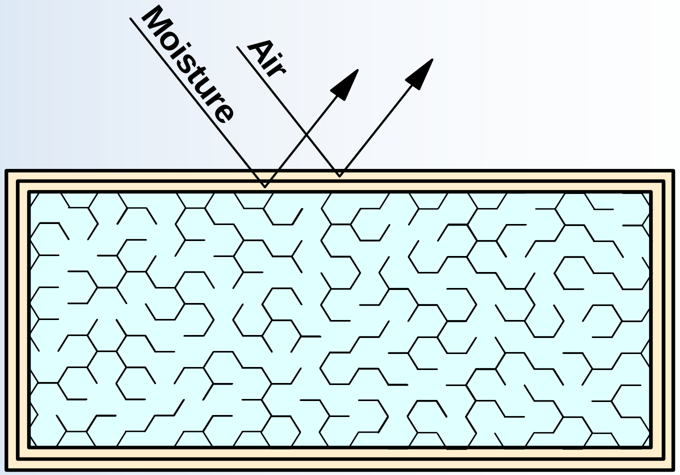




State-of-the-Art Thermal Insulation of Today

- 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?

- Vacuum Core
- Air and Moisture Tight Envelope

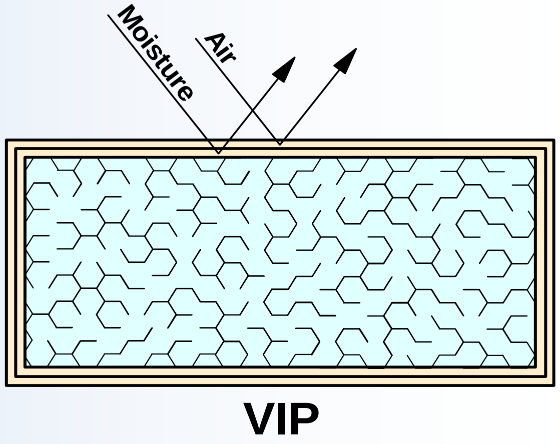


VIP

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?

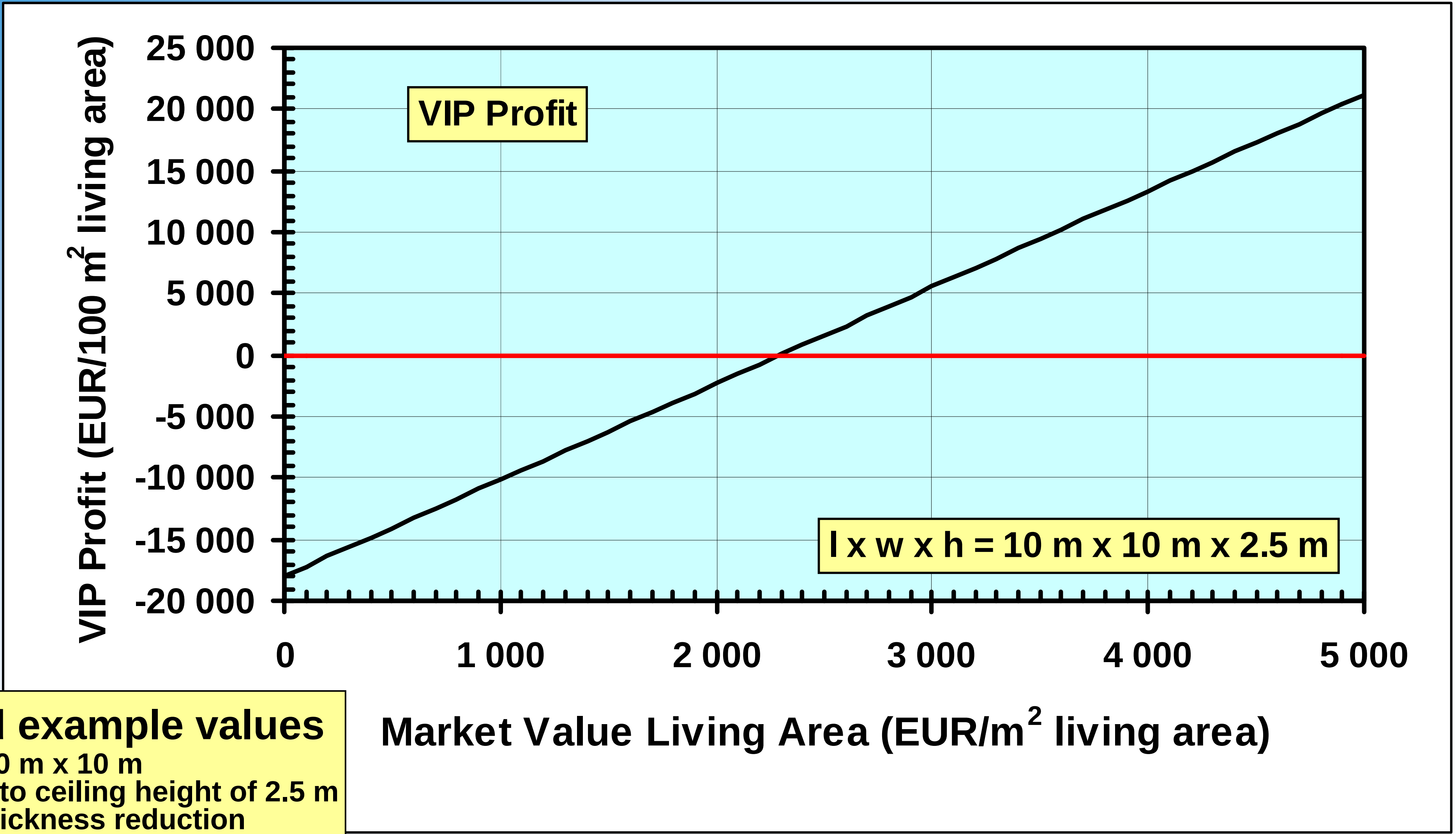
- Vacuum Core
- Air and Moisture Tight Envelope



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 m^2 ⇒ Reduced wall thickness ⇒ Large area savings ⇒ 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

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

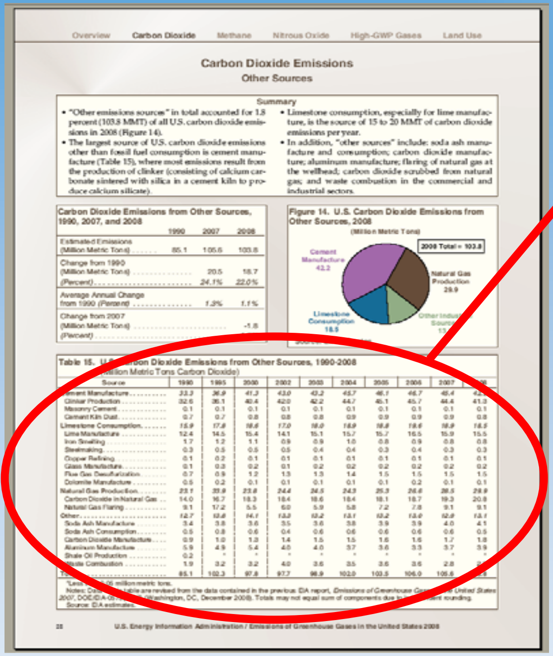
Some key properties of concrete (example values)

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.

