Vacuum-Isolation-Panels Calculation of increase of thermal conductivity according to differing climatic influences

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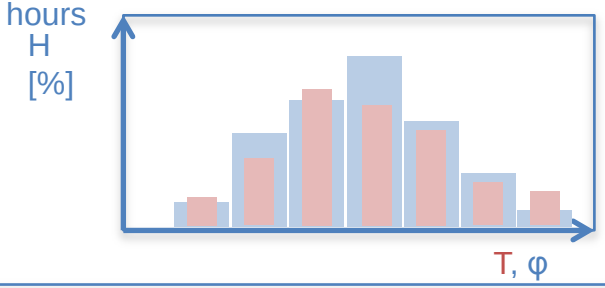
Scientific approach (priniciple sketches)

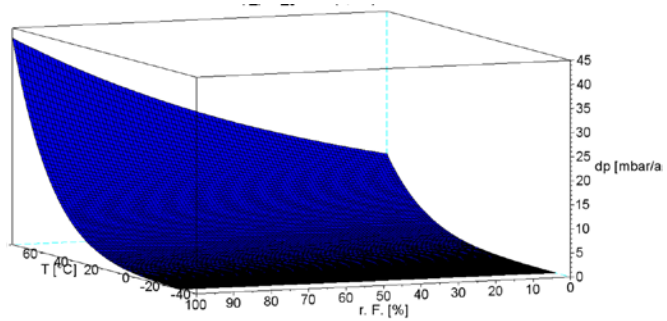
Typical applications:

- Flat roof / roof terrace
- Pitched roof
- Exterior insulation system
- Interior insulation
- Ventialted facades

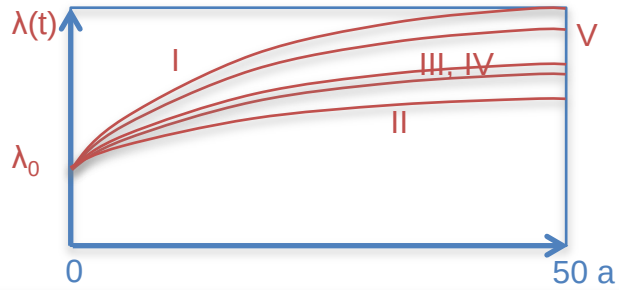
Calculation of hygro-thermal loads (WUFI):
Frequency of VIP adjacent climates by hours



Artificial Ageing dp = f(T, φ)



Calculation of λ = f(t)

