# Interactions between barrier envelopes and core material for service life assessment

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# Introduction

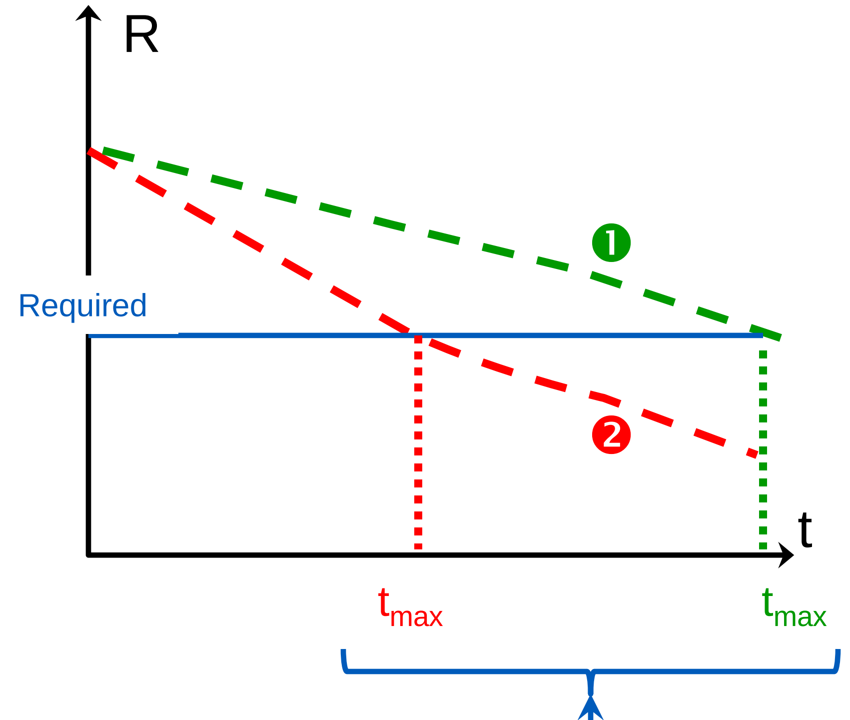
Applications

❶ T, HR

❷ T, HR

$P_{in}$ ↑

$\lambda_{cs}$ ↑




Core material

Barrier envelope

# Outline

- Operating conditions
  - Loading conditions in buildings
  - Severity indexes

This communication:
• Stationary conditions (or pseudo stationary)
• Regular ageing

- Interactions between core and envelope
  - Simple models available
  - Evaluation of life time: examples of methods
  - Simplified expressions of life time

- Conclusions and outlook

# Operating conditions in buildings 1/6

- Exposure conditions depend on applications, climatic zone, face, season and chosen time step
  - Example of a mean case in France with the whole year divided in 4 unequal periods

| | MAXIMUM service conditions | | | | | | | | | | | | NOMINAL service conditions | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Period 1 | | | | | | Period 2 | | | | | | Period 3 | | | | | | Period 4 | | | | | |
| | | | Hot face | | Cold face | | | | Hot face | | Cold face | | | | Hot face | | Cold face | | | | Hot face | | Cold face | |
| | Max. service cond. | | | | | | | | | | | | | | | | | | | | | | | |
| *APPLICATIONS* | **Duration (day/year)** | **Season** | **T(°C)** | **HR (%)** | T(°C) | HR (%) | Duration (day/year) | Season | T(°C) | HR (%) | T(°C) | HR (%) | Duration (day/year) | Season | T(°C) | HR (%) | T(°C) | HR (%) | Duration (day/year) | Season | T(°C) | HR (%) | T(°C) | HR (%) |
| ***Internal ins. of wall & floor*** | **30** | **H** | **30** | **60** | 25 | 80 | 30 | QH | 30 | 50 | 25 | 65 | 210 | C | 20 | 65 | 10 | 50 | 95 | I | 22 | 65 | 16 | 50 |
| ***Heating floor (wet sceed)*** | **10** | **VC** | **50** | **90** | 20 | 65 | 200 | C | 30 | 50 | 20 | 65 | 60 | H | 25 | 50 | 25 | 65 | 95 | I | 22 | 65 | 16 | 50 |
| ***Heating floor (dry sceed)*** | **10** | **VC** | **50** | **50** | 20 | 65 | 200 | C | 30 | 50 | 20 | 65 | 60 | H | 30 | 50 | 25 | 65 | 95 | I | 22 | 65 | 16 | 50 |
| ***Rendered ext. ins. & ventilated roof*** | **5** | **H+R** | **70** | **70** | 25 | 80 | 25 | H+S | 70 | 10 | 25 | 65 | 210 | C | 20 | 65 | 10 | 80 | 125 | I | 22 | 65 | 16 | 80 |
| ***Sandwich panel and classical door*** | **5** | **H+R** | **70** | **30** | 25 | 80 | 25 | H+S | 70 | 10 | 25 | 65 | 210 | C | 20 | 65 | 10 | 50 | 125 | I | 22 | 65 | 16 | 50 |
| ***Wood sandwich panel & door*** | **5** | **H+R** | **50** | **80** | 25 | 80 | 25 | H+S | 50 | 25 | 25 | 65 | 210 | C | 20 | 65 | 10 | 50 | 125 | I | 22 | 65 | 16 | 50 |
| ***Cladding, roller shutter box*** | **5** | **H+R** | **40** | **50** | 25 | 80 | 25 | H+S | 35 | 55 | 25 | 65 | 210 | C | 20 | 65 | 10 | 50 | 125 | I | 22 | 65 | 16 | 50 |
| ***Roof terrace balcony*** | **20** | **H+S** | **70** | **95** | 25 | 80 | 40 | H | 45 | 95 | 25 | 65 | 210 | C | 20 | 65 | 10 | 50 | 95 | I | 22 | 65 | 16 | 50 |
| ***Domestic hot water tank*** | **60** | **H** | **60** | **10** | 28 | 65 | | | | | | | 210 | C | 60 | 10 | 20 | 50 | 95 | I | 60 | 10 | 22 | 50 |
| ***Refrigerator*** | **60** | **H** | **28** | **55** | 6 | 90 | | | | | | | 210 | C | 20 | 65 | 10 | 50 | 95 | I | 22 | 65 | 16 | 50 |