Environmental Impact of Concrete

Large CO_2 emissions from cement production



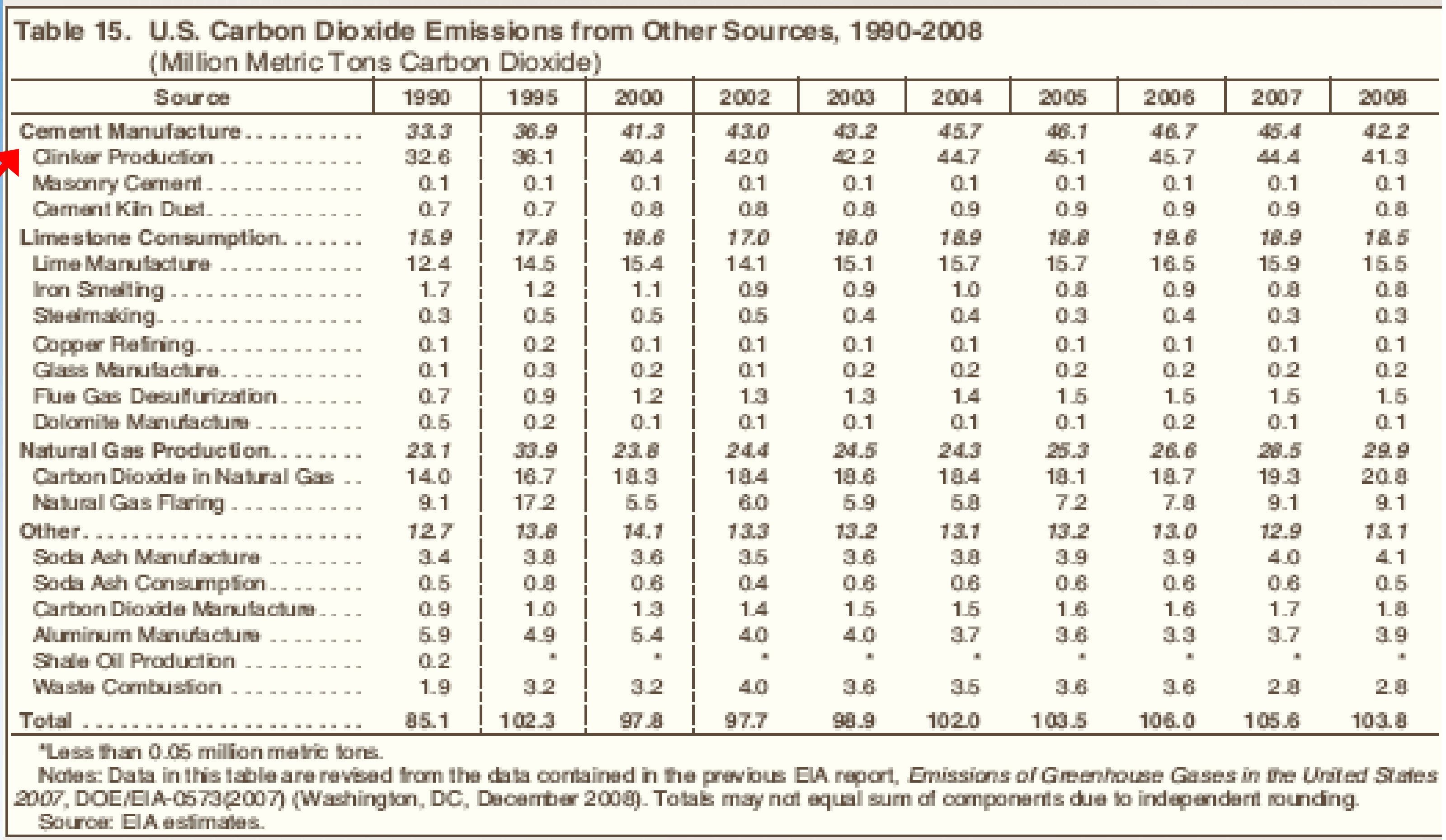


Table 15. U.S. Carbon Dioxide Emissions from Other Sources, 1990-2008
(Million Metric Tons Carbon Dioxide)

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 Kiln 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	0.8	0.9	0.8	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	0.8	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_2 Emissions from Cement Production

DEDICATED TO MAKING A DIFFERENCE

The cement sustainability initiative

our agenda for action

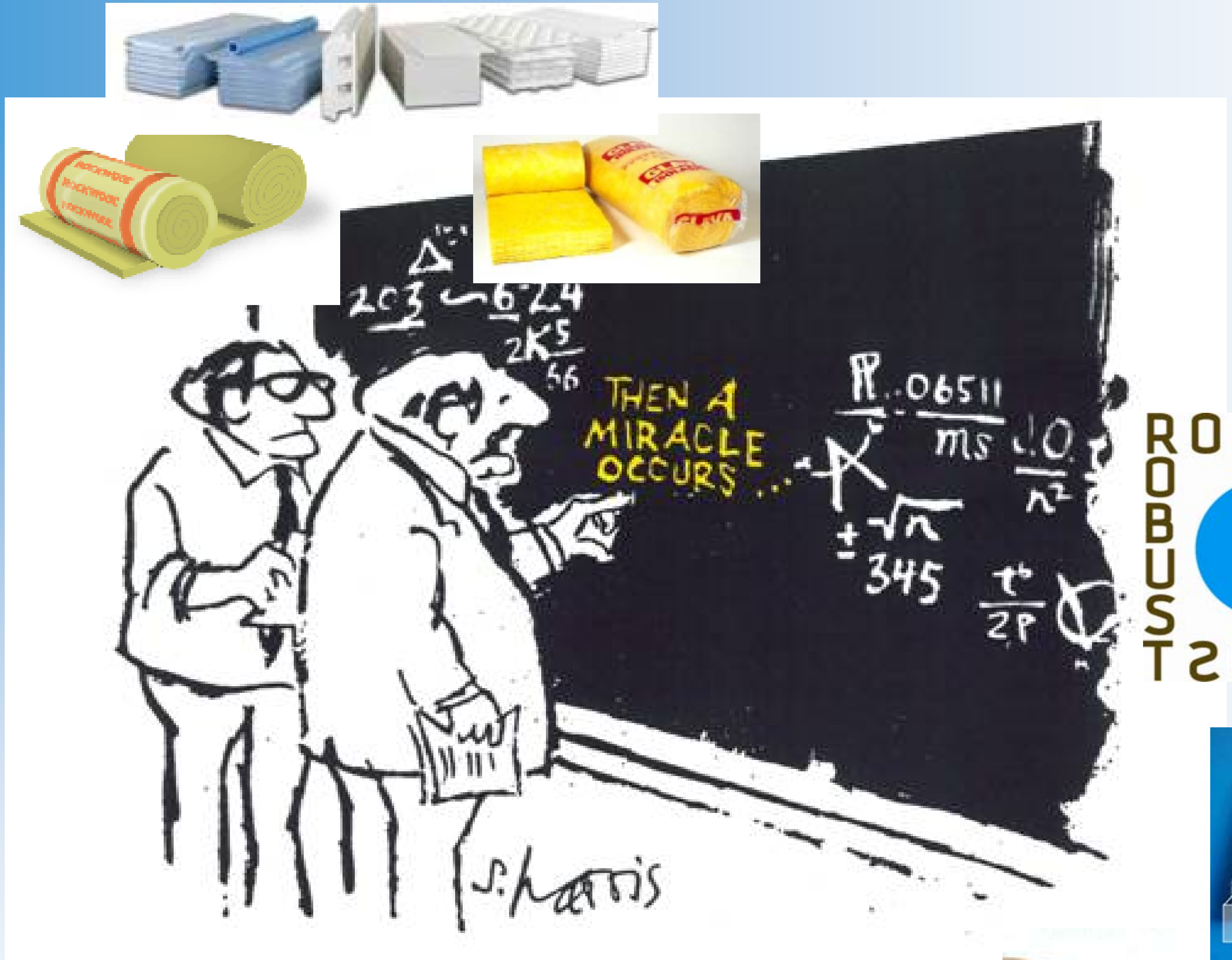
July 2002

World Business Council for Sustainable Development

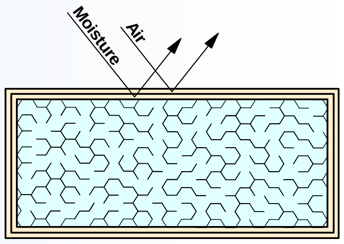
- The cement industry produces 5 % of the global man-made CO_2 emissions of which:
- 50 % from the chemical process
  - e.g.: $3CaCO_3 + SiO_2 \rightarrow Ca_3SiO_5 + 3CO_2$
    $2CaCO_3 + SiO_2 \rightarrow Ca_2SiO_4 + 2CO_2$
- 40 % from burning fossil fuels
  - e.g. coal and oil
- 10 % split between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

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

Beyond Traditional Thermal Insulation?



