Beyond Vacuum Insulation Panels - How May It Be Achieved?

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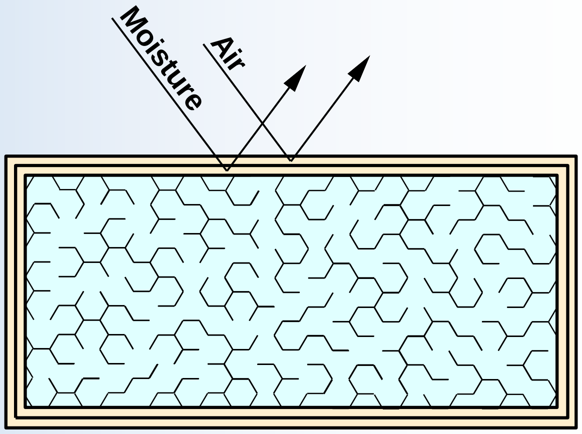
Thermal Insulation of Today

- 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

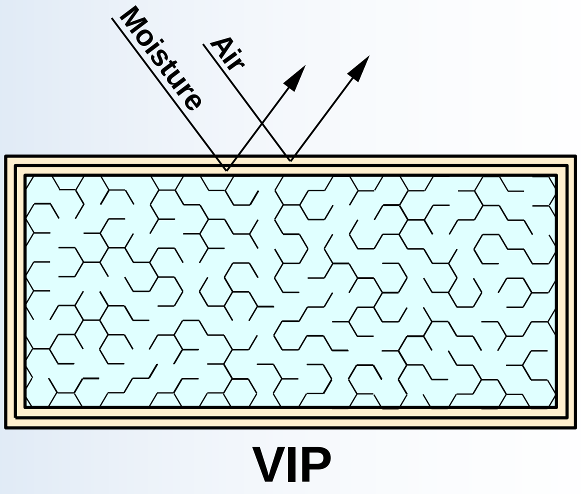


VIP

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 ?

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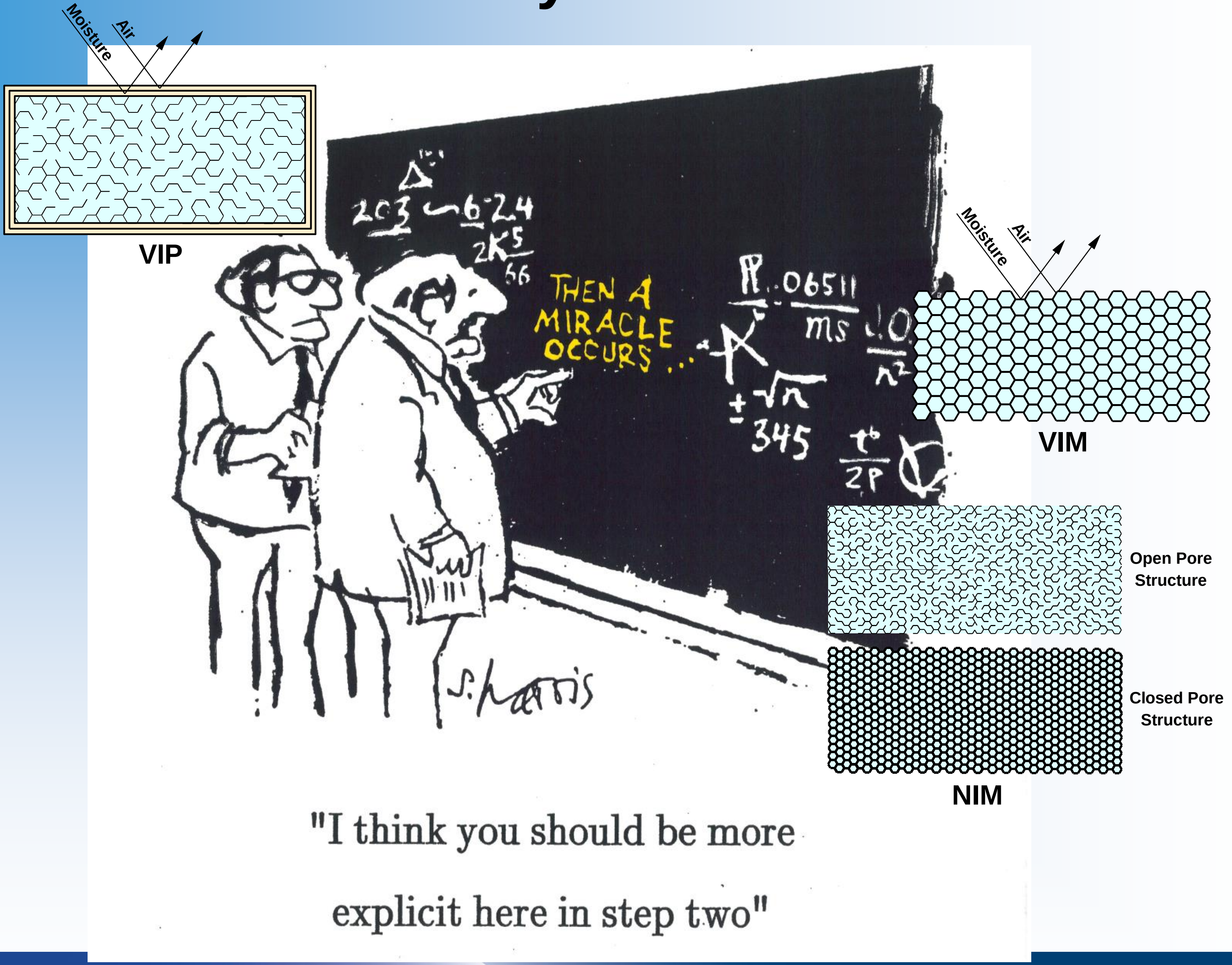
- VIPs - Despite large disadvantages - A large leap forward
- Thermal conductivities 5 to 10 times lower than traditional insulation
  - 4 mW/(mK) fresh
  - 8 mW/(mK) 25 years
  - 20 mW/(mK) perforated
- Wall and roof thicknesses up to 50 cm as with traditional insulation are not desired
  - Require 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 $m^2 \Rightarrow$ Reduced wall thickness $\Rightarrow$ Large area savings $\Rightarrow$ Higher value of the real estate
- VIPs - The best solution today and in the near future?
- Beyond VIPs?

