Aging and Service Life of VIP in Buildings

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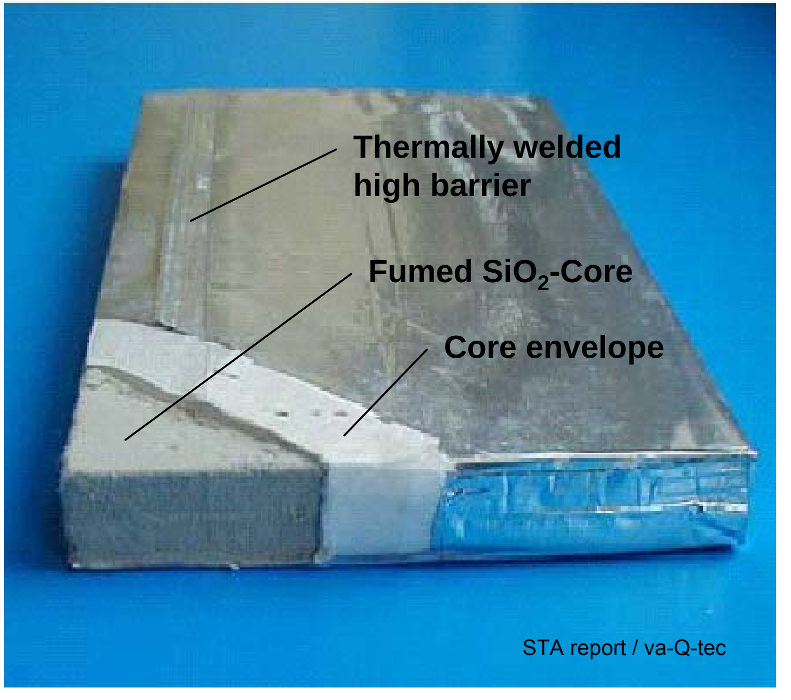
Content

- Introduction
- Core material
- Barrier materials
- Panel aging by permeation
- Aging under dynamic conditions
- Summary / outlook

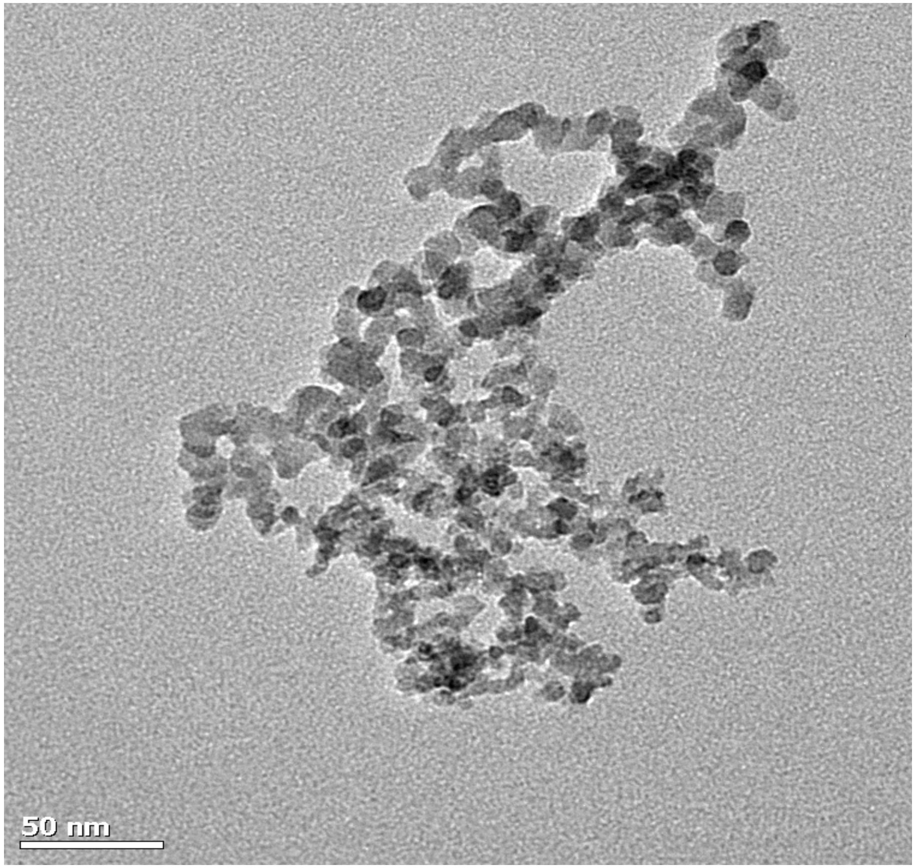
Introduction / Vacuum Insulation Panel (VIP)