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



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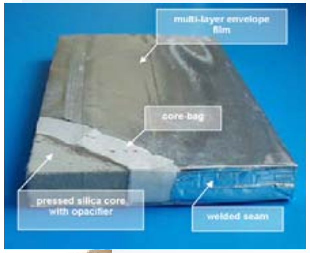
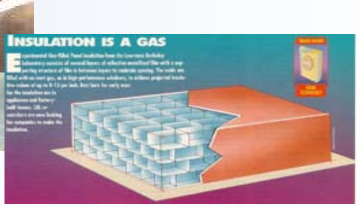
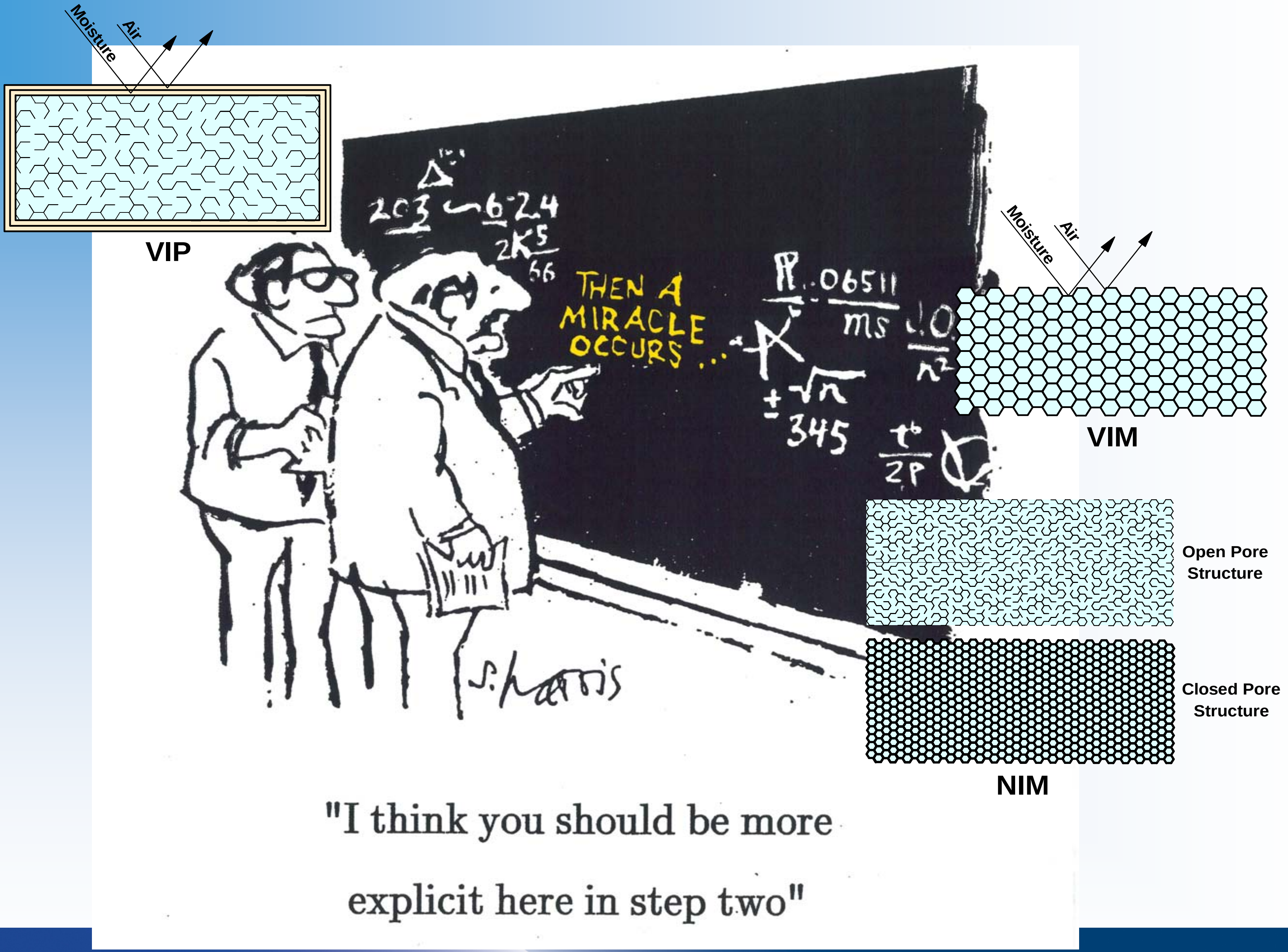


VIP

GFP



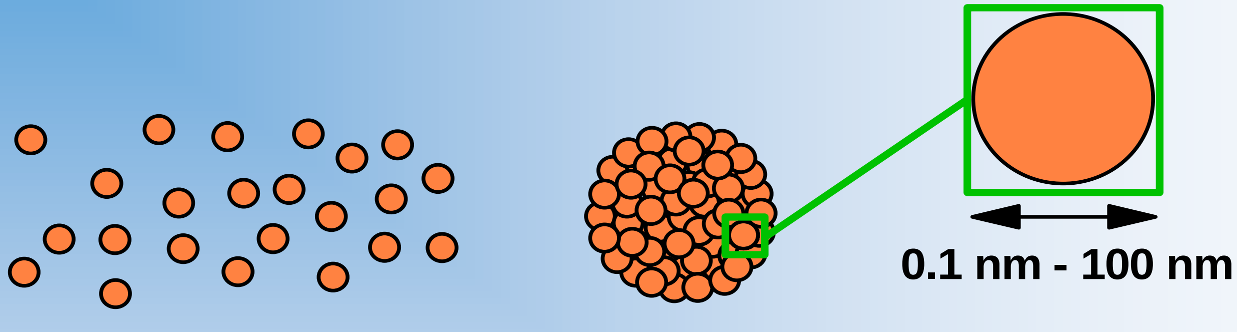
Beyond VIPs – How May It Be Achieved?



"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:

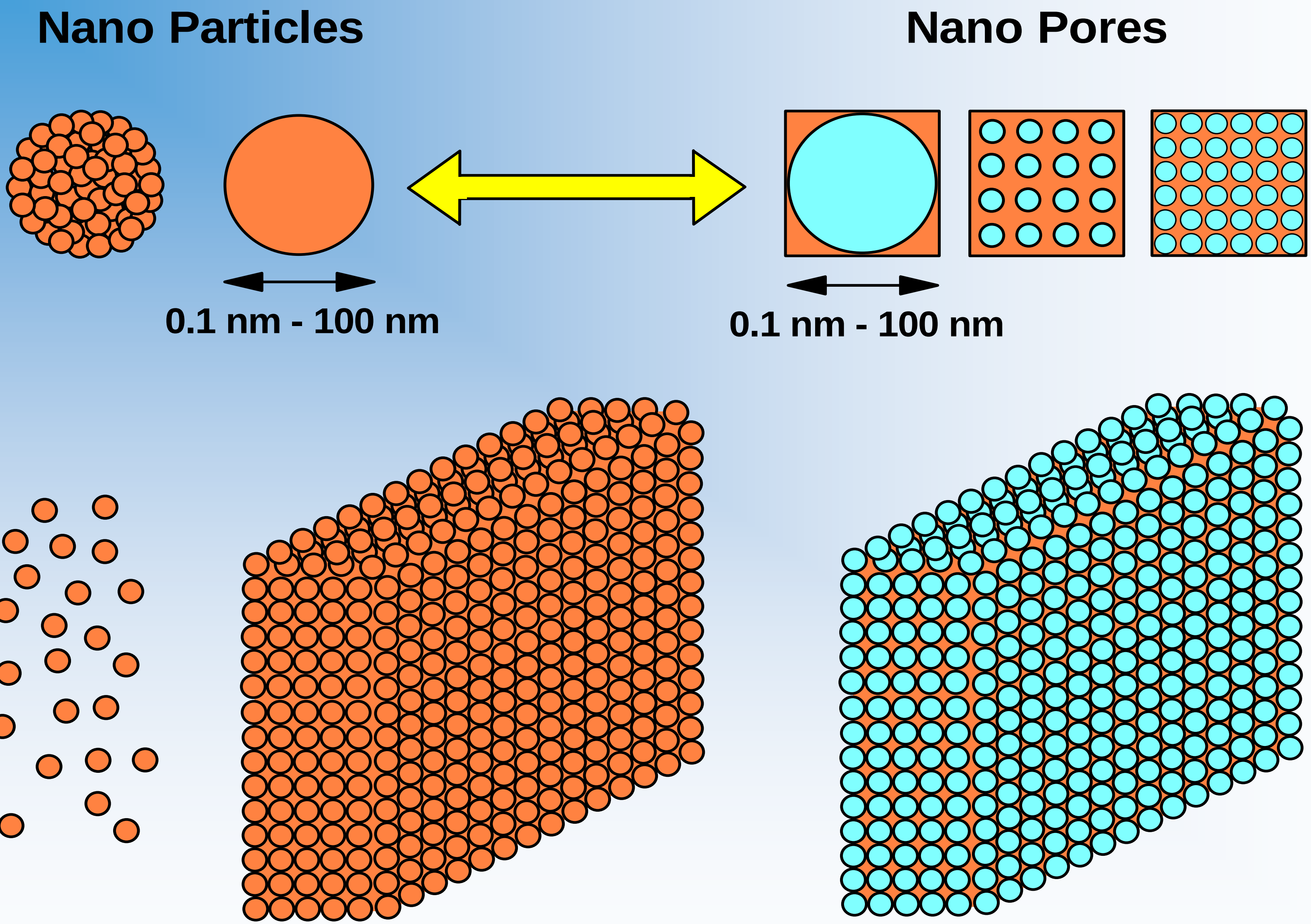
Solar radiation: 300 nm - 3000 nm

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



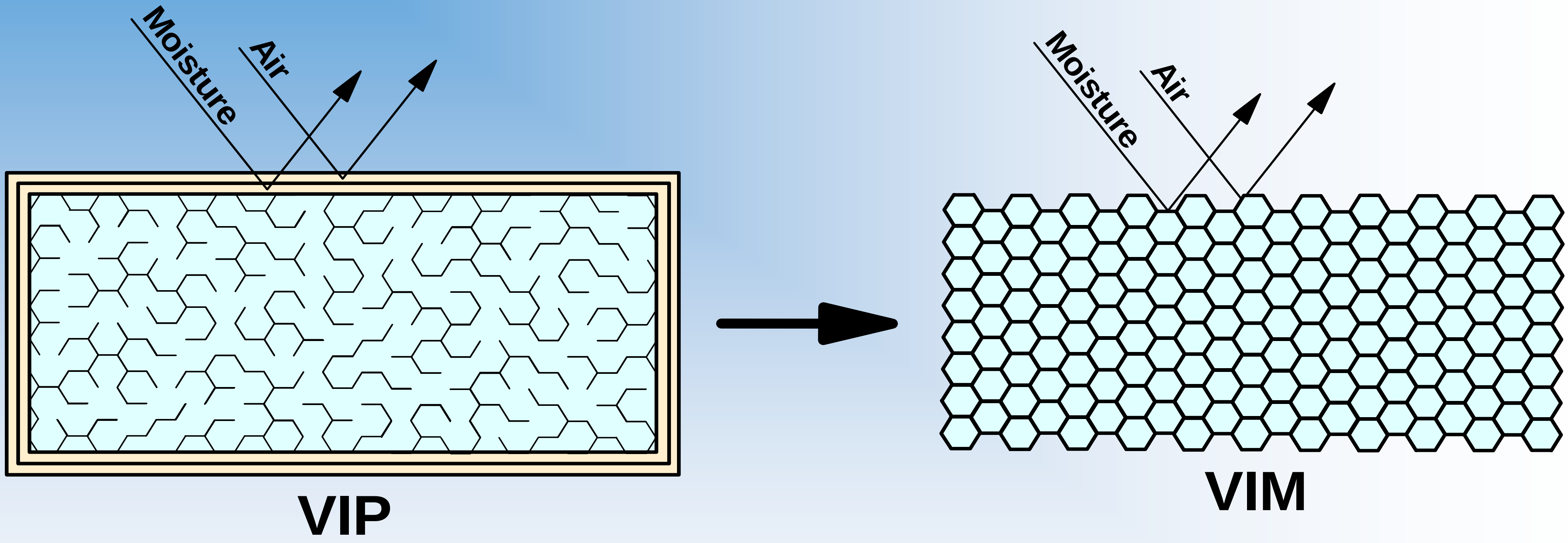
Beyond VIPs – How May It Be Achieved?

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.

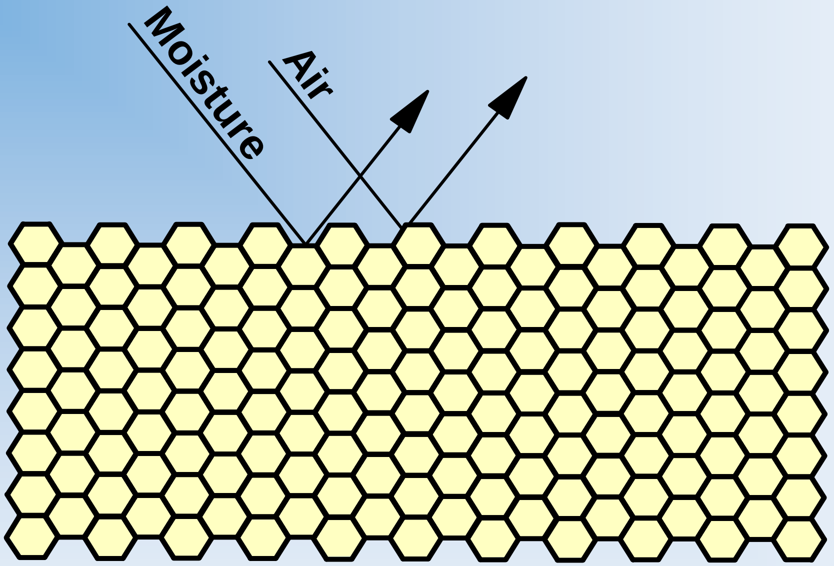
Vacuum Insulation Material (VIM)



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)

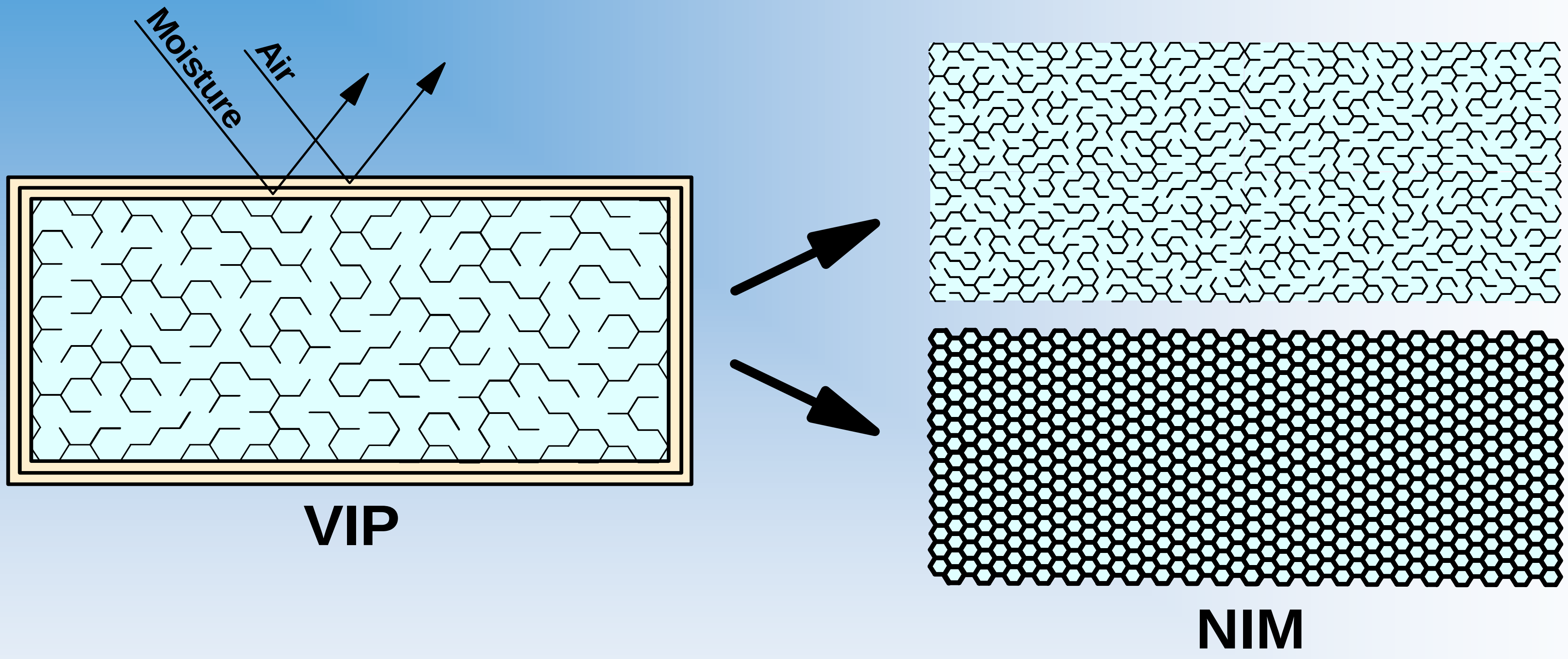
… and analogously with VIM we may define GIM as follows:



GIM

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_g

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

$\sigma_{mean} > \delta$

$\Rightarrow$ 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 $\approx 1.38\cdot10^{-23}$ J/K

T = temperature (K)

d = gas molecule collision diameter (m)