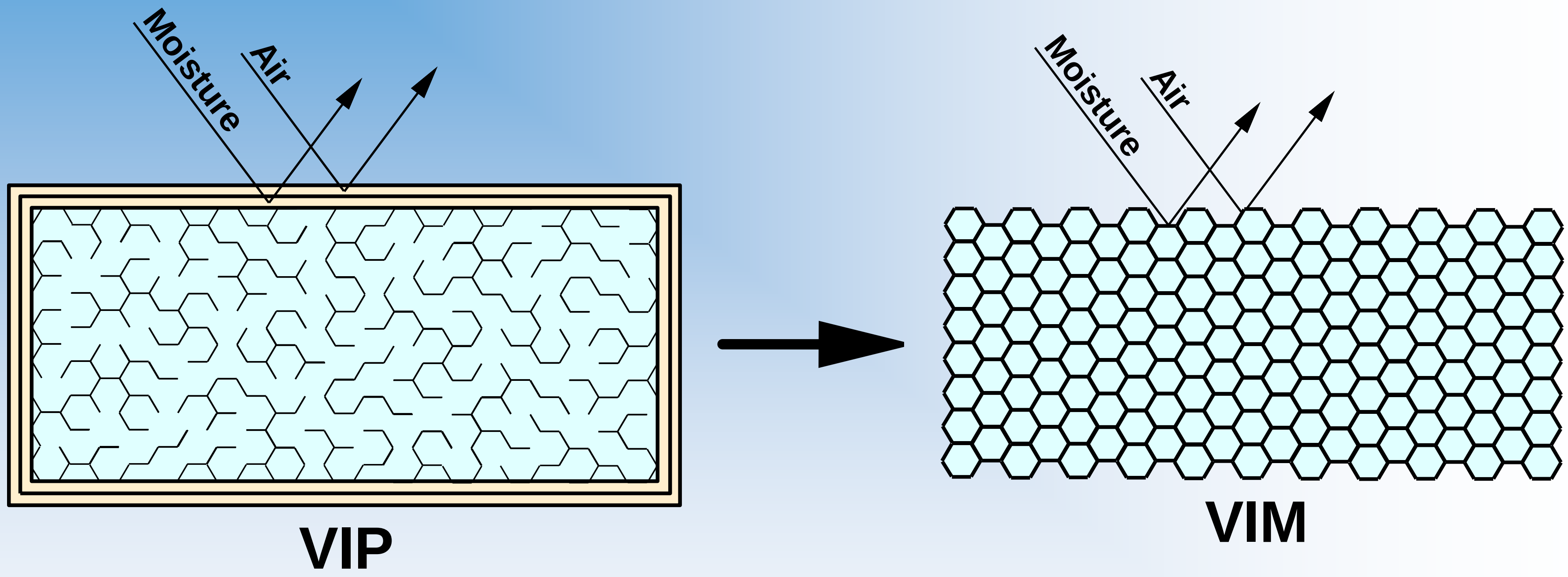
Requirements of the Thermal Insulation of Tomorrow

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

Beyond VIPs – How May It Be Achieved?