H = hot, QH = quite hot, C = cold, VC = very cold, R = rain, S = sun, I = intermediate

Values from: [B. Yrieix et al. Rapport final du projet ADEME PREBAT "Barisol" (2010)], * [S. Brunner and H. Simmler In situ performance assessment of vacuum insulation panels in a flat roof construction, Vacuum 82 (2008) 700–707 ], and present work

# Operating conditions in buildings 2/6

- Zoom on the hotest period

| APPLICATIONS | Max. service cond. Duration (day/year) | Season | T(°C) | HR (%) |
|---|---|---|---|---|
| *Internal ins. of wall & floor* | 30 | H | 30 | 60 |
| *Heating floor (wet sceed)* | 10 | VC | 50 | 90 |
| *Heating floor (dry sceed)* | 10 | VC | 50 | 50 |
| *Rendered ext. ins. & ventilated roof* | 5 | H+R | 70 | 70 |
| *Sandwich panel and classical door* | 5 | H+R | 70 | 30 |
| *Wood sandwich panel & door* | 5 | H+R | 50 | 80 |
| *Cladding, roller shutter box* | 5 | H+R | 40 | 50 |
| *Roof terrace balcony* | 20 | H+S | 70 | 95 |
| *Domestic hot water tank* | 60 | H | 60 | 10 |
| *Refrigerator* | 60 | H | 28 | 55 |

**Season**

H Hot

VC Very cold

R Rain

S Sun

1st severity criterion = T
linked risk of envelope degradation

# Operating conditions - Severity indexes 3/6

- For each gas (water vapour and dry air)
  - General expression of the incoming flux:

$$\Phi = \Delta P.A.t.\Pi \qquad \text{With} \qquad \Pi = \Pi_0 . e^{-\frac{Q_\delta}{RT}} \qquad \text{Eq. 1-2}$$

  - Derivate severity indexes:
    - Water

$$SI_W = \sum_{f=1}^{2} \sum_{i=1}^{4} \boxed{P_{w\,f,i} . t_i . e^{\frac{\boxed{-Q_{\delta W}}}{RT_{f,i}}}} \qquad \text{Eq. 3}$$

2 faces, 4 periods

Terms **P, t, T** depend on the **application**

Terms $\boldsymbol{Q_\delta}$ activation energies of permeation linked to the **envelope**

    - Air

$$SI_a = \sum_{f=1}^{2} \sum_{i=1}^{4} \boxed{P_a . t_i . e^{\frac{\boxed{-Q_{\delta a}}}{RT_{f,i}}}} \qquad \text{Eq. 4}$$

# Operating conditions - Severity indexes 4/6

- Result for water vapour (Using $Q_{\delta\,w}$ = 26 kJ/mol/K)*
  Without any additional protection

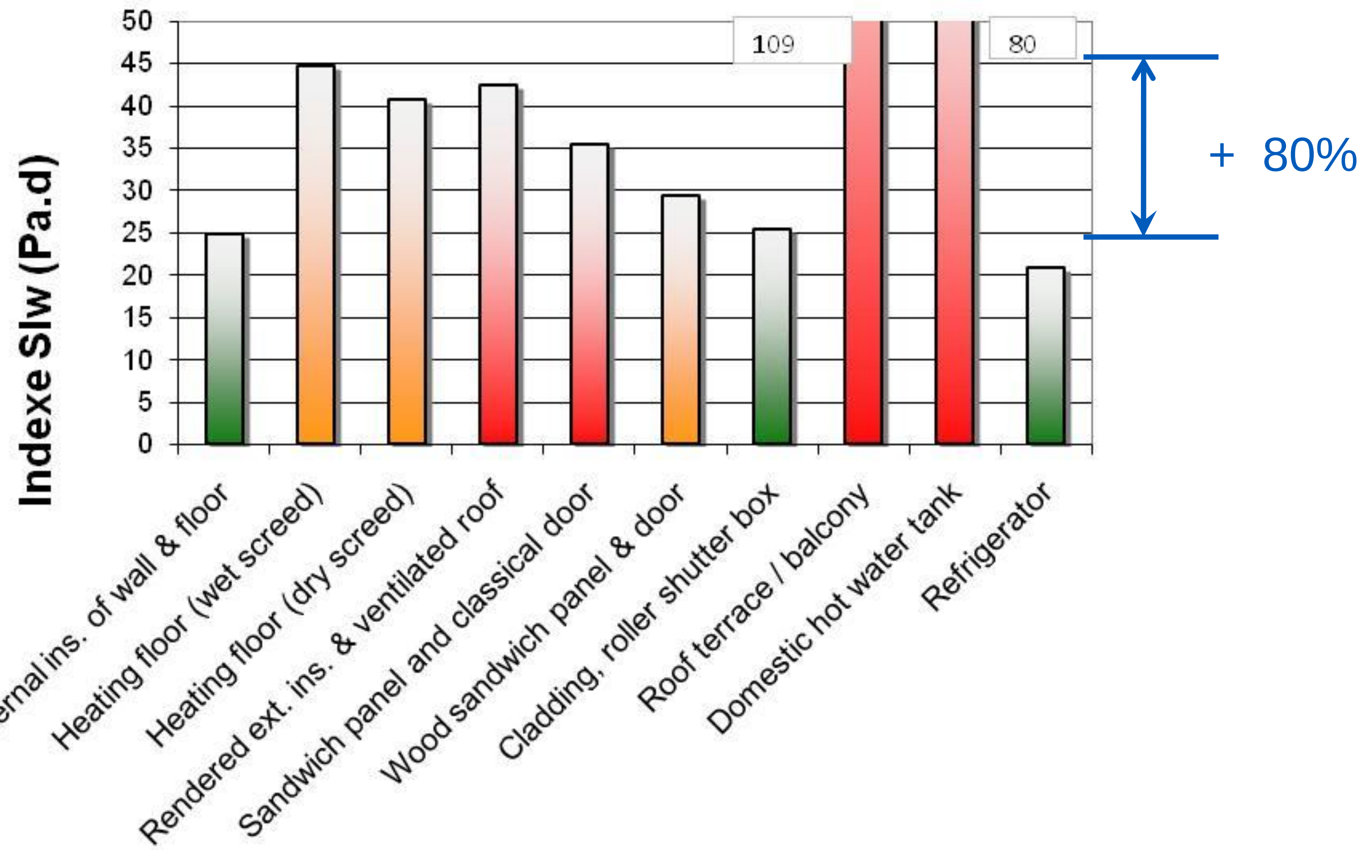
* [L. HEYMANS et al, IVIS (2013)]