Introduction / Typical Application in Switzerland

- Flat roof insulation in terrace or penthouse buildings

Core material / Nano-structured fumed silica



TEM Empa

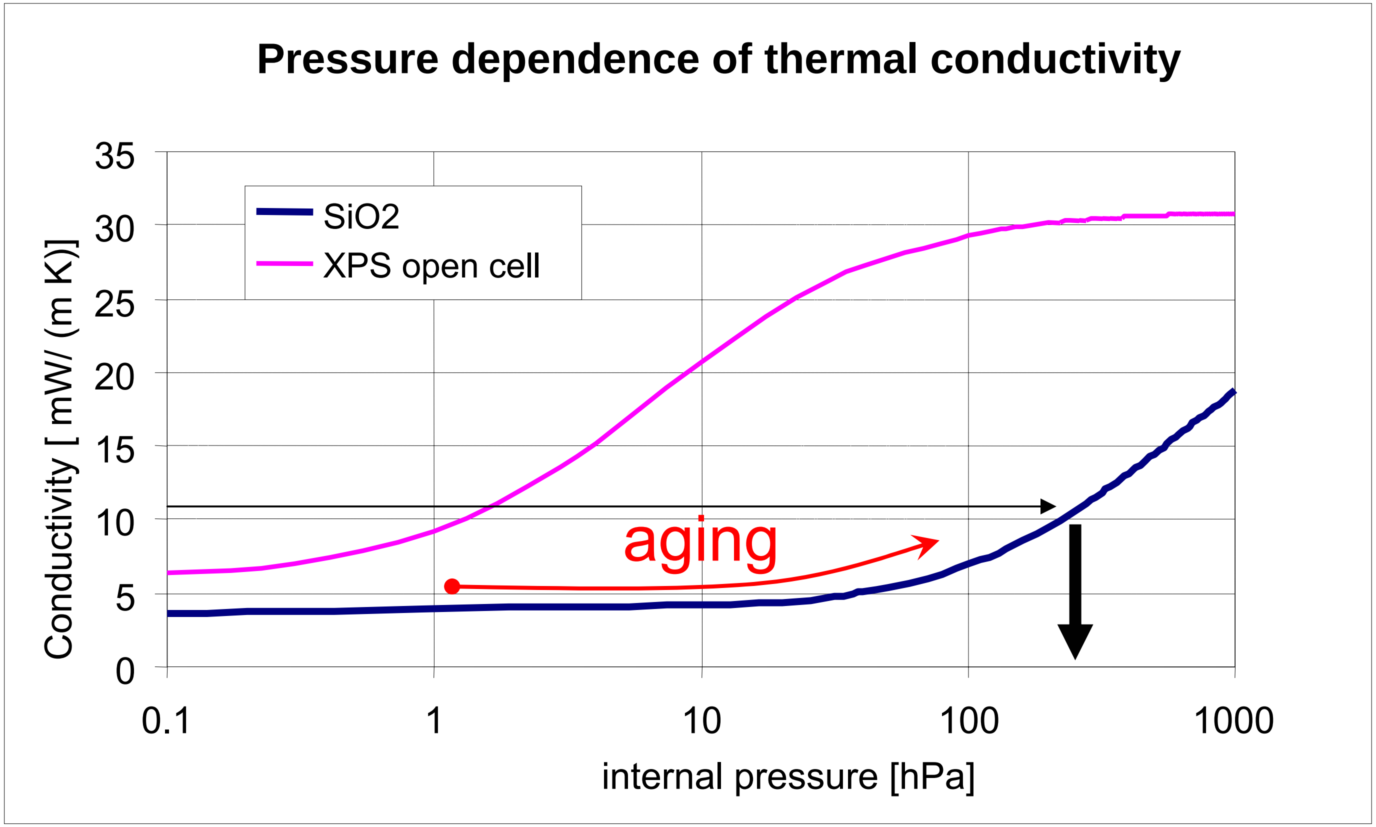
Fumed silica / Typical properties

- Results from IEA Annex 39 Subtask A (CSTB, ZAE Bayern)

Property	Unit	Value
Density (compressed)	kg/m^3	160 – 220
Porosity	%	90 – 95
Specific area	m^2/g	200 – 220
Pressure at 10% compression (23°C, 50 % r.F.)	kPa	90 – 120
Thermal conductivity (10°C, dry, $p_i < 5$ mbar)	10^{-3} W/(m K)	4 – 5
Heat capacity (0 to 150°C)	J/(kg K)	800 – 900
Slope of sorption isotherm $dX_w / d\varphi$ ($u_m < 8$ %-mass)	%-mass / 100% r.h.	7 - 8

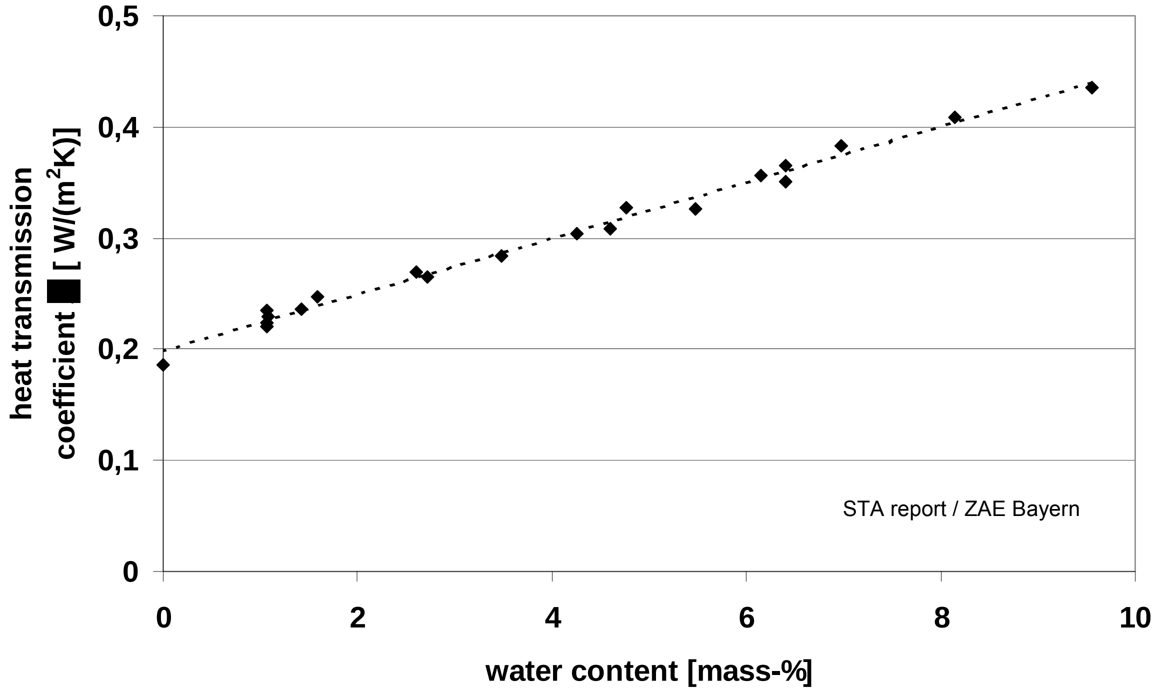
Fumed silica / Thermal conductivity

- Pressure dependence of the thermal conductivity



Fumed silica / Thermal conductivity

- Moisture dependence of the thermal conductivity



Fumed silica / Thermal conductivity

- Approximation for pressure and moisture content dependence of the thermal conductivity (up to 100 mbar, constant climate conditions)