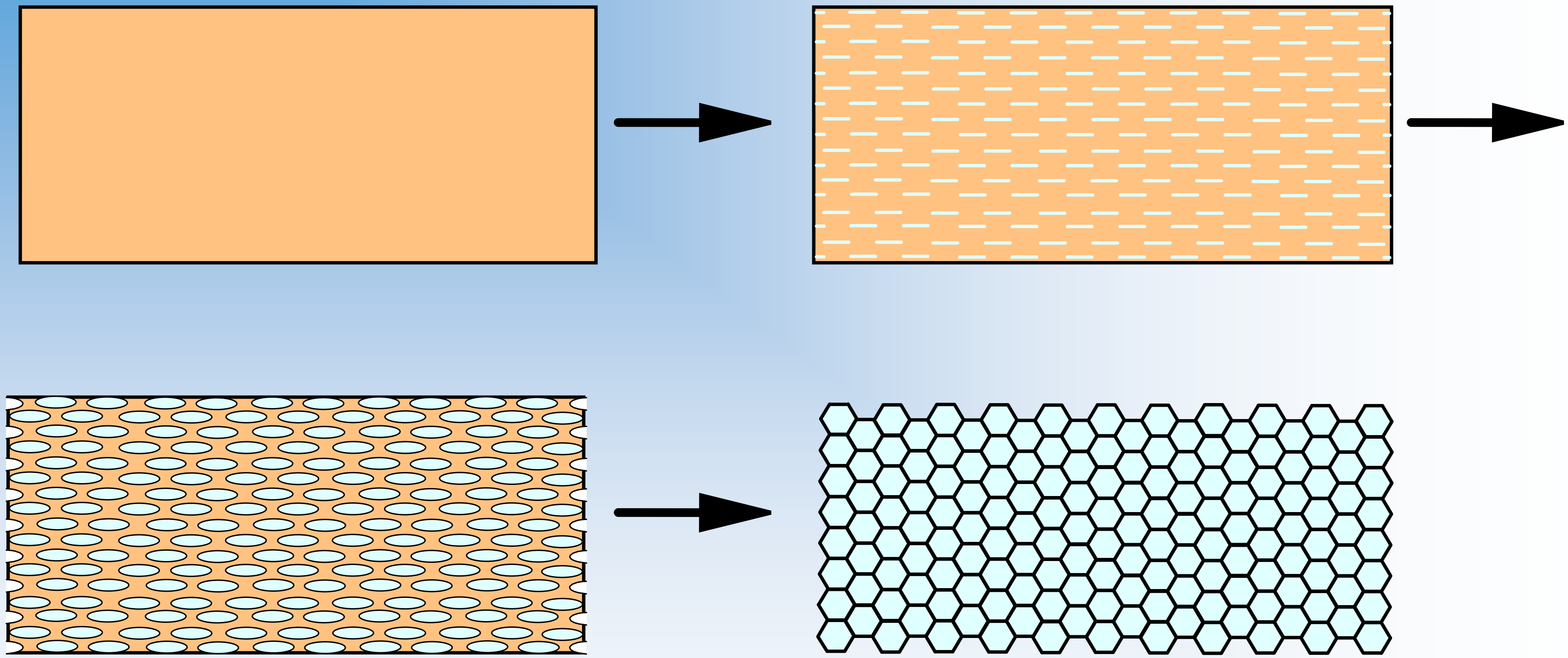


Vacuum Insulation Material (VIM)



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

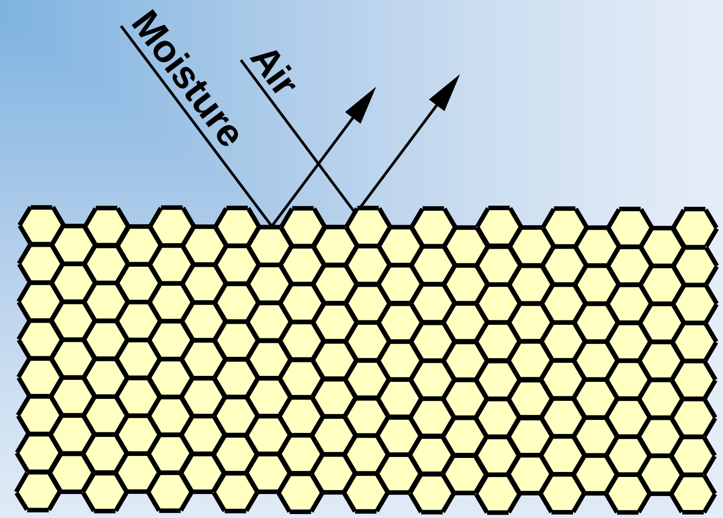
How to Make a VIM ?