$T_{U\,maxi}$ (°C)

> 50

40 to 50

≤ 40

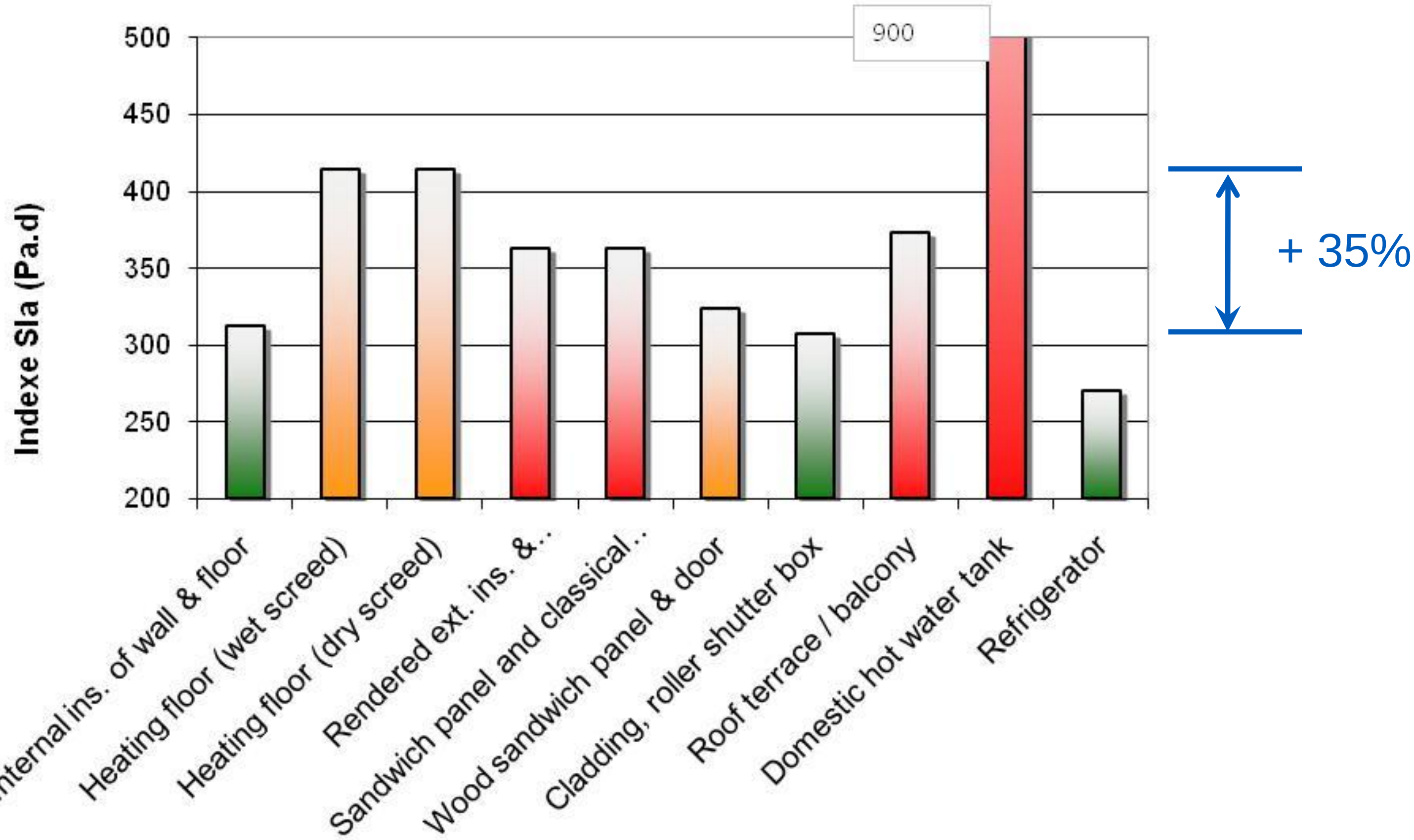


# Operating conditions - Severity indexes 5/6

- Result for dry air (Using $Q_{\delta\ a}$ = 30 kJ/mol) *
  Without any additional protection

*28 kJ/mol [Schawb et al. J. *Thermal Envelope and Building Science*, 28(4):293–317, avril 2005]

| $T_{U\ maxi}$ (°C) |
|---|
| > 50 |
| 40 to 50 |
| ≤ 40 |



# Operating conditions – Conclusion 6/6

- Three criteria can be used for evaluating the severity of an application:
  - Maximum temperature
  - Water vapour permeation severity index
  - Air permeation severity index

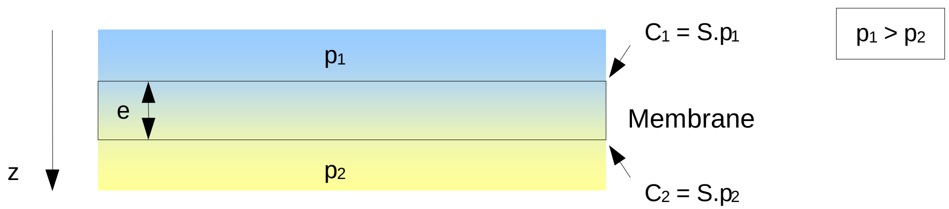
- Most severe applications:
  - Domestic hot water tank
  - Roof terrace balcony

- The difference between applications is more pronounced for water vapour than for air