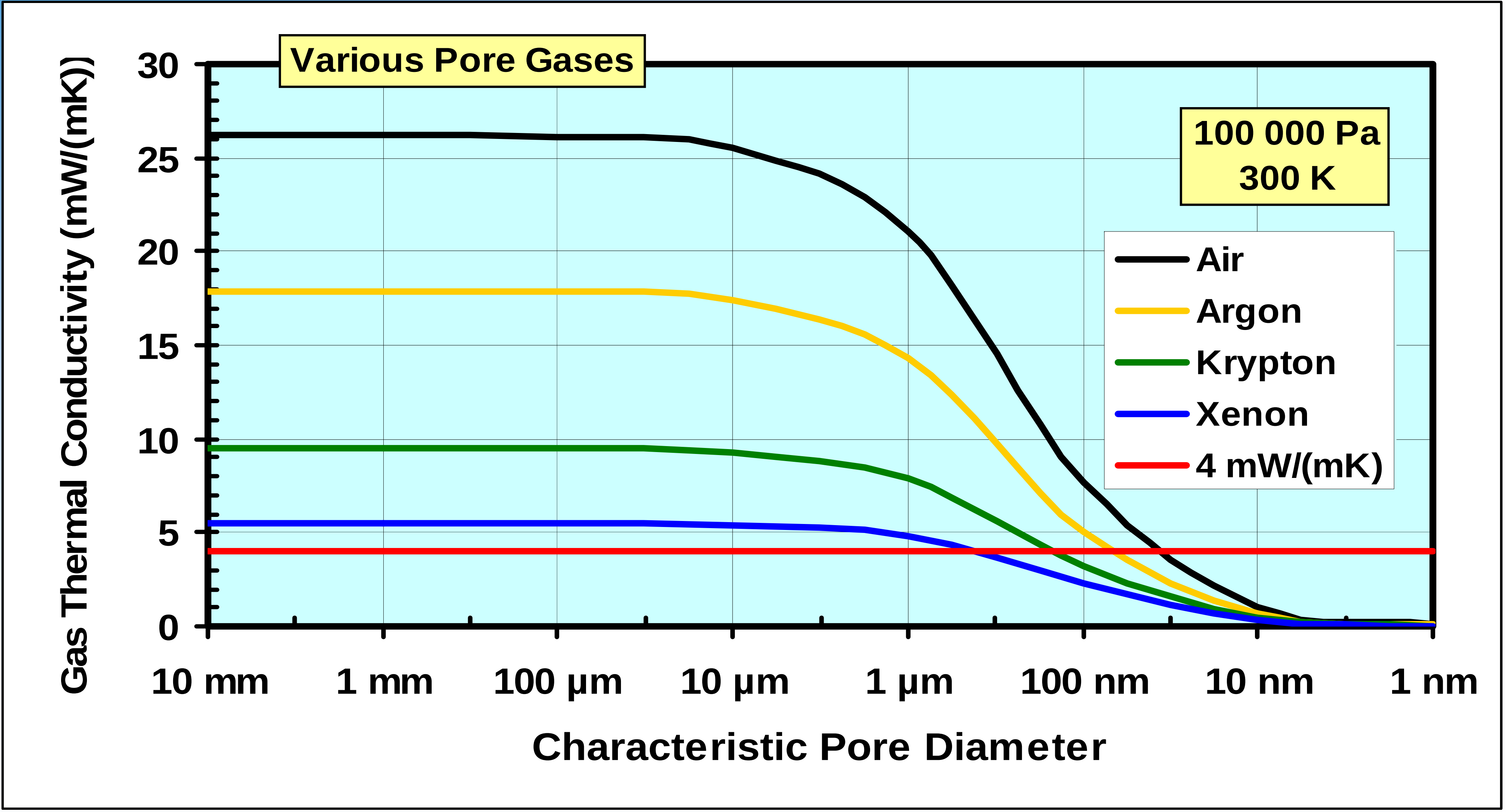
p = gas pressure in pores (Pa)

δ = characteristic pore diameter (m)

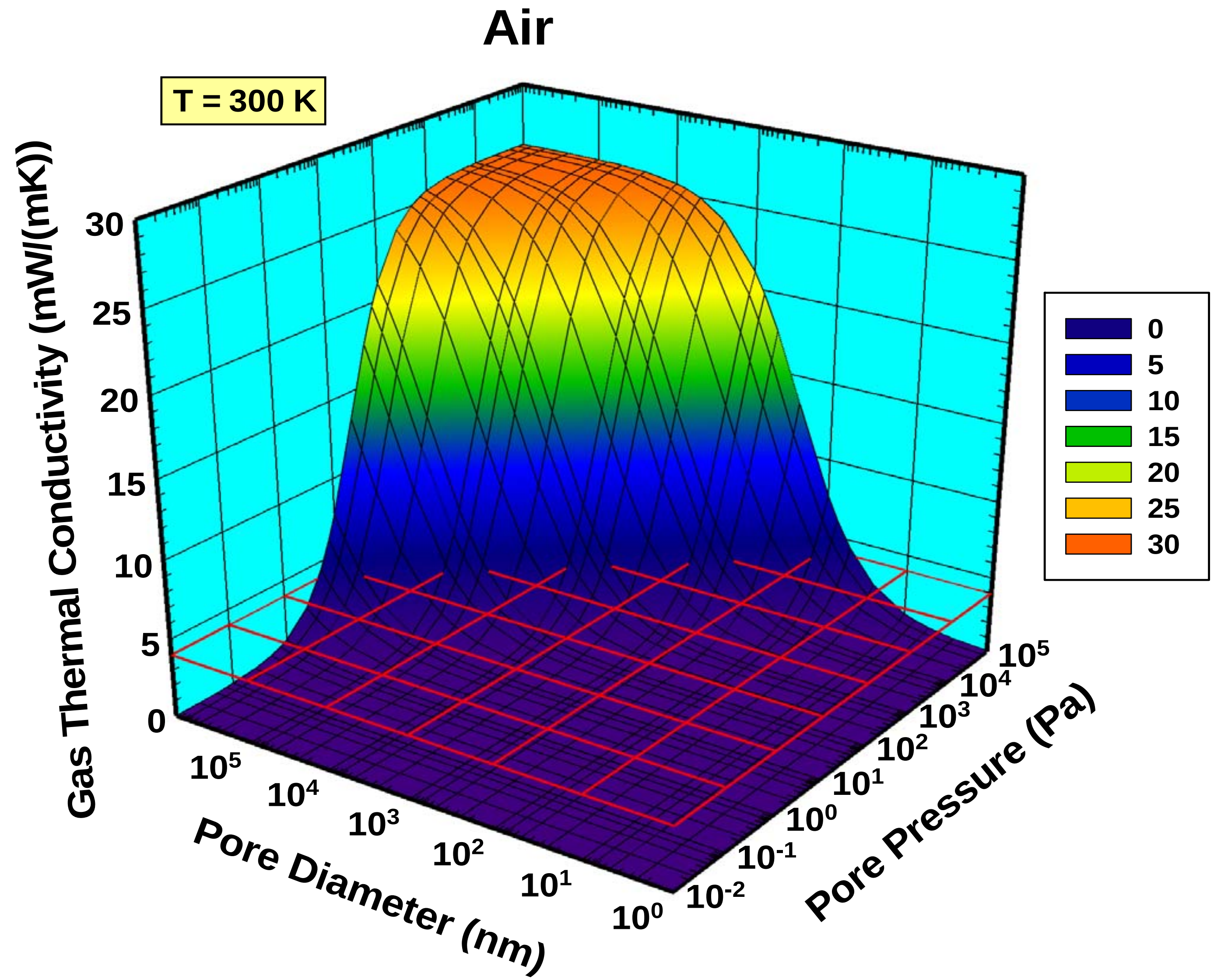
σ_{mean} = mean free path of gas molecules (m)