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

Gas Insulation Material (GIM)

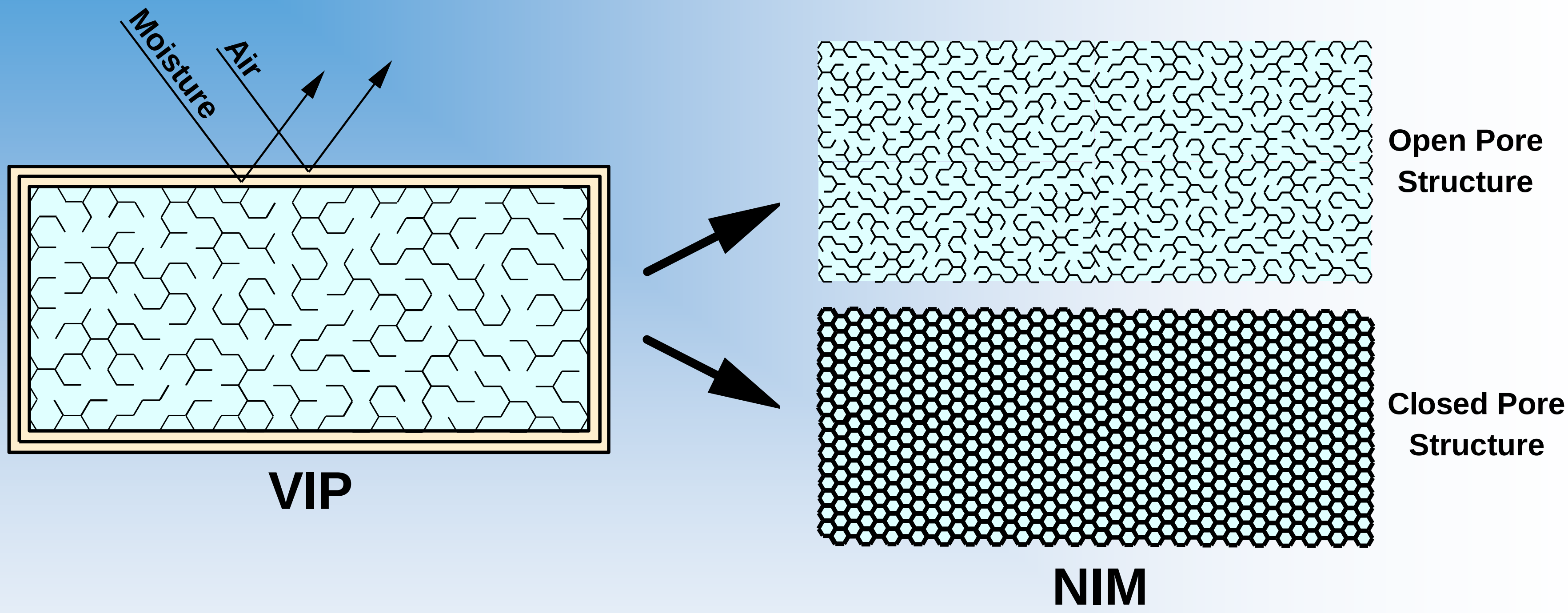
… and analogously with VIM we may define GIM as follows:



GIM

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

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

$\sigma_{mean} > \delta$
$\Rightarrow$ low λ_g

where

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

λ_g = gas thermal conductivity in the pores (W/(mK))
$\lambda_{g,0}$ = 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)
k_B = Boltzmann's constant $\approx 1.38 \cdot 10^{-23}$ J/K
T = temperature (K)
d = gas molecule collision diameter (m)
p = gas pressure in pores (Pa)
δ = characteristic pore diameter (m)
σ_{mean} = mean free path of gas molecules (m)