# Interactions core / envelope 1/6

- Physical models involved - **Barrier envelope permeance**

  - **"Solution - Diffusion"**




$$J = \langle v \rangle . X = \left( \frac{D}{k.T} \right) . F . X \qquad F = -\left( \frac{\partial \mu}{\partial z} \right) = -\left( \frac{\partial \mu}{\partial X} \frac{\partial X}{\partial z} \right) \qquad \mu_s = \mu_g = \mu^0 + k.T.\ln\left( \gamma \frac{X}{X^0} \right) \qquad \gamma = 1$$

Eq. 5-8

$$X = S.P$$

Henry's law (s = f(T), constant with RH)

Eq. 9

$$\boxed{J_D = \frac{D.S}{e}\left(P_1 - P_2\right)} \qquad \boxed{\delta = D.S} \qquad \boxed{\Pi = \frac{\delta}{e}}$$

Eq. 10-12

# Interactions core / envelope 2/6

## Physical models involved - **Barrier envelope permeance**

- No coupled effect between gases

(For other approach see [M. Bouquerel, PhD thesis (2012)])

- **Thermo activation**

$$\delta = \delta_0 . e^{-\frac{Q_\delta}{RT}} = D_0 . e^{-\frac{Q_D}{RT}} . S_0 . e^{-\frac{Q_S}{RT}} \quad \text{Eq. 13}$$

- Plasticizing effect

$$\delta = \delta_{(T)} . e^{\eta . X_W} = \delta_{(T)} . e^{\eta . S . P_{sat} . RH} \quad \text{Eq. 14}$$

- **"Ideal stacking multilayer"**

$$\Pi = \frac{1}{\sum_{j=1}^{n} \frac{1}{\Pi_j}} \quad \text{Eq. 15}$$

- Finally for *n* identical layers:

Eq. 16

$$\Pi = \frac{1}{n.x} \delta_0 . e^{-\frac{Q_\delta}{RT}} . e^{\eta . X_W} = \frac{1}{n.x} D_0 . e^{-\frac{Q_D}{RT}} . S_0 . e^{-\frac{Q_S}{RT}} . e^{\eta . S . P_{sat} . RH}$$

# Interactions core / envelope 3/6

- Physical models involved - **Core material conductivity**
  - General assumption

$$\lambda = \lambda_r + \lambda_{cs} + \lambda_{cg}$$ Eq. 17

Radiativity (IR radiation)

$$\lambda_r = \frac{16}{3}\frac{\sigma T^3}{E}$$ Eq. 18

Gaseous conductivity

(Bimodal pore size distribution)

$$\lambda_{cg} = \lambda_{cg\,0}\left(\frac{1}{1+\frac{CT}{\phi_1 . P_g}} + \frac{1}{1+\frac{CT}{\phi_2 . P_g}}\right)$$ Eq. 19

[A. Rigacci, PhD thesis (1997)]

# Interactions core / envelope

- Physical models involved – **Core material conductivity**
  - Consequences of **incoming water and air**

Solid contribution of water

Gaseous contribution of air and water (air generally dominant)

$$\lambda = \lambda_r + (\lambda_{cs0} + B.\tau_W) + \left( \frac{\lambda_{a0}}{1 + \frac{C_a.T}{\phi.P_a}} + \frac{\lambda_{W0}}{1 + \frac{C_w.T}{\phi.P_w}} \right) \qquad \text{Eq. 20}$$

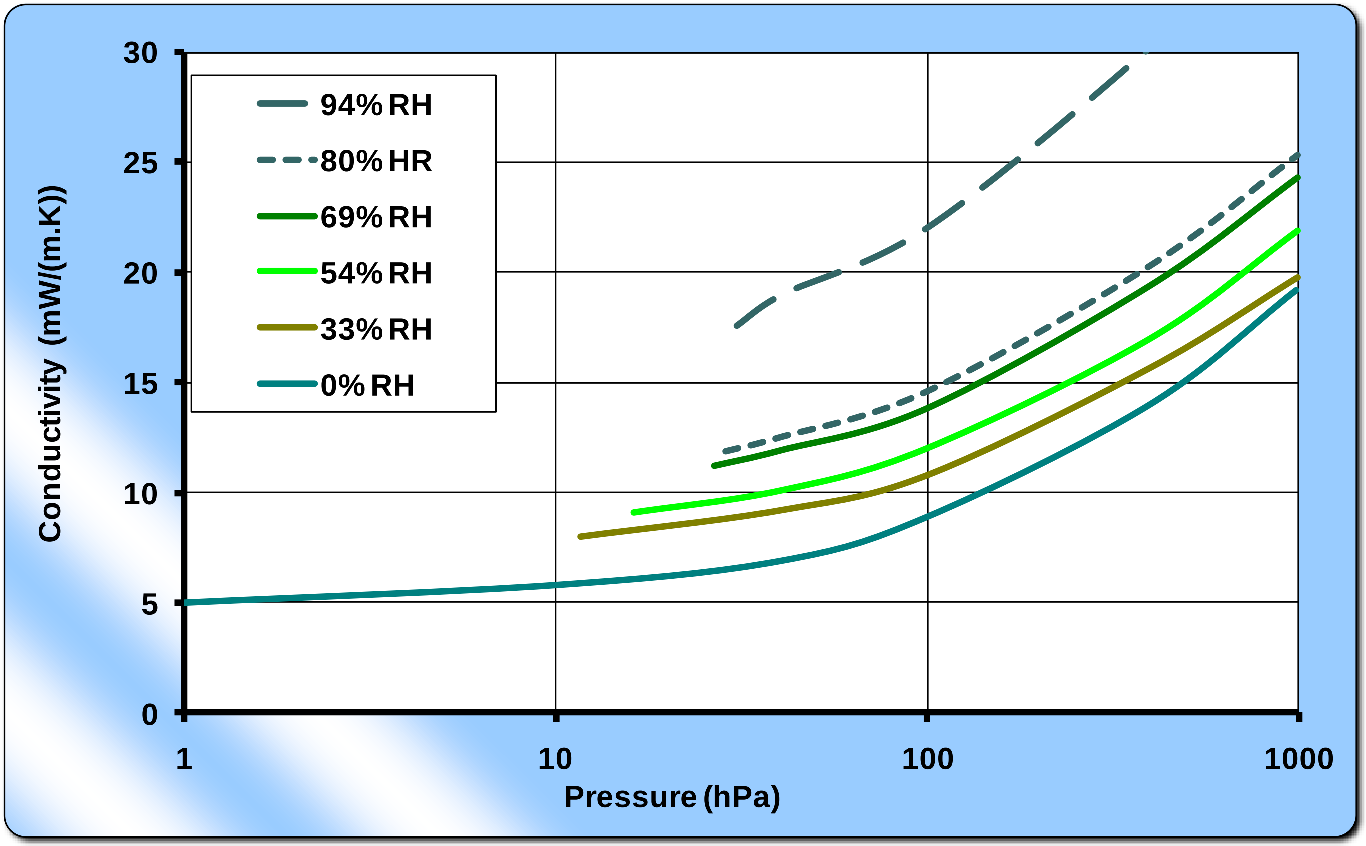
**Influence usually taken into account**