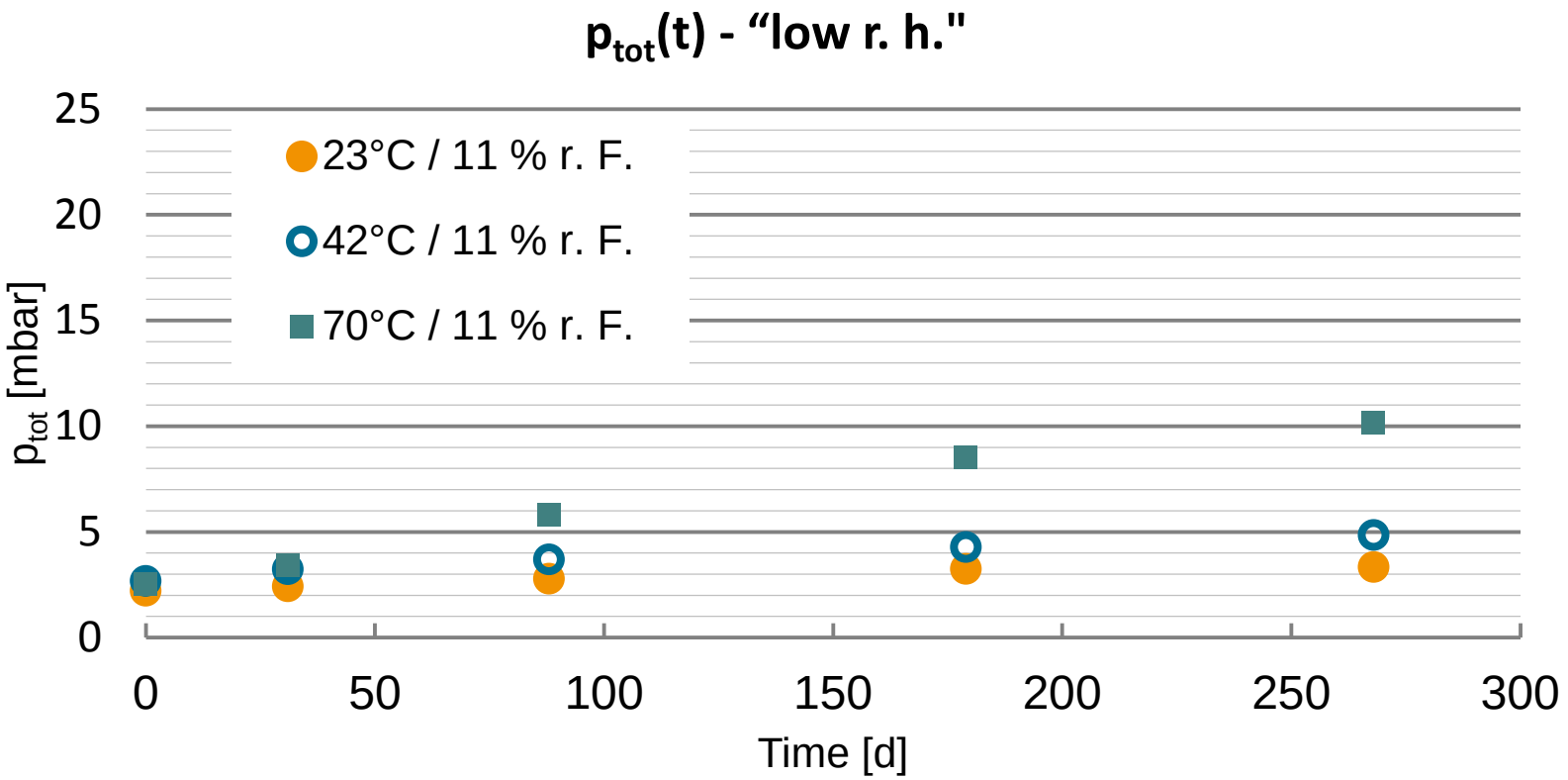


Laboratory investigations (artificial ageing)