Nano Pores – Thermal Radiation

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

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

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

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

Gas Thermal Conductivity

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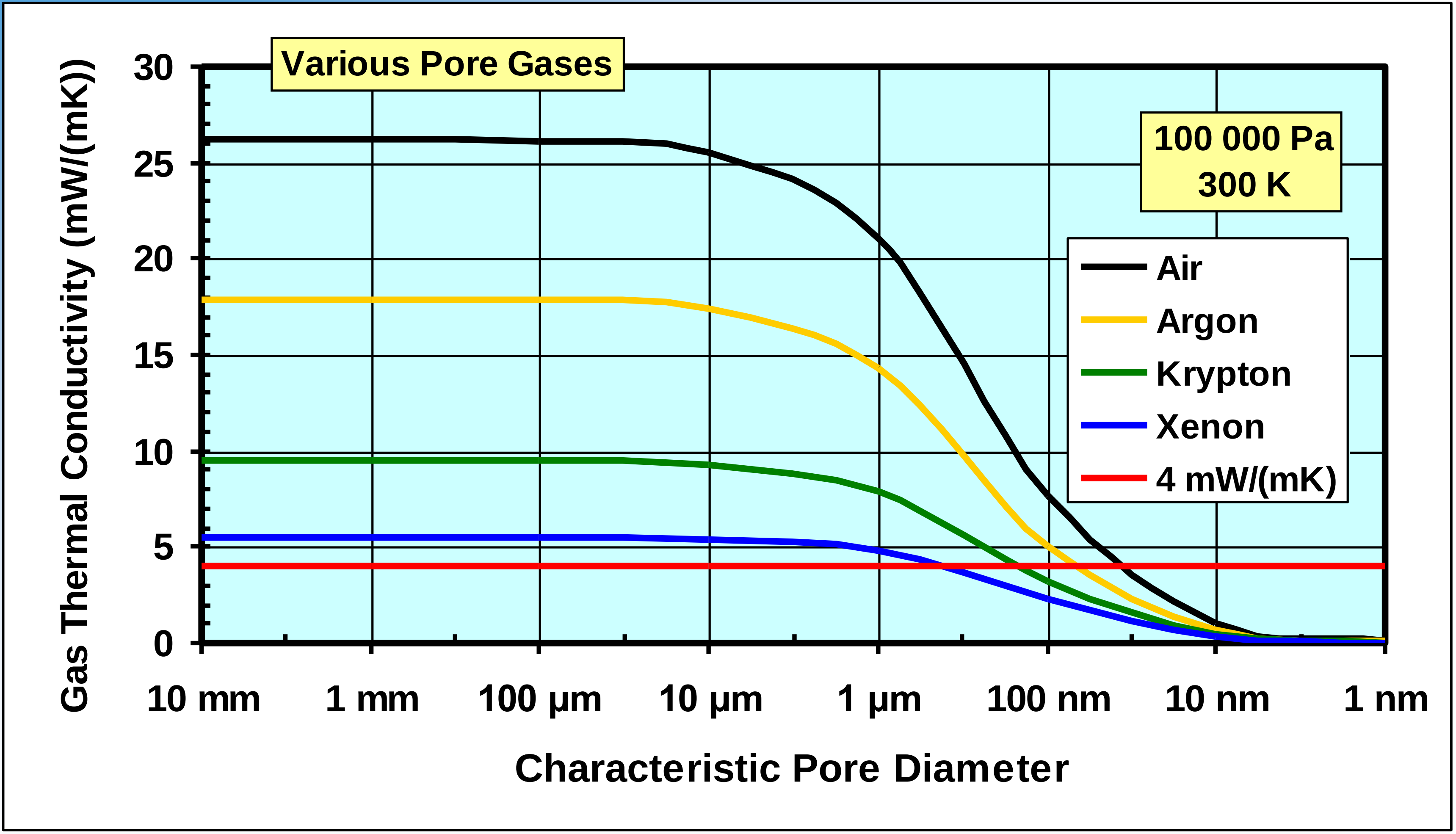
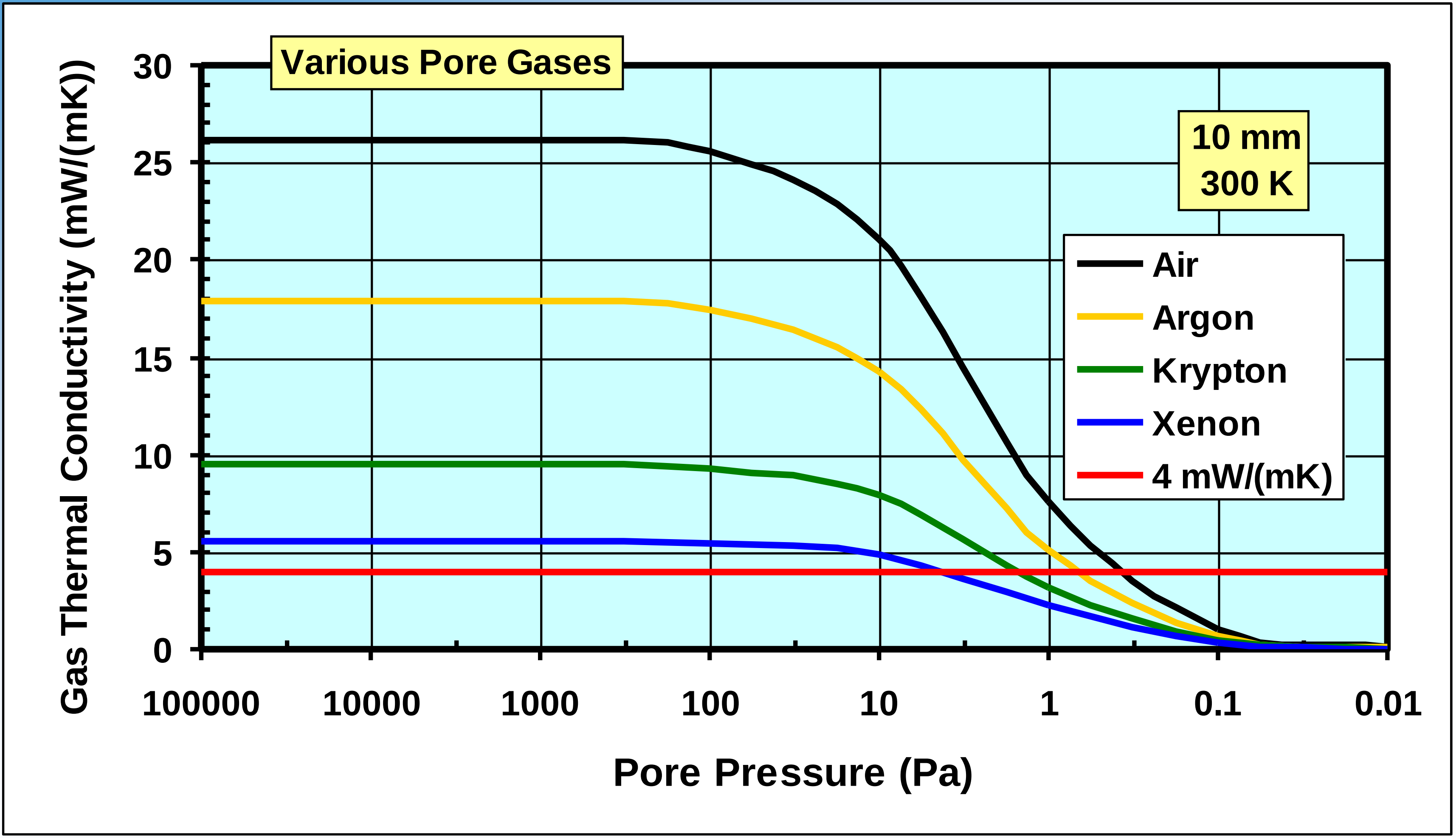
Conductivity vs. Pore Diameter