* [J. FRICKE et al. Int. J. of Thermophysics, 27(4):1123–1139, (2006)]

# Interactions core / envelope 5/6

- Physical models involved - **Core material conductivity**

  - Coupled effects of pressure and humidity on core conductivity

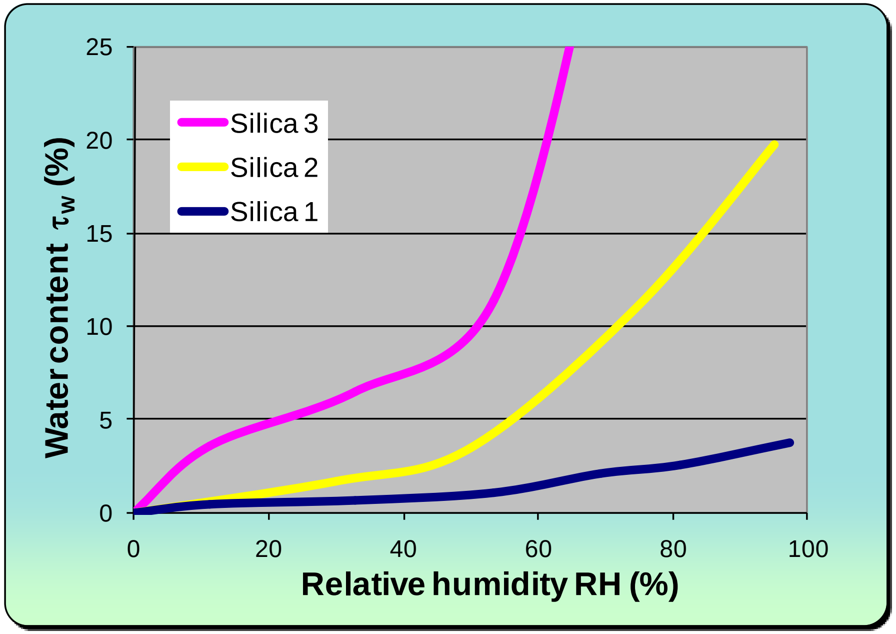


# Interactions core / envelope 6/6

- Physical models involved - **Core material sorption**

$$\tau_W = \frac{RH}{A.RH^2 + B.RH + C}$$ Eq. 21

[K. Kumaran, IEA, 1996]




or one of the many models of isotherm reported in the literature

Only required: it has to fit well with the real core behaviour

Caution: silicas age in VIP during use as well as during characterization by methods that are not suitable [B. MOREL, IVIS 2013]