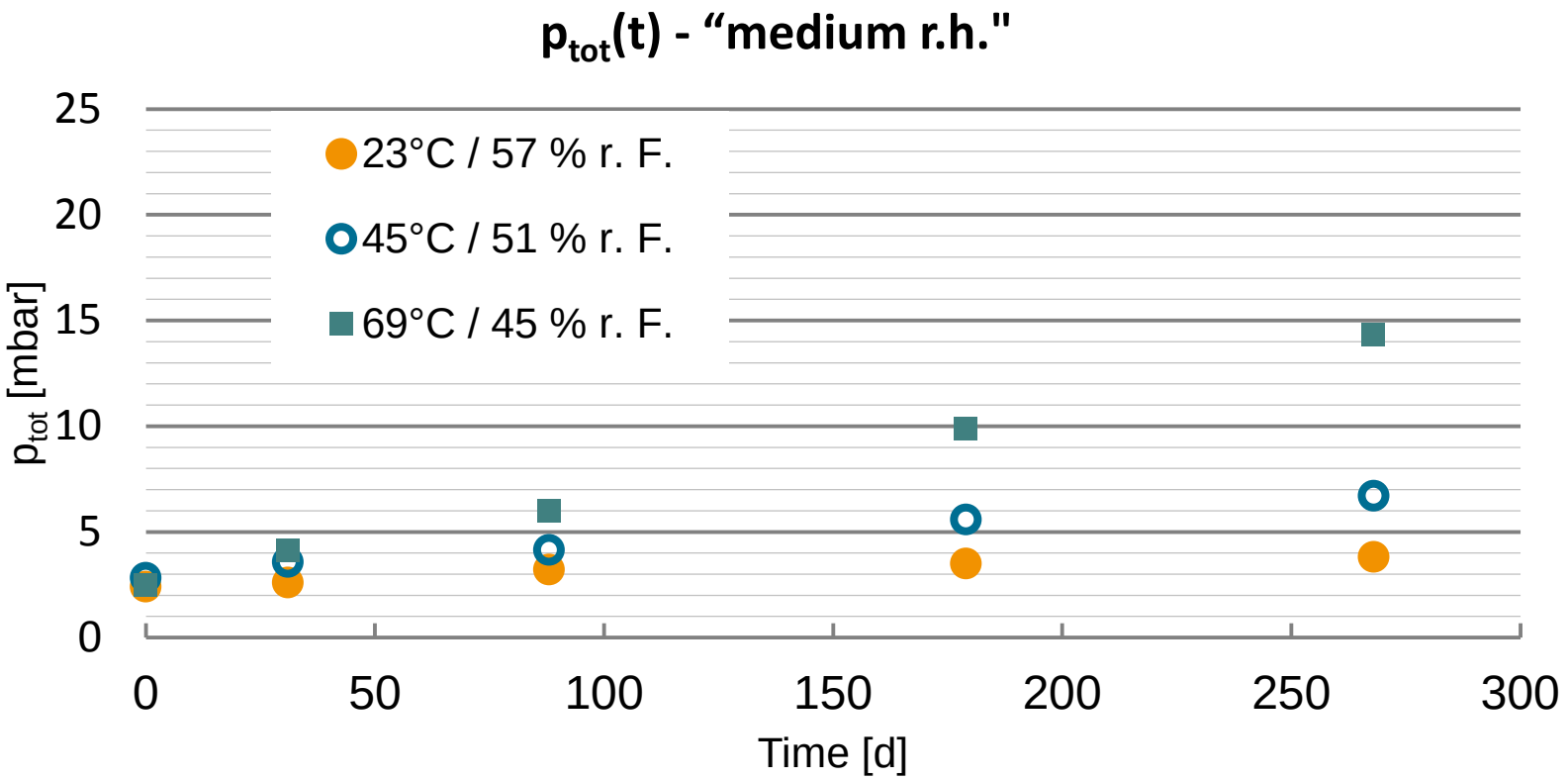
- Determination of total internal pressure (p_{tot}) @20°C and 40°C
  - Calculation of partial pressure of dry air (p_{dry}) and water vapor (p_{H2O})
- Determination of thermal conductivity (GHP, $\lambda_{10°C}$)

T	11 % r. h.	50 % r. h.	96 % r. h.
23°C	p_i, $\lambda = f(T, \varphi, t)$	p_i, $\lambda = f(T, \varphi, t)$	p_i, $\lambda = f(T, \varphi, t)$
45°C	p_i, $\lambda = f(T, \varphi, t)$	p_i, $\lambda = f(T, \varphi, t)$	p_i, $\lambda = f(T, \varphi, t)$
70°C	p_i, $\lambda = f(T, \varphi, t)$	p_i, $\lambda = f(T, \varphi, t)$	p_i, $\lambda = f(T, \varphi, t)$