$$\boxed{\Delta\lambda(t) \cong 0.035 \frac{10^{-3} W}{m\,K\,mbar}\, p_i(t) + 0.50 \frac{10^{-3} W}{m\,K\,\% - mass}\, X_w(t)}$$

with $p_i(t) \approx \dot{p}_i \cdot t$

$$X_w(t) \approx X_{w,equilibrium} + (X_{w0} - X_{w,equilibrium}) \exp(-t/\tau)$$

$$X_{w,equilibrium} \approx \left(8\,\% - mass \,/\, 100\%\ r.h.\right) \cdot \varphi$$

$$\tau = X_{w,equilibrium} \Big/ \dot{X}_{w,start}$$

- Wanted: Increase rates $\dot{p}_i\,[mbar/yr],\ \dot{X}_w\,[\% - mass/yr]$

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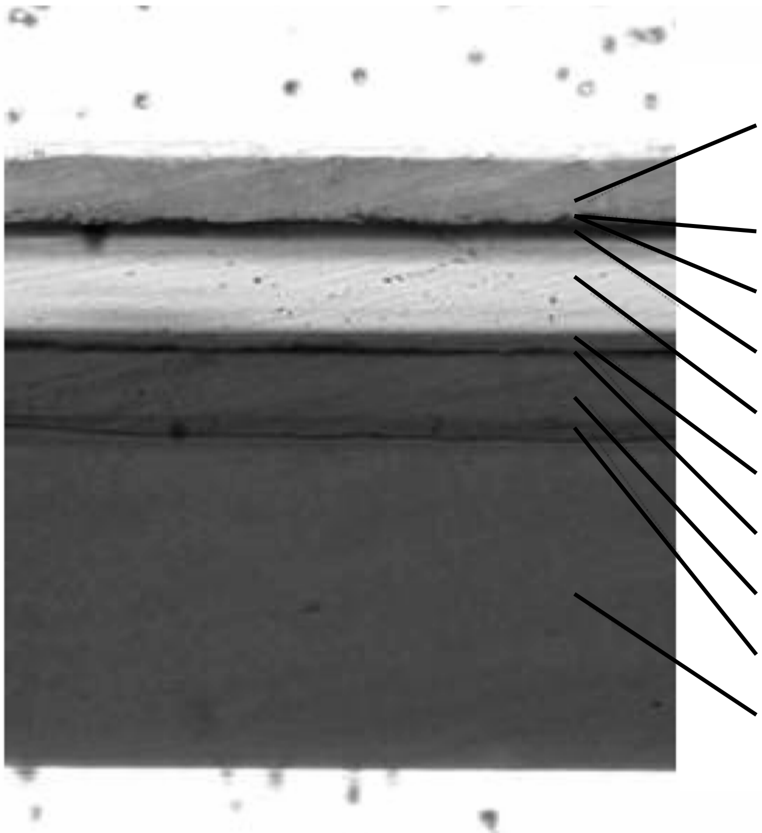
Barrier materials / Laminate composition

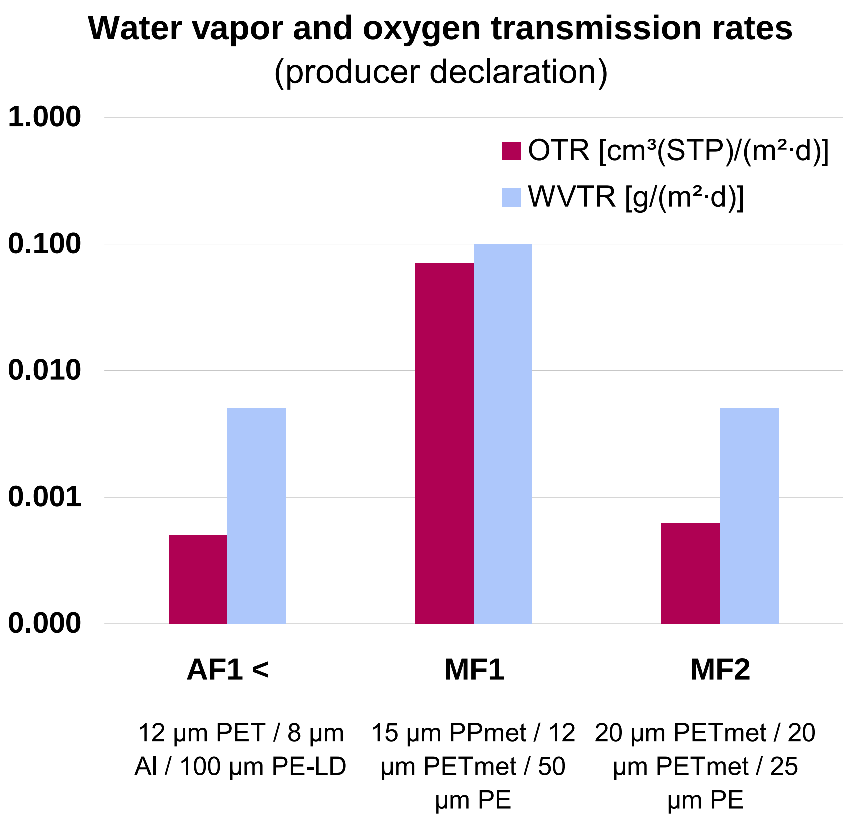
- Example: 3-fold metallised polymer laminate