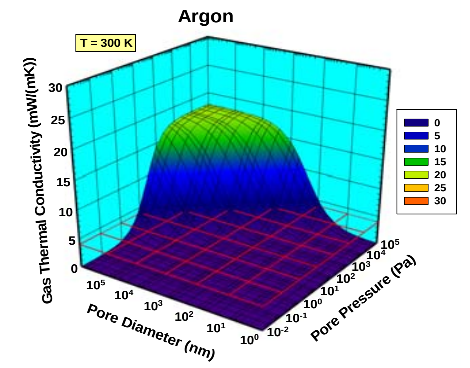
Gas Thermal Conductivity

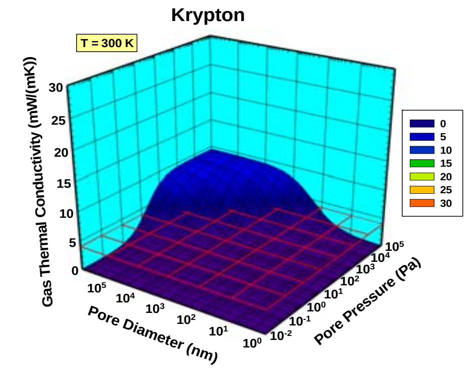
Conductivity vs. Pore Diameter

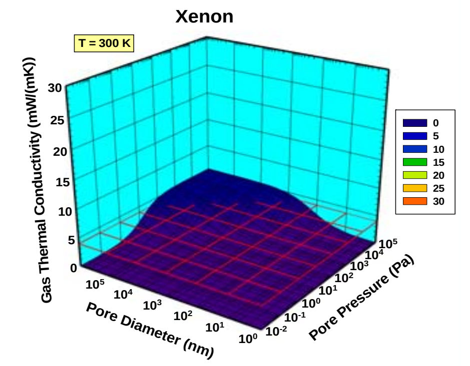


Gas Thermal Conductivity









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:**

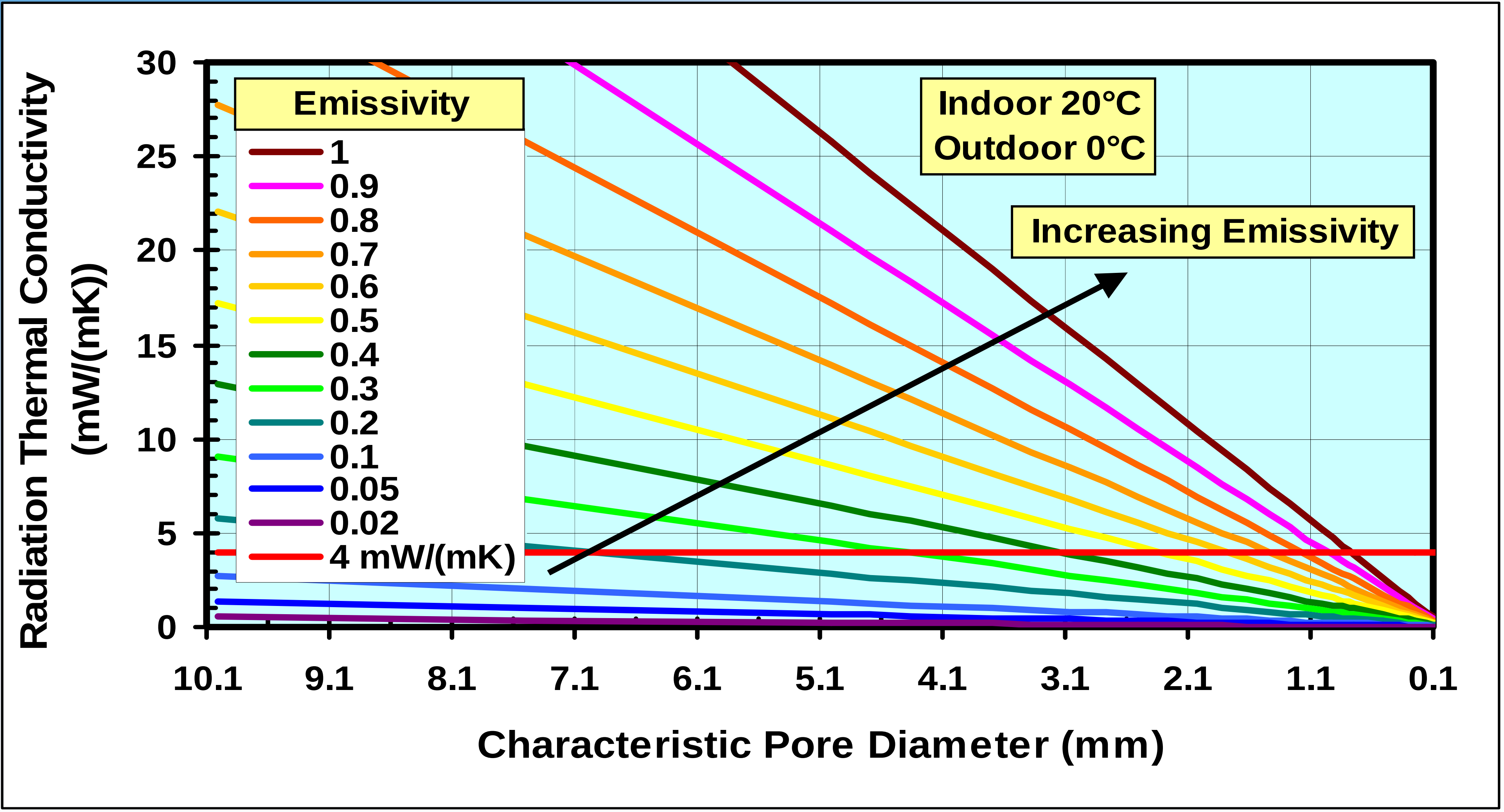
$$\lambda_{rad} = \frac{\pi^2 k_B^4 \delta}{60\hbar^3 c^2\left[\frac{2}{\varepsilon}-1\right]} \frac{(T_i^4 - T_e^4)}{(T_i - T_e)}$$

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 ≈ $5.67\cdot10^{-8}$ W/(m^{2}K^4)
k_B = Boltzmann’s constant ≈ $1.38\cdot10^{-23}$ J/K
$\hbar = h/(2\pi) \approx 1.05\cdot10^{-34}$ Js = reduced Planck’s constant (h = Planck’s constant)
c = velocity of light ≈ $3.00\cdot10^{8}$ 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)
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…**

Radiation Thermal Conductivity

Conductivity vs. Pore Diameter



Dynamic Insulation Material (DIM)

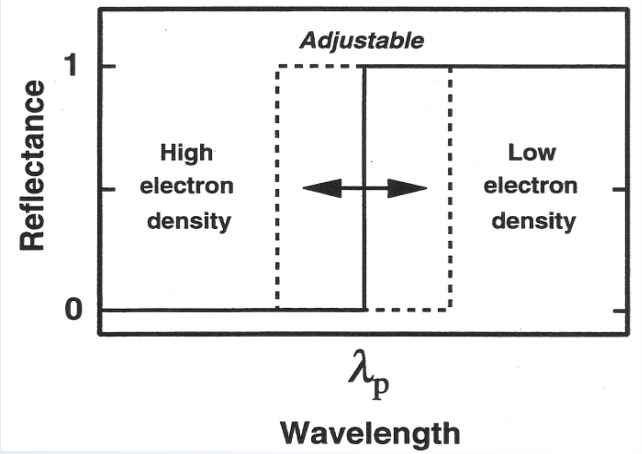
DIM – A material where the thermal conductivity can be controlled within a desirable range

- **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?***

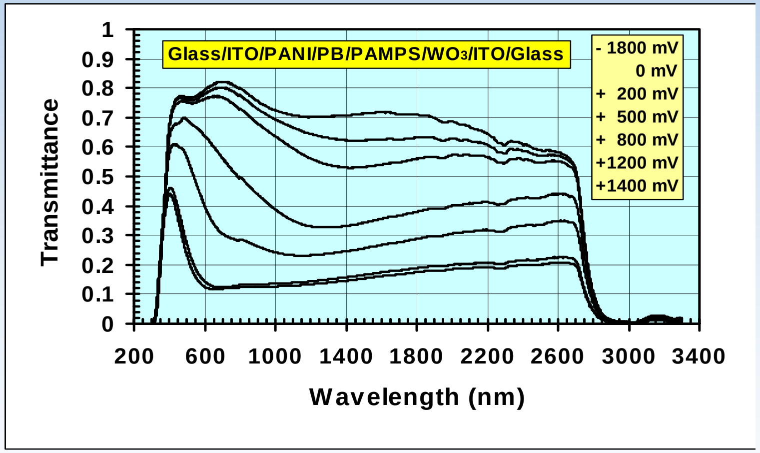
Inspiration and Ideas - DIMs

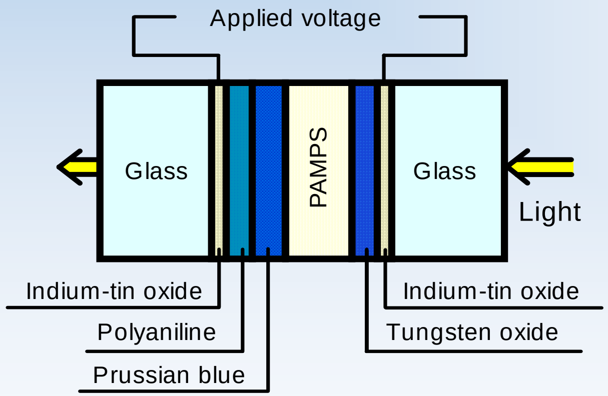
Could other fields of science and technology inspire and give ideas about how to be able to make DIMs, e.g. from?:

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



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.





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

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).