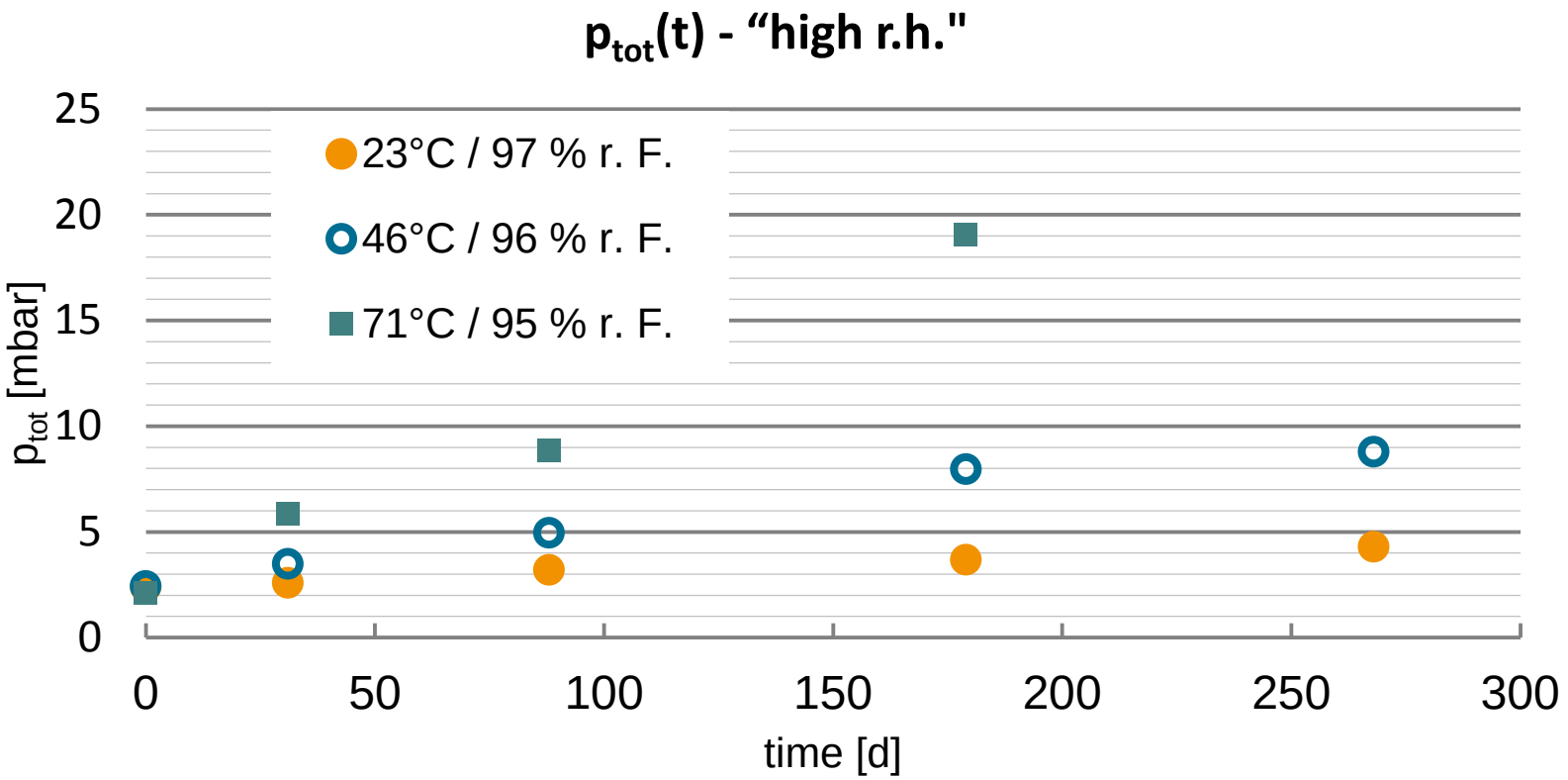
Artificial Ageing – results



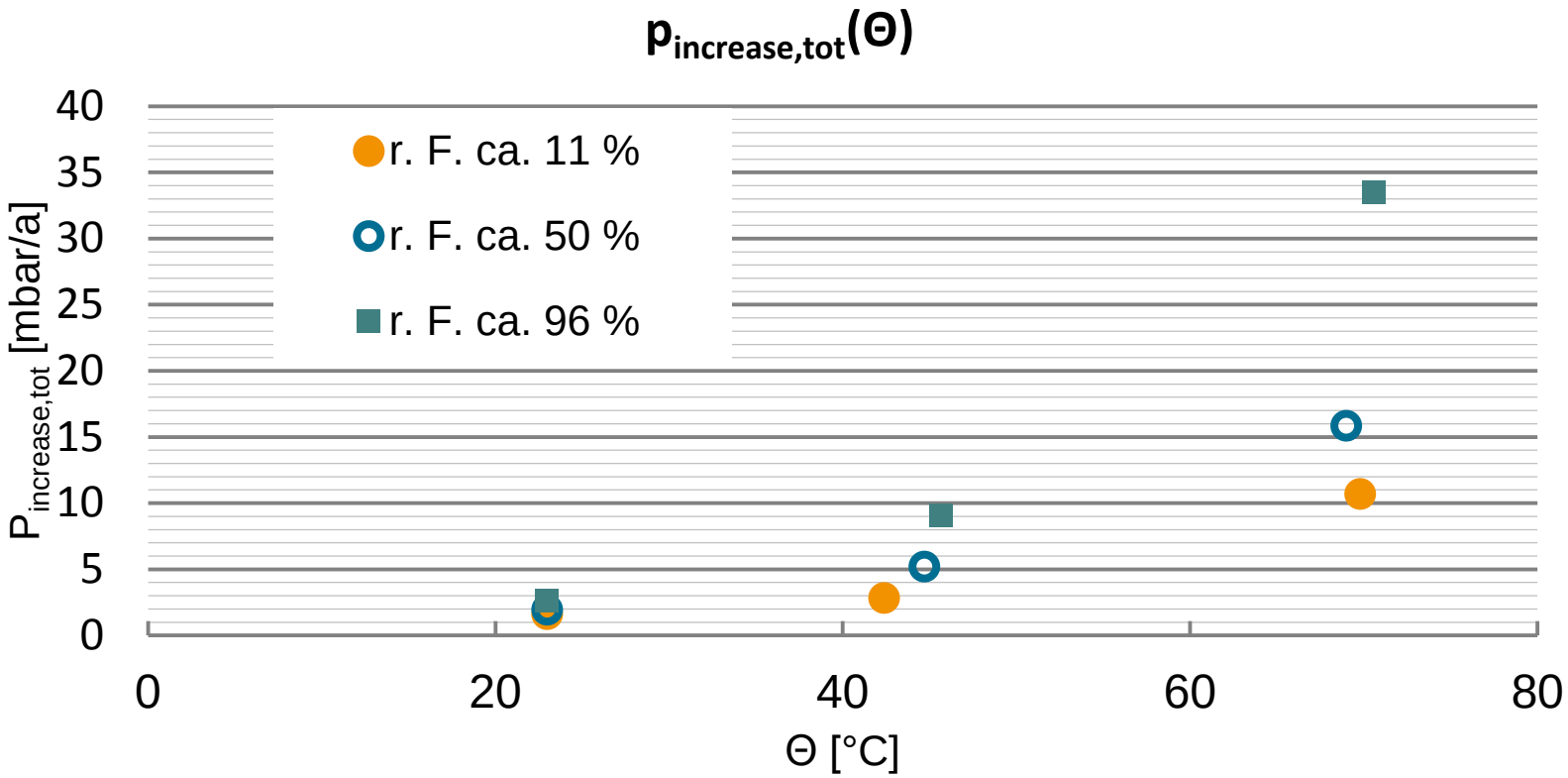
Artificial Ageing – results