Layer #	Material	Function	Thickness
1	PET	Protecting layer (substrate for 2)	12 µm
2	ALU	Barrier layer	30 nm
3	PUR	Glue	2 µm
4	ALU	Barrier layer	30 nm
5	PP	Substrate for 4	18 µm
6	PUR	Glue	2 µm
7	ALU	Barrier layer	30 nm
8	PET	Substrate for 7	12 µm
9	PUR	Glue	2 µm
10	PE-LD	Sealing layer	60 µm

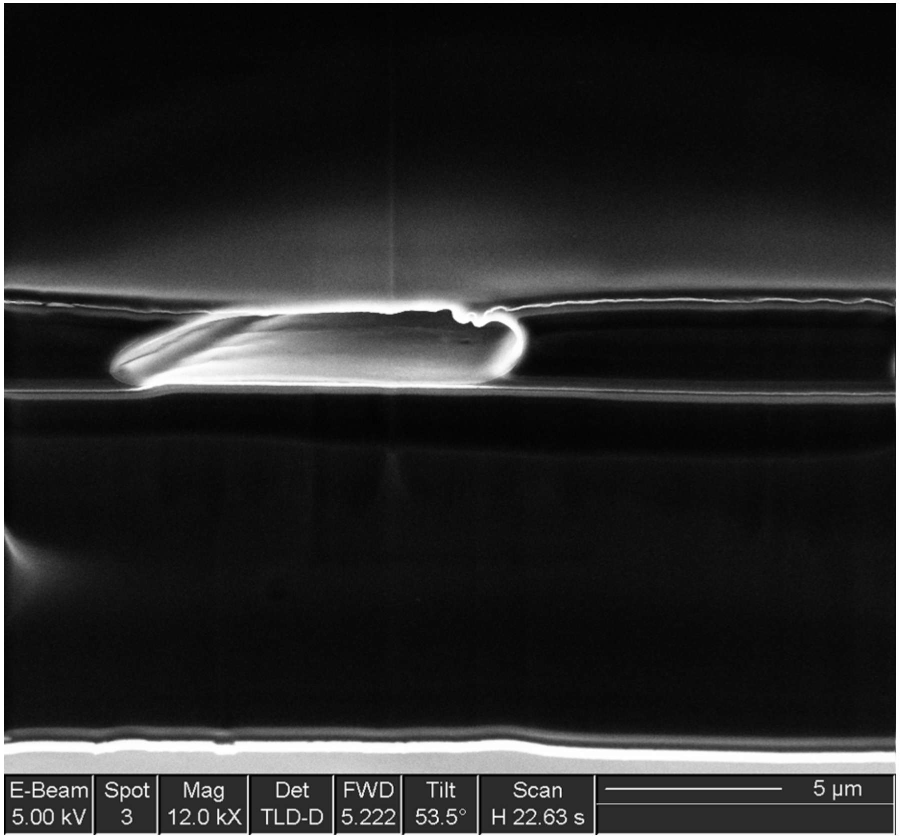
Barrier materials / Permeation rates

- Laminates: Al-foil (AF1), metallised polymer films (MF1, MF2)



Barrier materials / Defects

- Example: Gas bubble in PU layer (FIB Empa)



Vertical scale = 0.78 x horizontal

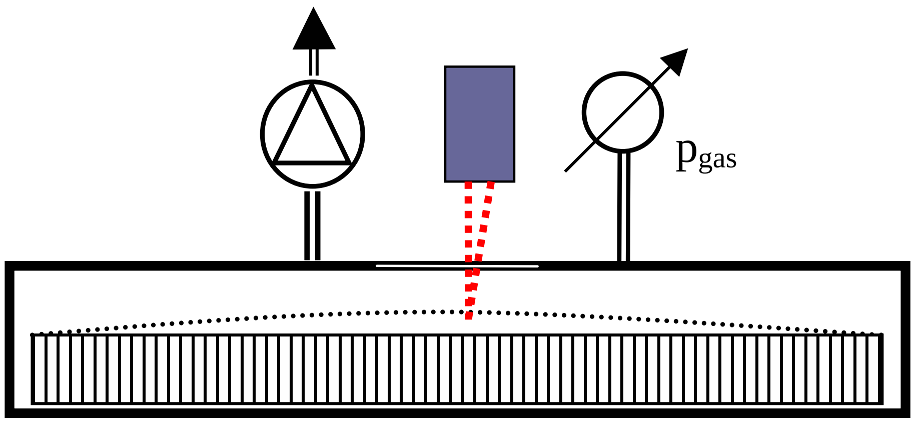
Barrier materials / Potential aging mechanisms

- Aluminium coating
  - Oxidation at high humidity + temperature (80 % r.h., 80°C)
  - pH-values: to be limited between 3 and 8.5
- PU adhesive layer
  - Potential hydrolysis in hot water
- PE
  - PE (LD): 80°C short-term, 60°C long-term approved (stabilized)
- PET
  - Stable up to 130°C, long-term exposure (stabilized)

- Conclusion: Materials aging not shortening service life
- Main issue: Panel aging by permeation (N_2, O_2, H_2O)
- Requirement: pressure increase < 2 mbar/yr

VIP / Detection of the internal pressure

- Principle: Determine „lift-off pressure“
- EMPA:
  - Depressurization chamber for 0.50 x 0.50 m² specimens
  - Laser distance detection of the surface