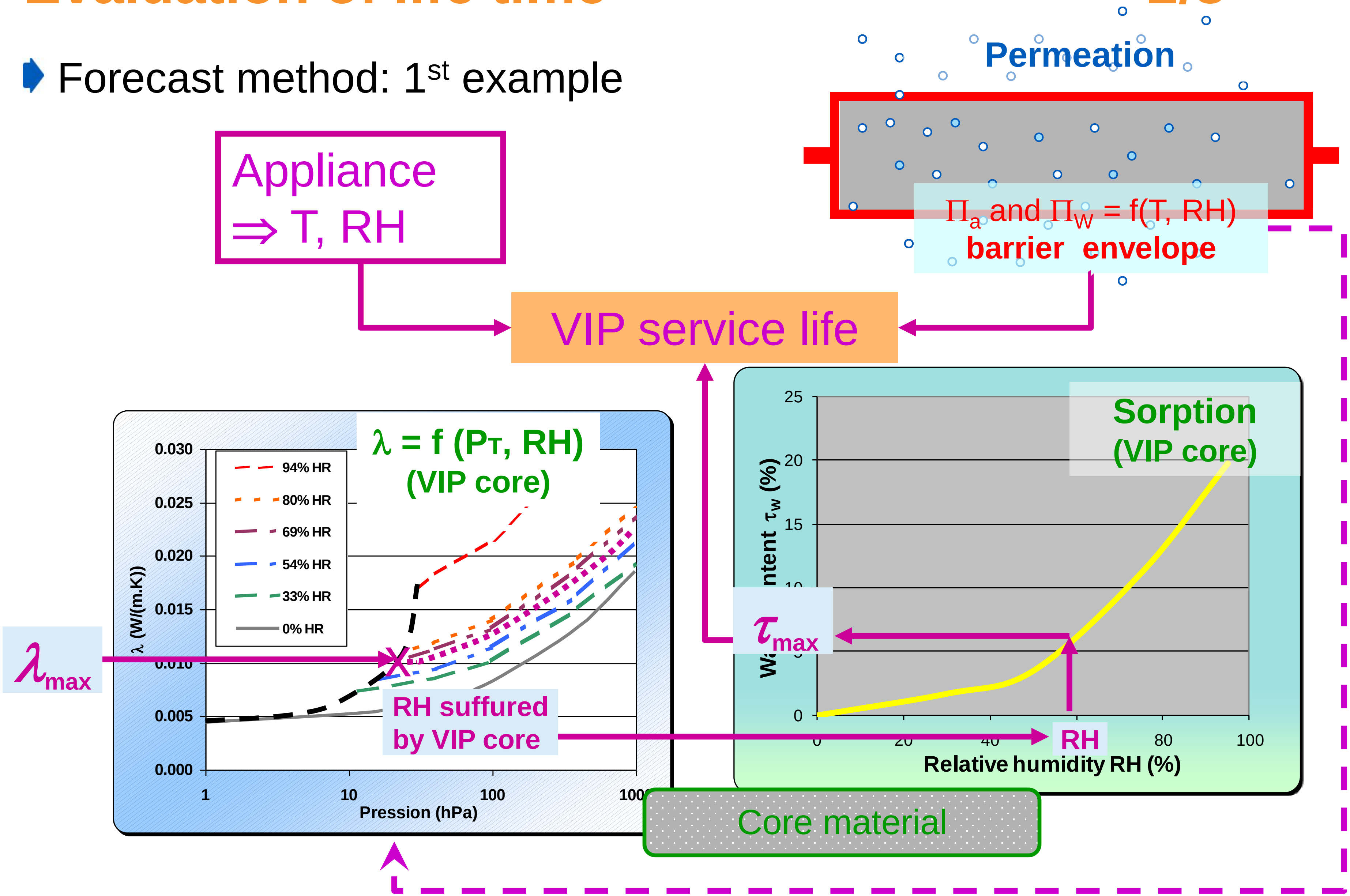
# Evaluation of life time 1/8

- Many methods exists!
  They can be classified according to different criteria
  - From global approach to step by step approach
  - With one or two gases
  - With coupled effect between gases or not
  - More or less physical or empirical
  - With ageing of the core material or not
  - With ageing of the envelope or not
  - Stationary sequences or actual dynamics
  - …

# Evaluation of life time

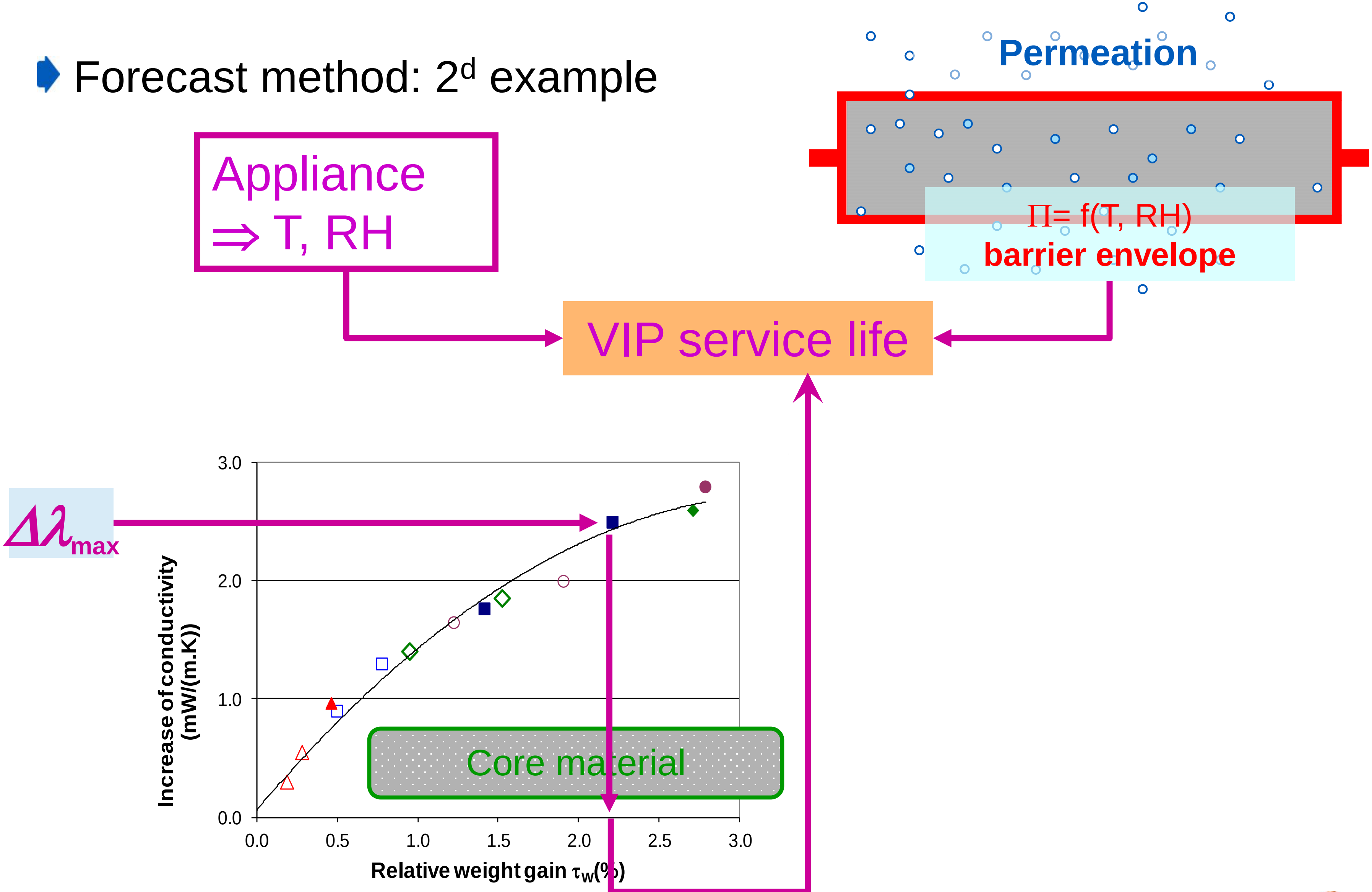


- Forecast method: 1st example



# Evaluation of life time 3/8

- Forecast method: 2[d] example



# Evaluation of life time 

- Forecast method: 3rd example

- Conductivity

$$\lambda = \underset{\text{Initial}}{\lambda_0} + \underbrace{B.\tau_W}_{\text{water impact}} + \underbrace{C.P_a}_{\text{air impact}} \qquad \text{Eq. 22}$$