Aerogels – Approaching the NIMs

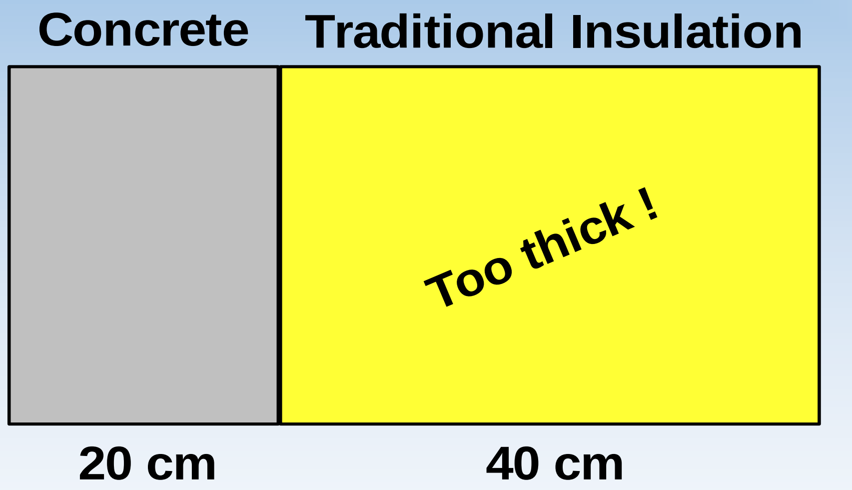
- Aerogels – At the moment the closest commercial approach to NIMs
- 12 – 14 mW/(mK)
- Aspen Aerogels
  - Spaceloft
- Cabot Aerogel
  - Nanogel

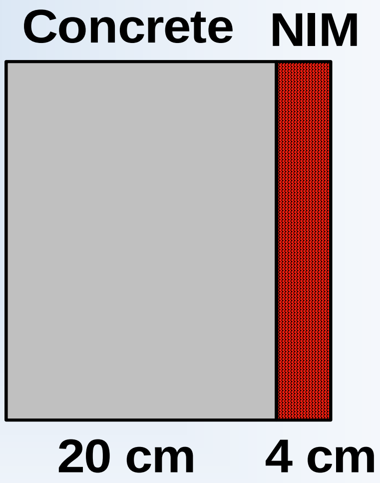
- Production costs still high
- Relatively high compression strength
- Very fragile due to very low tensile strength
- Tensile strength may be increased by incorporation of a carbon fibre matrix
- May be produced as either opaque, translucent or transparent materials
  - → Thus enabling a wide range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

Thinner Concrete Buildings with NIMs

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

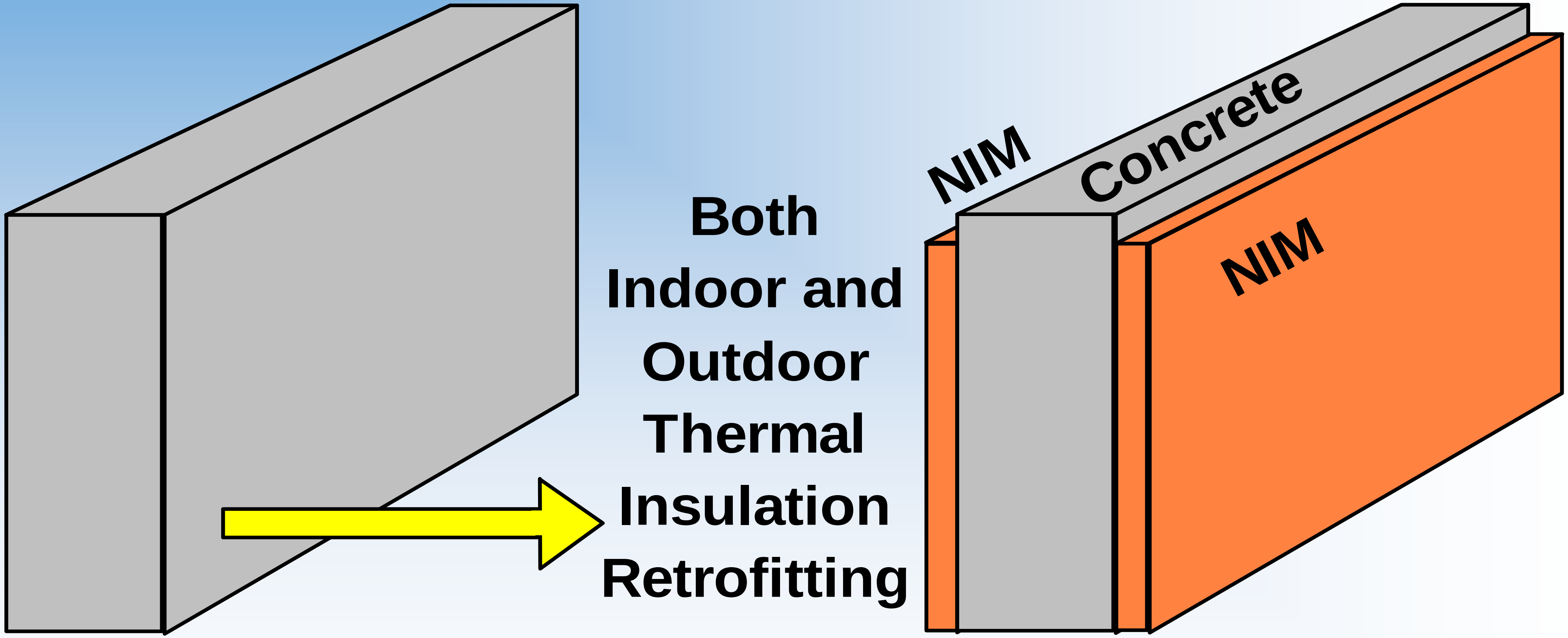
- NIM
- 3.6 mW/(mK)
- 4 cm NIM thermal insulation retrofitting





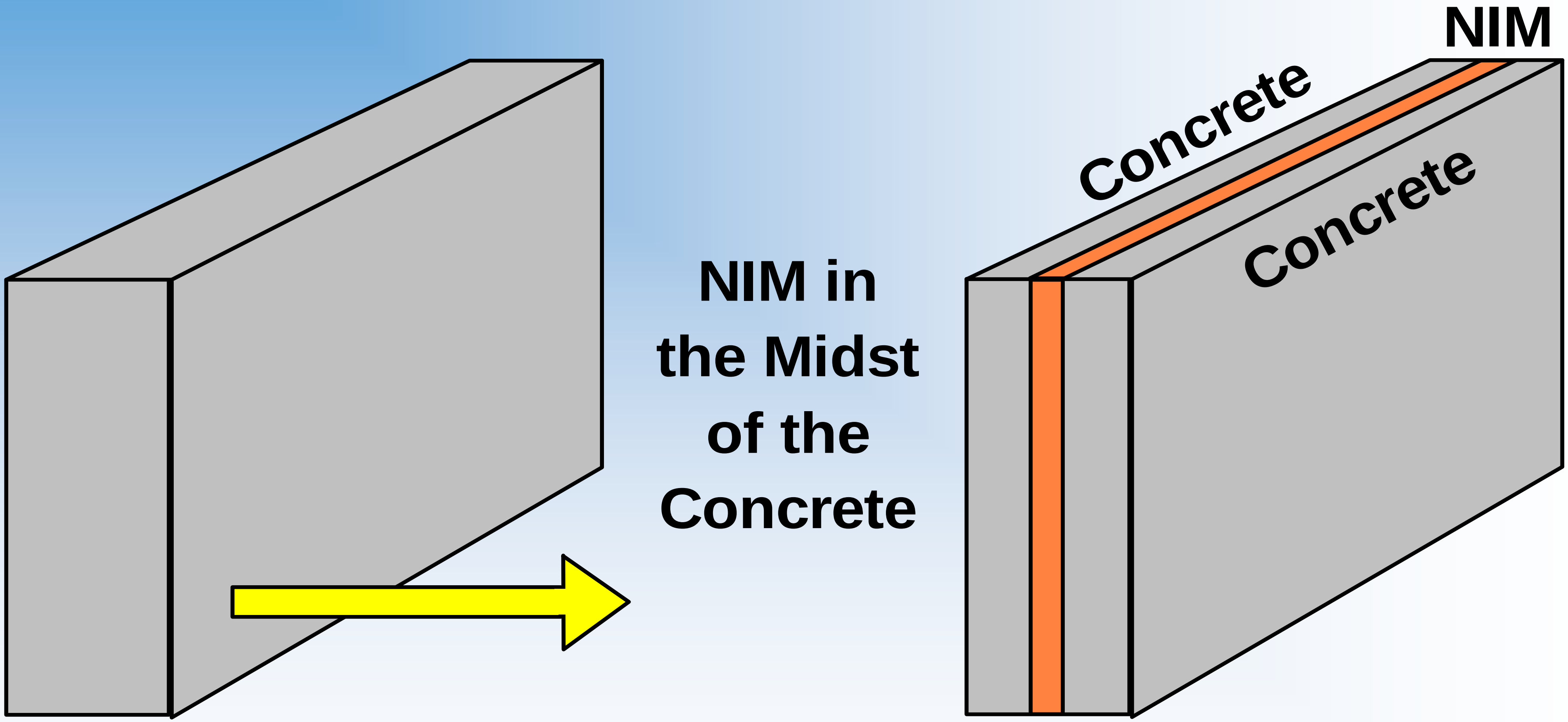
- A vast reduction – factor 10 – of the thermal insulation layer and thereby the total building envelope thickness.