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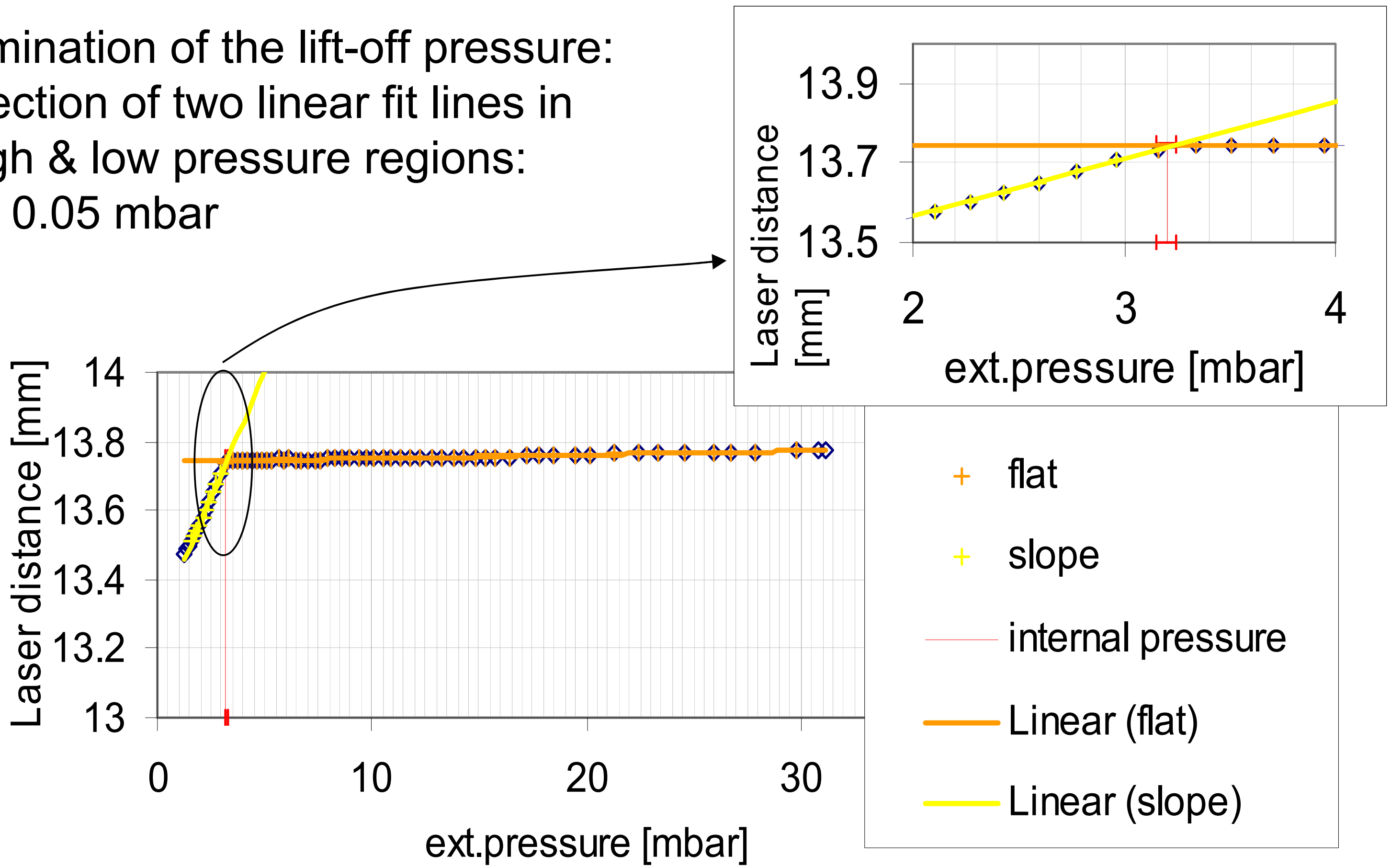
VIP / Detection of the internal pressure

Determination of the lift-off pressure:
Intersection of two linear fit lines in the high & low pressure regions:
3.20 ± 0.05 mbar



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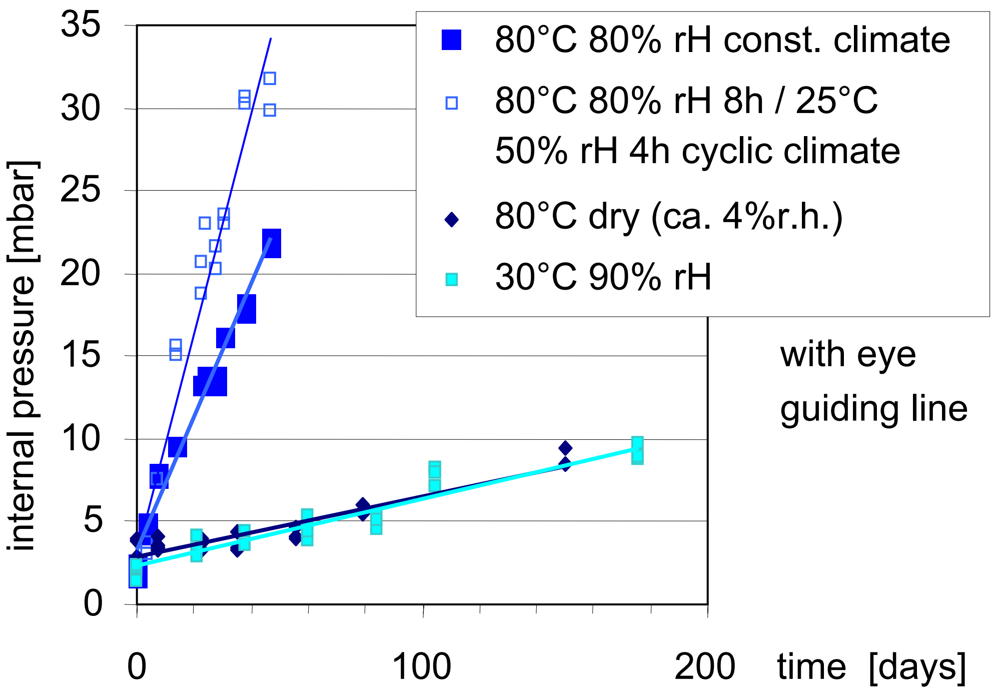
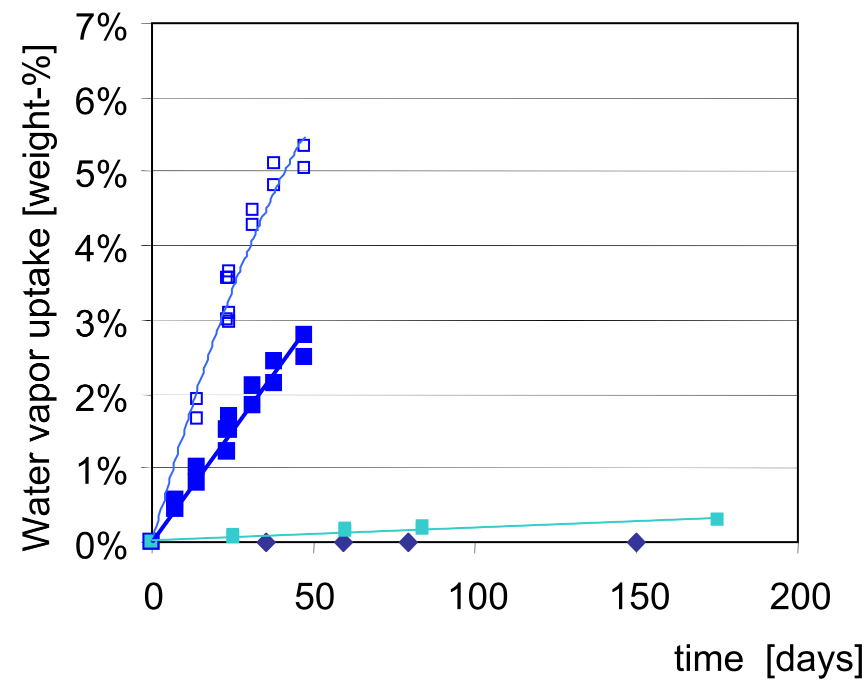
VIP / Aging by permeation