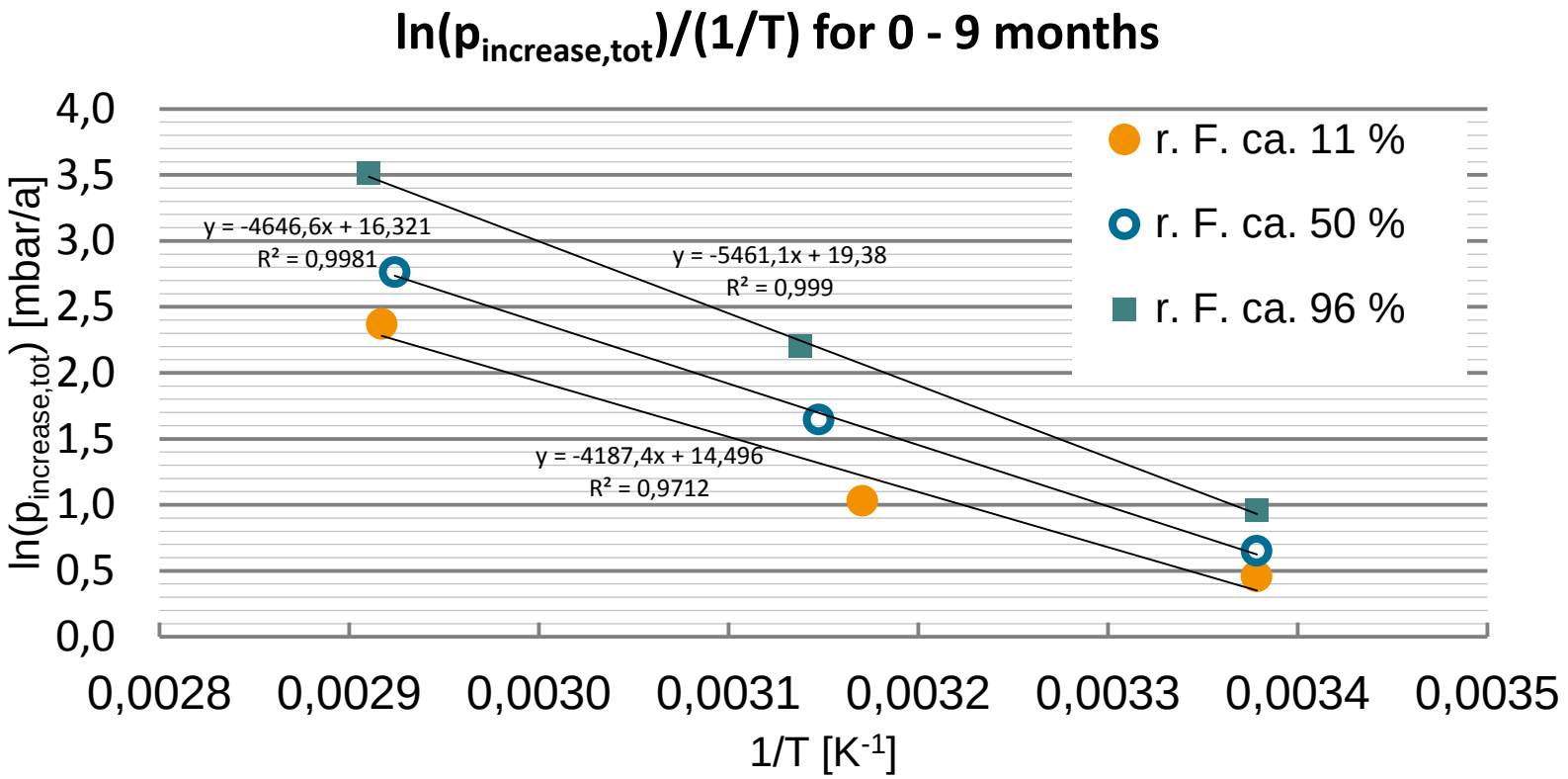
Artificial Ageing – results



Increase of internal pressure (regression for t = 0 – 9 