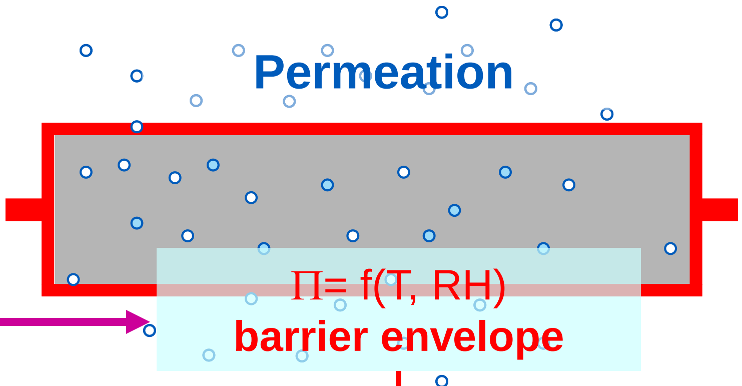
- Kinetic

$$\lambda_{(t)} = \lambda_0 + B \cdot \tau_{W,\infty}\left(1 - e^{\frac{-t.\Delta m_{W(t)}}{\tau_{W,\infty}}}\right) + C \cdot \Delta Pa_{(t)} \cdot t \qquad \text{Eq. 23}$$

# Evaluation of life time 4/8

- Forecast method: 3rd example

Appliance
⇒ T, RH




- Conductivity

$$\lambda = \lambda_0 + B.\tau_W + C.P_a$$ Eq. 22

Core material

- Kinetic

$$\lambda_{(t)} = \lambda_0 + B\cdot\tau_{W,\infty}\left(1 - e^{\frac{-t.\Delta m_{W(t)}}{\tau_{W,\infty}}}\right) + C\cdot\Delta Pa_{(t)}\cdot t$$ Eq. 23

# Service life of VIP



- Forecast method: 4th example
  **Lump sum assessment**

Laboratory test

$T^{\text{high}}$, $RH^{\text{high}}$, $t_{\text{short}}$

Service conditions

$T_{\text{low}}$, $RH_{\text{lower}}$, $t^{\text{long}}$

What conditions?

Same test for each application?

How representative?

e.g. 80°C > $T_{g\ PET}$

Micro condensation over 90%RH

Hydrolysis of PET and adhesive at high T and RH

# Evaluation of life time 6/8

## Simplified assessment of $t_{max}$ corresponding to $\lambda_{max}$

- Permeation $$\Phi_j = \Delta P_j .2At.\Pi_j$$ Eq. 1
- Increase of core conduction conductivity $$\Delta\lambda = \Delta\lambda_{cs,W} + \Delta\lambda_{cg,a}$$ Eq. 24

- for **vapour** permeation: the life time is reached when $\boldsymbol{\tau_{max}}$ **is reached**

$$m_{W,\max} = \Delta P_W .2At_{W,\max} .\Pi_W \qquad \tau_W = \frac{m_W}{A.x.\rho + m_W}$$ Eq. 25-26

- for **air** permeation: the life time is reached when $\boldsymbol{P_{max}}$ **is reached**

$$m_{a,\max} = P_{a,atm} .2At_{a,\max} .\Pi_a \qquad \lambda_{g,\max} = \frac{\lambda_{a,Patm}}{1 + \dfrac{C_a .T}{\phi .P_{a,\max}}}$$ Eq. 27-28

# Evaluation of life time 7/8

- Simplified assessment of $t_{W,max}$ (from **vapour** permeation)

$$t_{W,\max} = \frac{1}{P_W} . x . \frac{\tau_{\max}}{1-\tau_{\max}} . \rho . \frac{1}{\Pi_W} \cdot \frac{1}{2} \quad \text{Eq. 29}$$

- Parameters
  - Environment
    - $P_W$ = f(T, RH) vapour pressure (temperature, relative humidity)
  - VIP
    - x Thickness
  - Core
    - $\tau_{max}$ maximum humidity content (deduced from $\lambda_{max}$, maximum acceptable conductivity)
    - $\rho$ core density
  - Multilayer film
    - $\Pi$ permeance

# Evaluation of life time 8/8

## Simplified assessment of $t_{a,max}$ (from **air** permeation)

$$t_{a,\max} = \frac{1}{P_{atm}} . x . \frac{\lambda_{g\max}}{\lambda_{g,Patm} - \lambda_{g\max}} . \frac{1}{\phi} . \frac{1}{\Pi_a} . \frac{C.M_a}{2R}$$

Eq. 30

- Parameters
  - Environment
    - $P_{air}$ or $P_{O2}$
  - VIP
    - x Thickness
  - Core
    - $\lambda_{g\ max}$ maximum admissible gaseous conductivity (deduced from $\lambda_{max} = \lambda_r + \lambda_s + \lambda_{g\ max}$ )
    - $\phi$ pores size
  - Multilayer film
    - $\Pi$ permeance

# Conclusions …

- Common applications of VIPs in buildings are **± 40 %** severe with respect to ageing
  (without considering both extremes and without corrective measures)

- Four components should be considered with regard to life time:
  - barrier envelope
  - core material

  interact with

  - service conditions
  - thickness of the panels

- Any assessment method of life time or declared resistance or conductivity must take into account the reality / contribution of these **four** components