Due to penetrating O_2, N_2 and H_2O





VIP / Aging by permeation

- Behaviour of VIP with different barriers (23°C, 50 % r.h.)

	Size, cm	**X_{wa}, %-mass/yr** extrapol. from 103 days	**p_a, mbar/yr** extrapol. from 103 days
AF1	25x25x2	0.02% ± 0.01%	0.7 ± 0.1
	50x50x2	0.03% ± 0.01%	0.6 ± 0.2
MF3	25x25x2	0.15% ± 0.02%	3.3 ± 0.9
	50x50x2	0.10% ± 0.01%	1.8 ± 0.2
MF4	25x25x2	0.16% ± 0.01%	1.4 ± 0.6
	50x50x2	0.12% ± 0.01%	1.0 ± 0.1

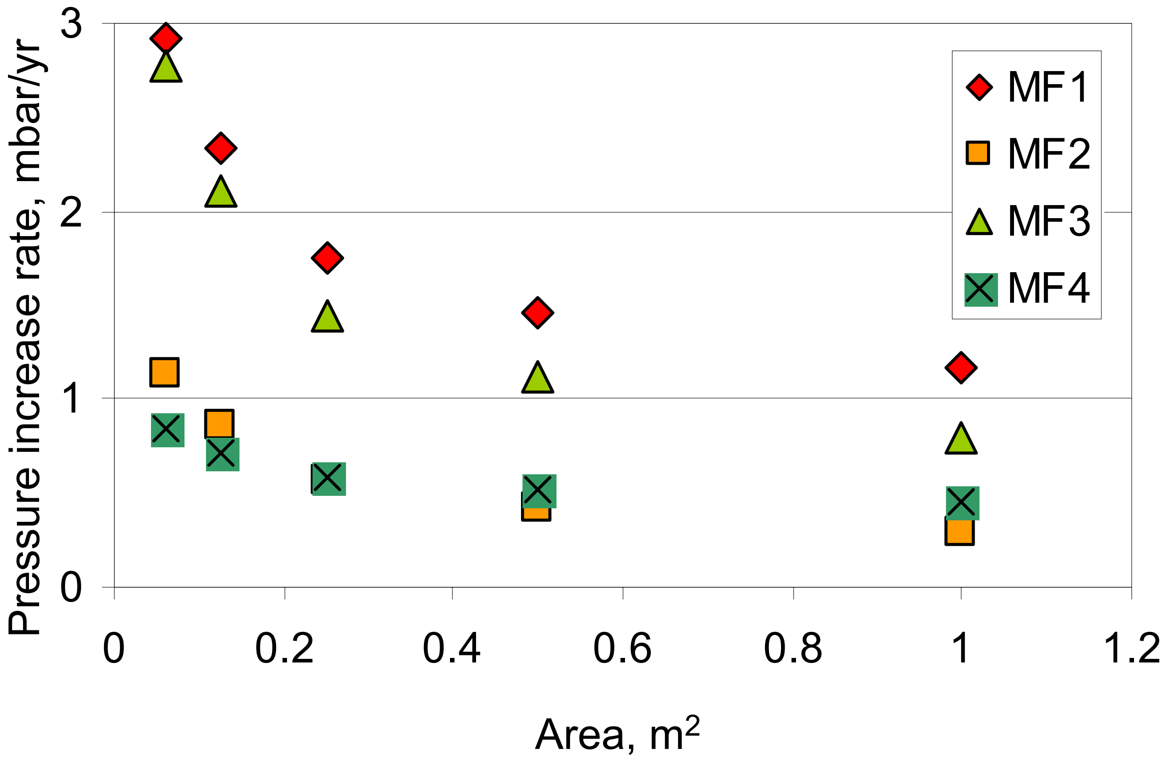
VIP / Aging by permeation

- Increase rates depend on various impact factors:
  - Permeation properties of the barrier (intrinsic defects, grain boundaries,...)
  - Additional defects by faults, wrinkles, corners, scratches etc.
  - Panel geometry (perimeter, area, volume)
  - Climate conditions (temperature: Arrhenius)
- Increase rates are higher than calculated from barrier permeability data
- Results from IEA Annex 39 (23°C, 50 % r.h., 1 bar):