months) as a function of temperature



Arrhenius behaviour



ln(p) = f(T,φ)

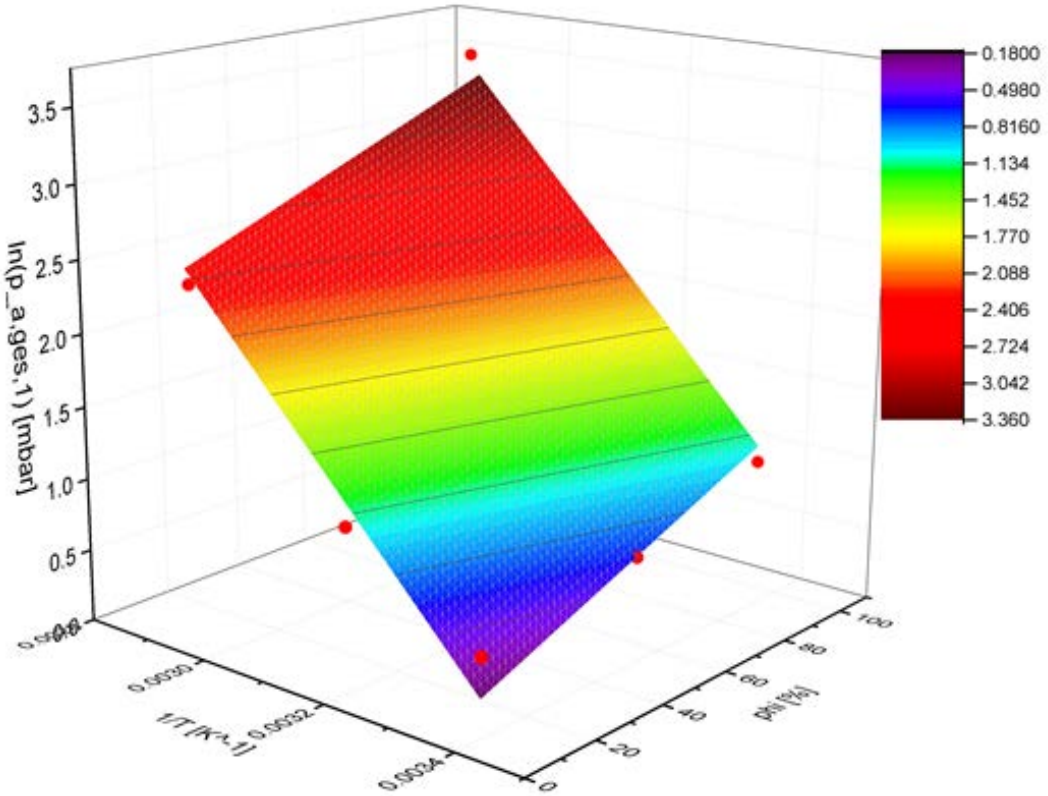
- Plane approximation:

$$z = a \cdot x + b \cdot y + c$$

z = ln(p) [mbar]
x = 1/T [1/K]
y = φ [%]

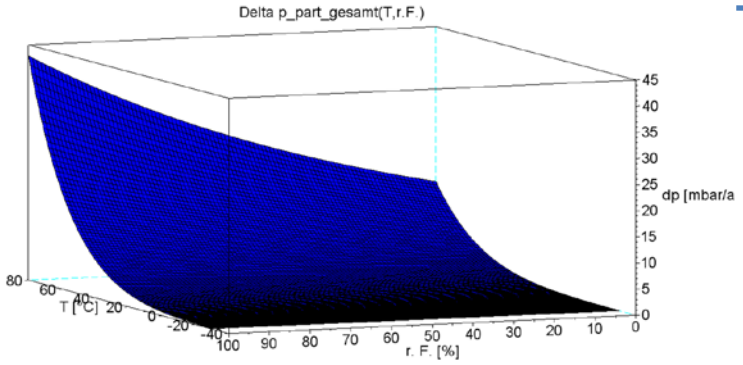
- Results:

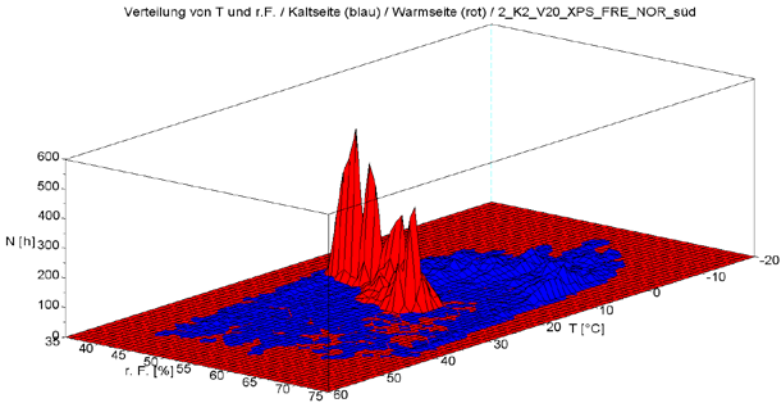
	p_{tot}	p_{dry}	p_{H2O}
a	-4885.39	-4612.24	-5407.13
b	0.01	0.01	0.02
c	16.57	15.42	16.87
R^2	0.98	0.93	0.98



Determination of p(t)