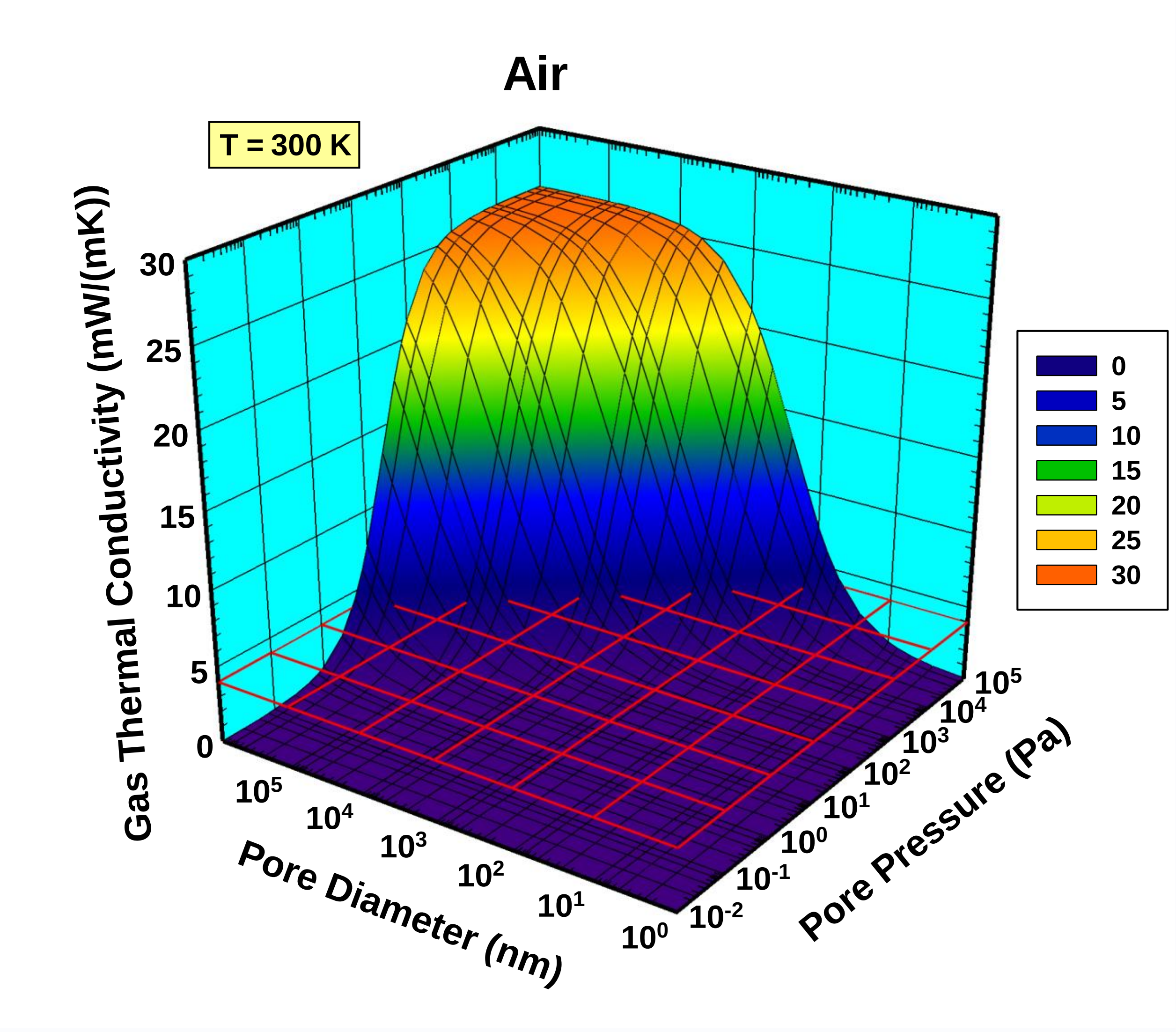


Gas Thermal Conductivity

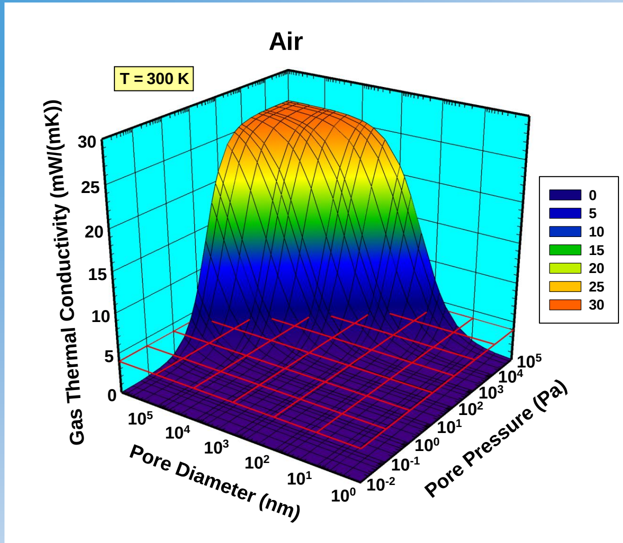
Conductivity vs. Pore Pressure

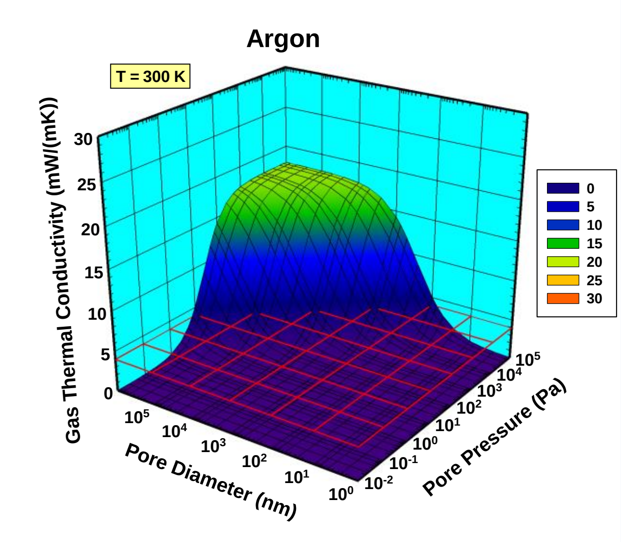


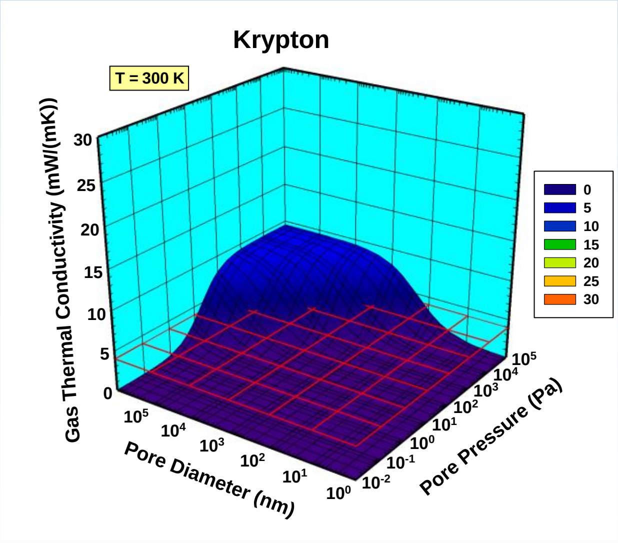
Gas Thermal Conductivity

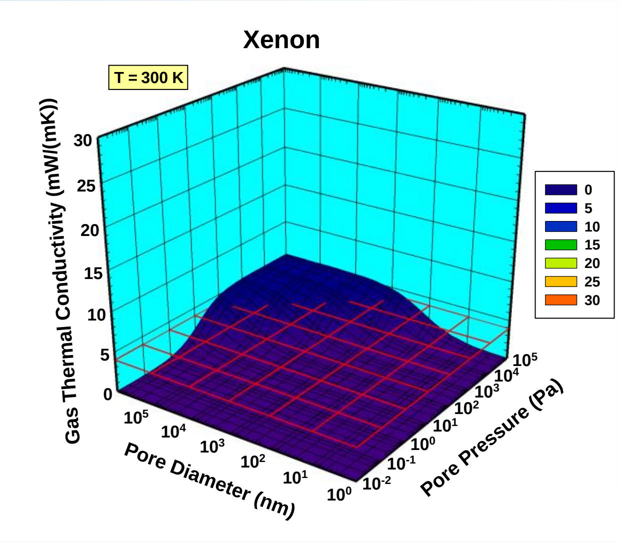


Gas Thermal Conductivity









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?***

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

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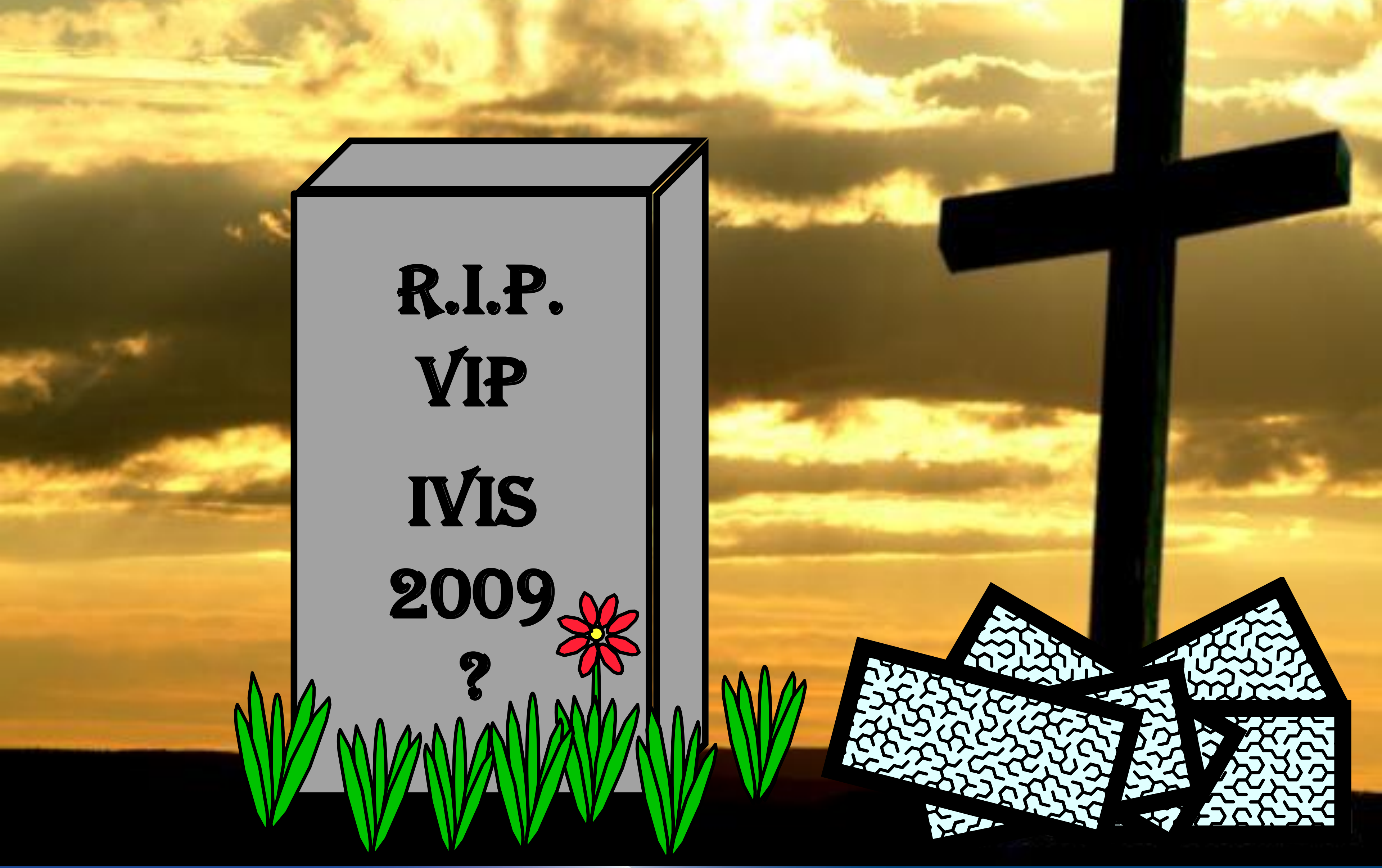
Thermal Insulation Materials and Solutions	Low Pristine Thermal Conductivity	Low Long-Term Thermal Conductivity	Perforation Robustness	Possible Building Site Adaption Cutting	A Thermal Insulation Material and Solution of Tomorrow ?
Traditional					
Mineral Wool and Polystyrene	no	no	yes	yes	no
Todays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

Conclusions

- Beyond the state-of-the-art of today
- New concepts have been introduced
  - Vacuum Insulation Materials (VIM)
  - Gas Insulation Materials (GIM)
  - Nano Insulation Materials (NIM)
  - Dynamic Insulation Materials (DIM)
- Fundamental theoretical studies - basics of thermal conductance
- Requirements of the future high performance thermal insulation materials and solutions have been proposed
- NIMs seem to represent the best high performance low conductivity thermal solution for the foreseeable future
- DIMs have great potential due to their controllable thermal insulating abilities

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

Sunset...



Sunrise…
and the Phoenix rises again…!