Barrier	$WVTR_A$ $g/(m^2\ d)$	$WVTR_L$ $g/(m\ d)$	ATR_A $cm^3/(m^2\ d)$	ATR_L $cm^3/(m\ d)$
MF1	0.0233	-	0.0160	0.0080
MF2	0.0057	-	-	0.0039
MF3	0.0030	0.0008	0.0034	0.0091
MF4	0.0048	0.0006	0.0088	0.0018

VIP / Aging by permeation

- For advanced high barriers, dimensions ≥ 1.0 x 0.5 m^2:
  ≤ **1 mbar / yr** (23°C, 50 % r.h., 1 bar)



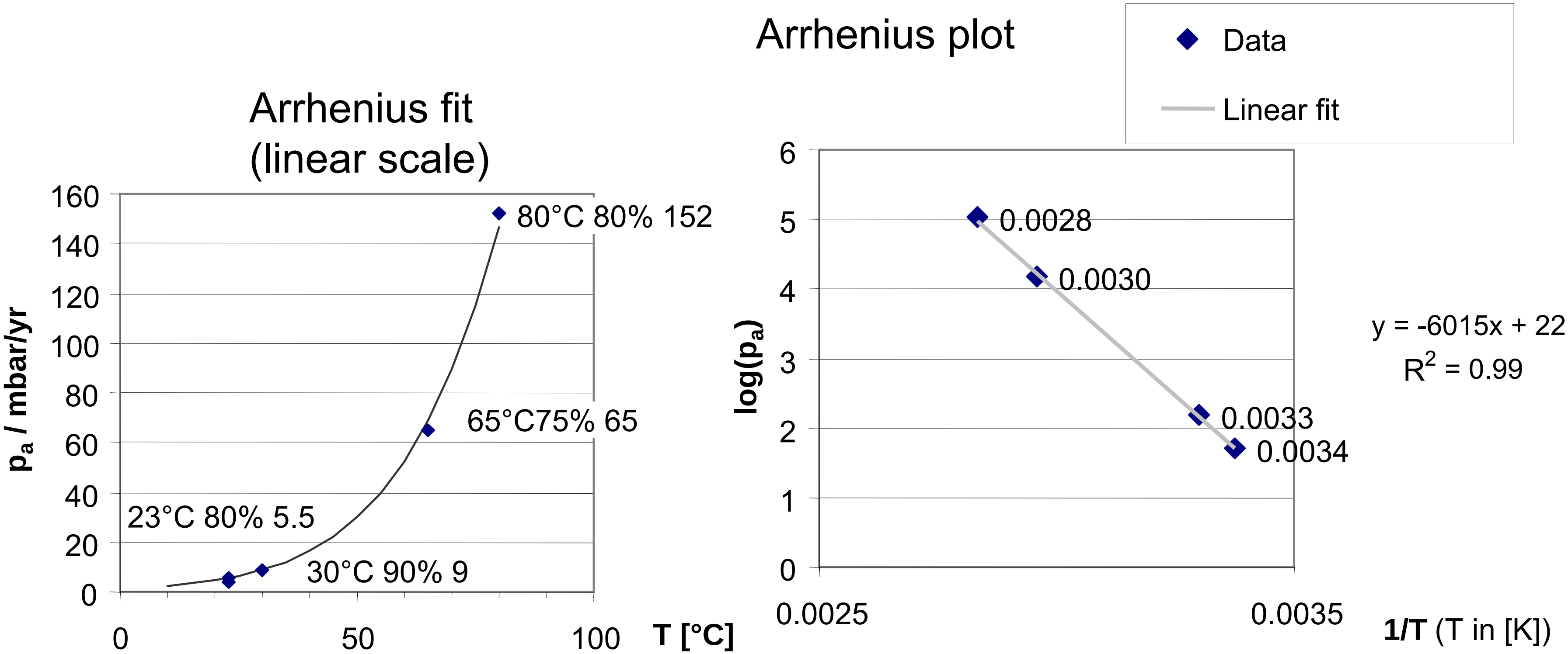
VIP / Aging under dynamic conditions

- Dynamic temperature / moisture environment (different on adjacent faces)
- Accelerated aging due to cyclic stress ?
- Modelling assumptions (simplifications):
  - Stationary permeation behaviour (superposition of hourly boundary conditions data)
  - Averaging between cold & warm part of VIP
  - VIP in open assembly: Environmental vapour pressure
  - VIP in sealed construction: Constant relative humidity (e.g. flat roof insulation with bituminous sealing layers)
  - Weighted averaging to account for non-linear permeability behaviour:

$$p_a = \sum_i A \exp\left(-\frac{E_a}{RT_i}\right)\Delta t_i \Big/ \sum_i \Delta t_i \equiv A \exp\left(-\frac{E_a}{RT_{effective}}\right)$$