# … and outlook

- For cyclic climatic loads we need more accurate models and physical data

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# BACKUP

# Definitions

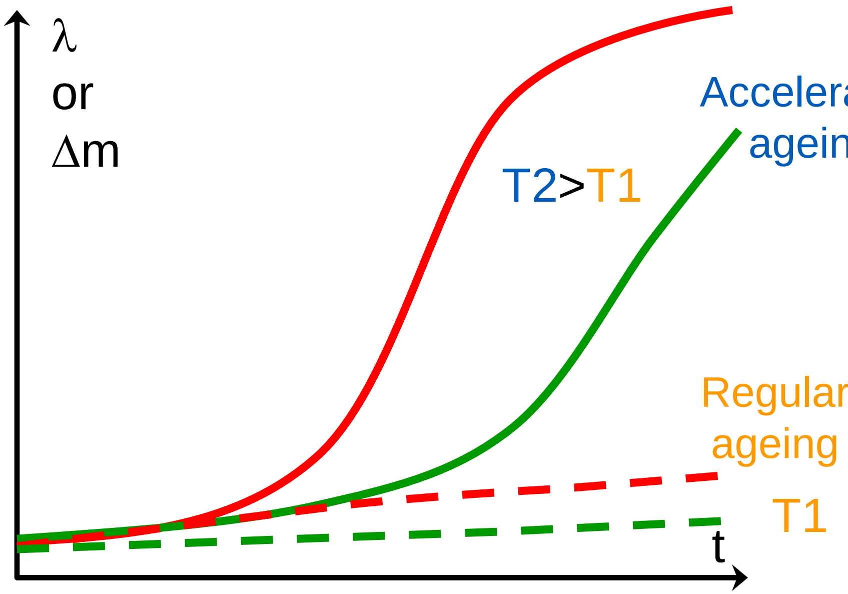
- Life expectancy, time or duration
  - Time for the thermal resistance to drop below the required minimum

- Ageing
  - Mechanism(s) of the chemical and physical modification(s)
  - Kinetic(s) of the mechanism(s)

- Durability
  - Ability at the time to insulate at the required level

# Type of ageing presently studied

## Ageing of VIP




## Ageing of barrier laminate

Delamination
⇔ T

Corrosion
⇔ RH

Limit depend on the product and batch

No ageing
*(permeance point of view)*

- Based on:
  - 10 different commercial laminates
  - Over 400 measurements
  - 4 different aging conditions
  - Up to 28 month duration

[ G. Garnier, PhD thesis. Institut Polytechnique de Grenoble (2009)]
[B. Yrieix et al. Rapport final du projet ADEME PREBAT "Barisol" (2010)]

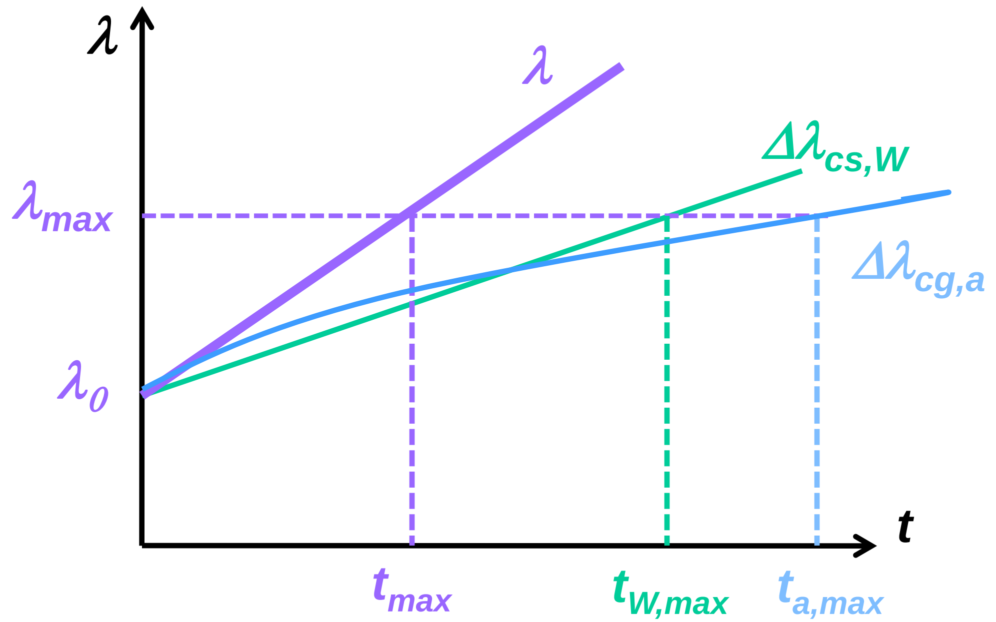
# Evaluation of life time

- Simplified assessment of $t_{max}$ (from **vapour** and **air** permeation)
  - Based on equations slide 22

$$\Delta\lambda = \Delta\lambda_{cs,W} + \Delta\lambda_{cg,a}$$ Eq. 31

$$\Delta\lambda_{cs,W} = \frac{2P_W.\Pi_W}{x.\rho}.B.t$$ Eq. 32

$$\Delta\lambda_{cg,a} = \frac{\lambda_{g0}}{1+\dfrac{C.M_a.x}{2\phi.P_{atm}.R.\Pi_a.t}}$$ Eq. 33



# Definitions

| **Variables** | | $X$ | Concentration |
|---|---|---|---|
| $A$ | Area | $\lambda$ | Conductivity |
| $B$ | Conductive impact of moisture | $\Phi$ | Flux |
| $D$ | Diffusion coef. | $\rho$ | Density |
| $M$ | Molecular mass | $\delta$ | Permeability |
| $m$ | Mass | $\Pi$ | Permeance |
| $n$ | Number of layer | $\eta$ | Plastisizing coef. |
| $P$ | Pressure | $\phi$ | Pores size |
| $Q$ | Activation energy | $\tau$ | Mass humidity |
| $RH$ | Relative humidity | $\Delta$ | Variation, gradient |
| $S$ | Solubility coef. | **Constants** | |
| $t$ | Time, duration | C | Gas constant in Knudsen's relation |
| $T$ | Temperature | R | Gas constant |
| $x$ | Thickness | | |

| **Indices** | | $_r$ | radiative |
|---|---|---|---|
| $_a$ | air | $_s$ | Solubility |
| $_{cg}$ | Gazeous conduction | $_{max}$ | Maximum or end of life |
| $_{cs}$ | Solid conduction | $_u$ | Use |
| $_D$ | Diffusion | $_w$ | Water |
| $_f$ | Face | $_0$ | Reference or Initial |
| $_g$ | Gas | $_\delta$ | Permeability |
| $_i$ | Period | | |