Concrete with NIM Indoor and Outdoor - Retrofitting



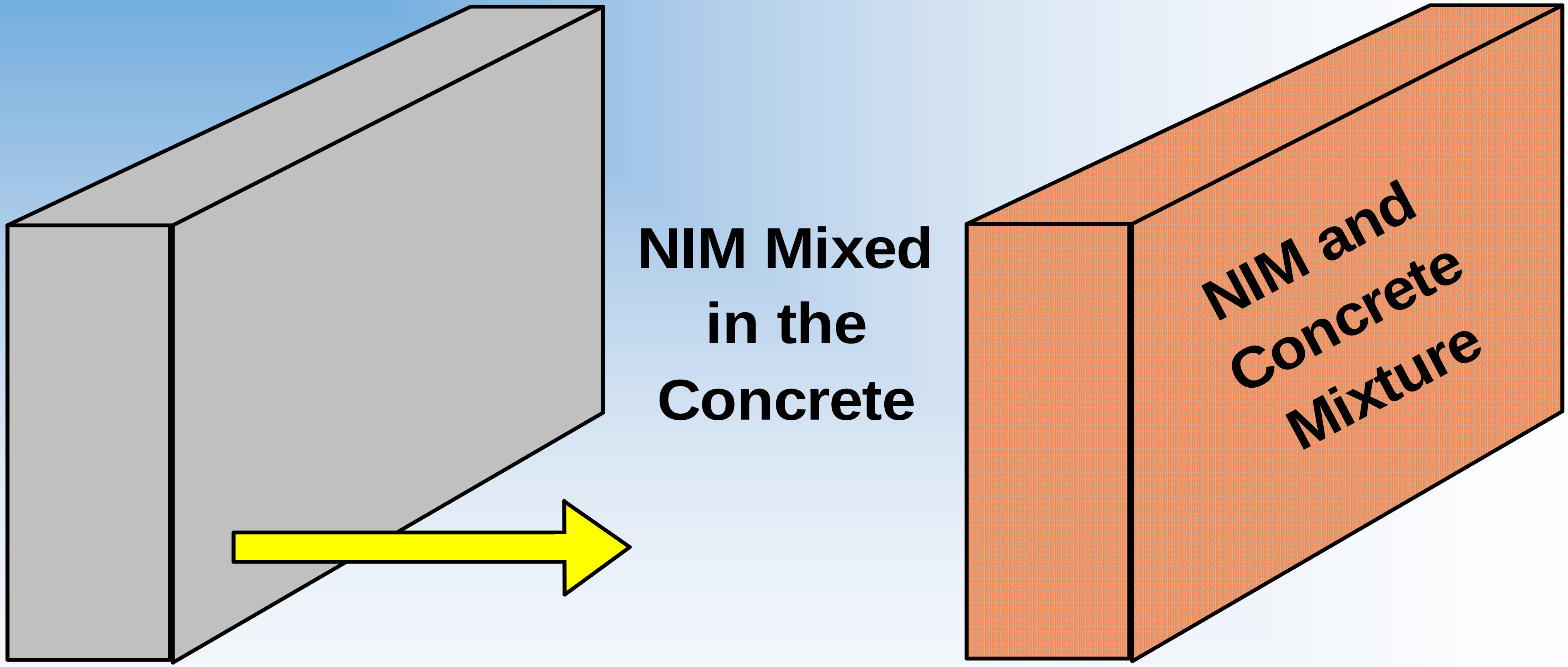
Both Indoor and Outdoor Thermal Insulation Retrofitting

NIM in the Midst of Concrete



NIM in the Midst of the Concrete

NIM and Concrete Mixture



To Envision Beyond Concrete ?

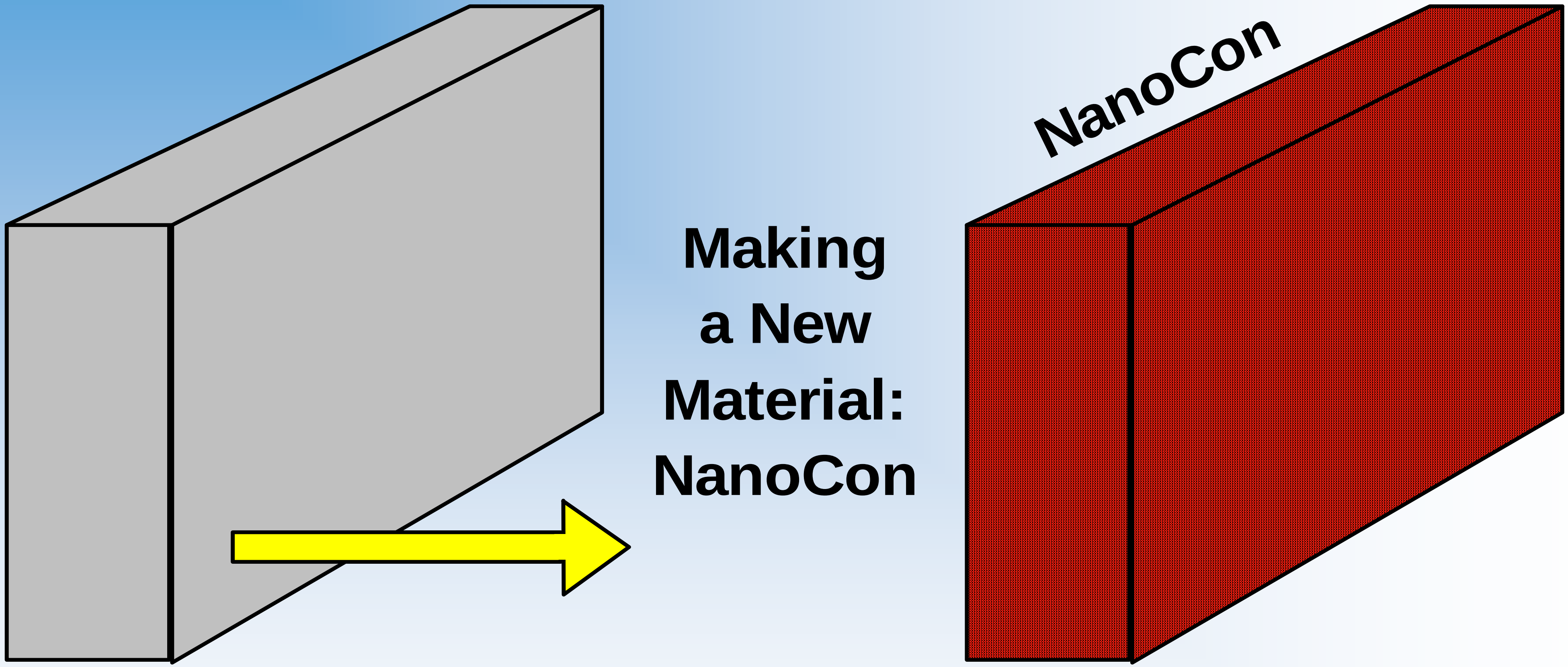
- *In the community of concrete it might be compared to using profane language in the church and close to blasphemy to suggest that maybe the answer is not concrete after all…* 👍☺

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?

NanoCon – Introducing a New Material



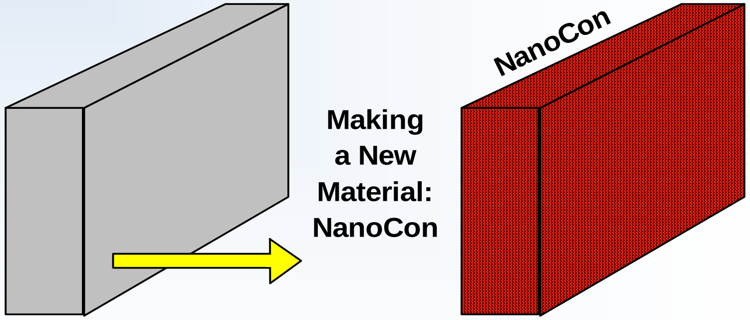
Making a New Material: NanoCon

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.

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



Comparison of Weaknesses and Strengths

- Robustness of traditional thermal insulation materials
- Thermal conductivity of state-of-the-art thermal insulation materials
- Thermal conductivity of future thermal insulation materials
- Thermal conductivity and other properties
- Requirements of future thermal insulation materials and solutions
- The potential of miscellaneous thermal insulation materials and solutions
- Potential cost savings by applying VIPs
- Condensation risk by applying VIPs in the building envelope
- The cardinal weaknesses of VIPs
- EPS encapsulated VIPs
- VIMs and GIMs versus NIMs
- The regulating potential of DIMs
- The construction potential of NanoCon
- Assessing weaknesses and strengths
- Does the future belong to NIMs, DIMs and NanoCon?
- Future research paths

The Thermal Insulation Potential

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

- Properties, Requirements and Possibilities
- The path ahead:
  - Choose the most suitable one from today's existing traditional and state-of-the-art thermal insulation materials and solutions.
  - Conduct research and continuously improve today's existing traditional and state-of-the-art thermal insulation materials and solutions.
  - Initiate research which explores the possibilities of discovering and developing novel high performance thermal insulation materials and solutions with properties surpassing all of today's existing materials and solutions.
- Several possibilities of applying nano technology and nano insulation materials (NIM) have been presented.
- NanoCon as essentially a NIM with construction properties matching or surpassing those of concrete has been introduced and defined.