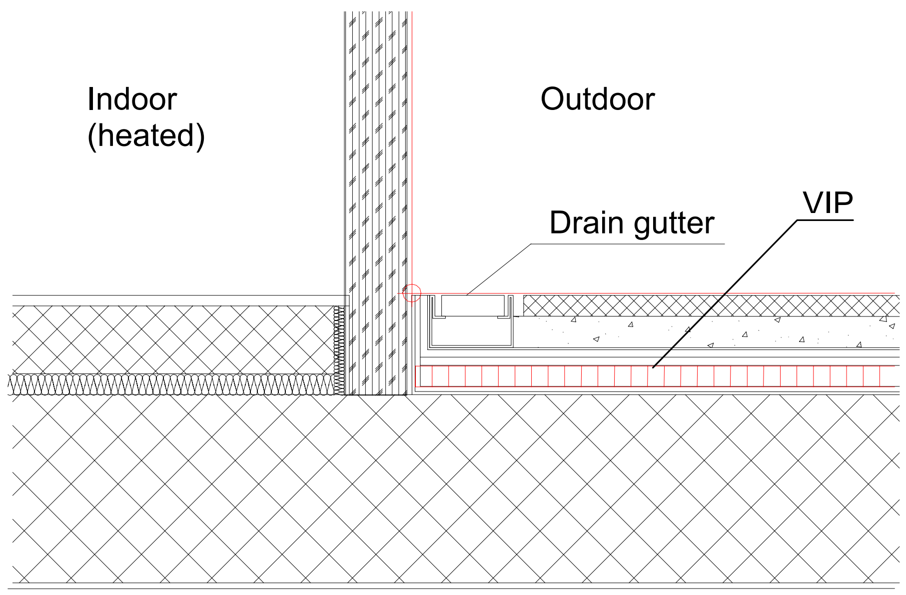
VIP / Aging under dynamic conditions

- High humidity data



VIP / Aging under dynamic conditions

- Application of high humidity data to terrace VIP insulation
- Climate: Design Reference Year Zurich, indoor air temperature 22°C
- VIP surface temperature calculation: HELIOS (Empa)



Apartment below terrace (heated)

VIP / Aging under dynamic conditions

- Calculated results

Quantity		*VIP inside*	*VIP outside*
Maximum temperature	[°C]	22.5	44.1
Minimum temperature	[°C]	19.9	-18.2
Temperature (Average)	[°C]	21.5	11.9
Effective temperature (Arrhenius)	[°C]	21.5	16.0
Pressure increase rate (Average)	[mbar/yr]	2.6	1.3
Pressure increase rate (Arrhenius)	[mbar/yr]	2.6	1.8
Moisture accumulation (Average)	[%-mass/yr]	0.21	0.09
Moisture accumulation (Arrhenius)	[%-mass/yr]	0.21	0.14

- Time function of thermal conductivity increase:

$$\Delta\lambda(t) = 0.035 \cdot 2.1 \cdot t + 0.50 \cdot 6.4\left(1 - \exp(-t/35.6)\right)$$

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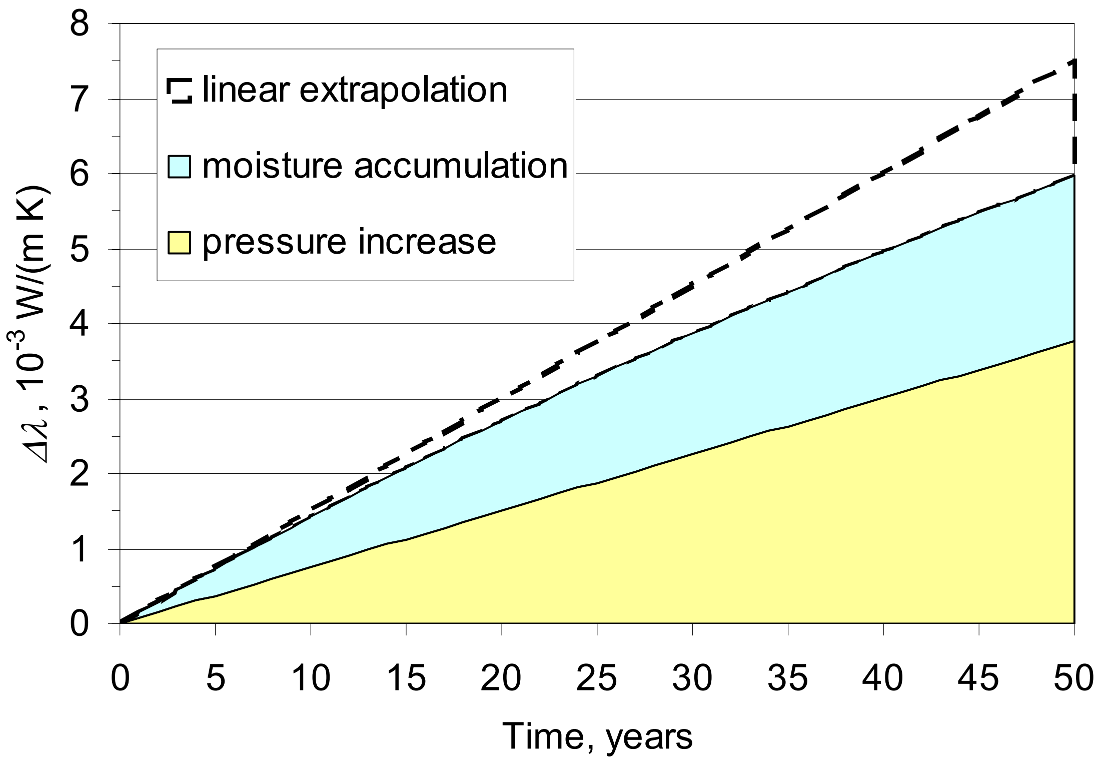
VIP / Aging under dynamic conditions



- Service life of several decades expected (end-of-life criterium...)
- Reliability of prediction?

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Summary / outlook

- Quality management, reliability, service life: **progress**!
- Service life of several decades expected in suitable applications
- ATTENTION TO IMPLEMENTATION!
  - > Layout, joints, protective layers, logistics, laying, ...
- Dilemma “safety / service life” vs. “minimal edge heat loss” persists

- Further needs

➔ Verification of service life prediction

➔ Improved barriers, damage protection, quality management

➔ VIP integrated insulation elements and light-weight envelope parts

➔ Standardization of test methods, specification, design