Laboratory data and WUFI model



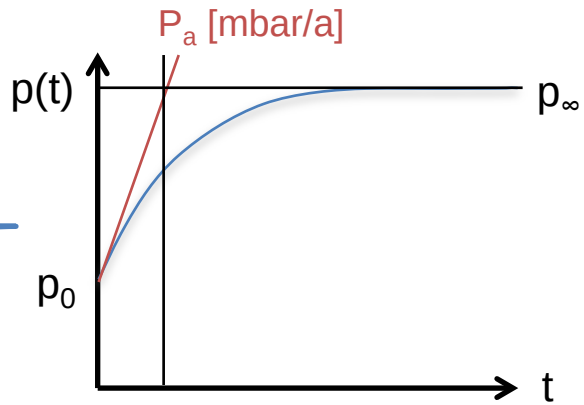


Increase of internal pressure

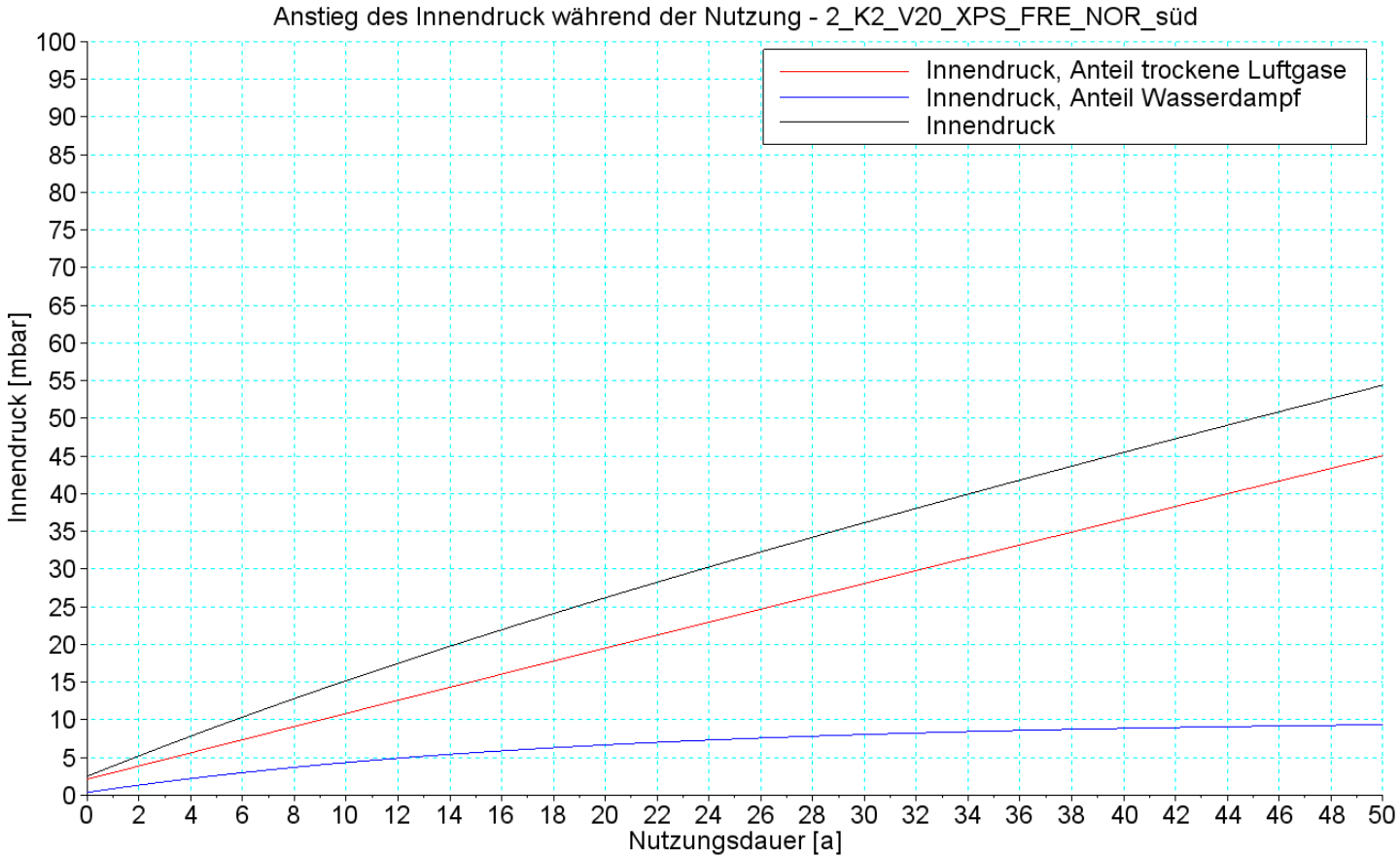
$p_{increase}$ [mbar/a]

Specific for the modelled application

Long-time-behavior (saturation function)



Increase of internal pressure over 50 years



Calculation of increase of thermal conductivity

- $\lambda = \lambda_G + \lambda_F + \lambda_S + \lambda_K$
- $\Delta\lambda_G = \Delta\lambda_{dry} + \Delta\lambda_{H2O}$

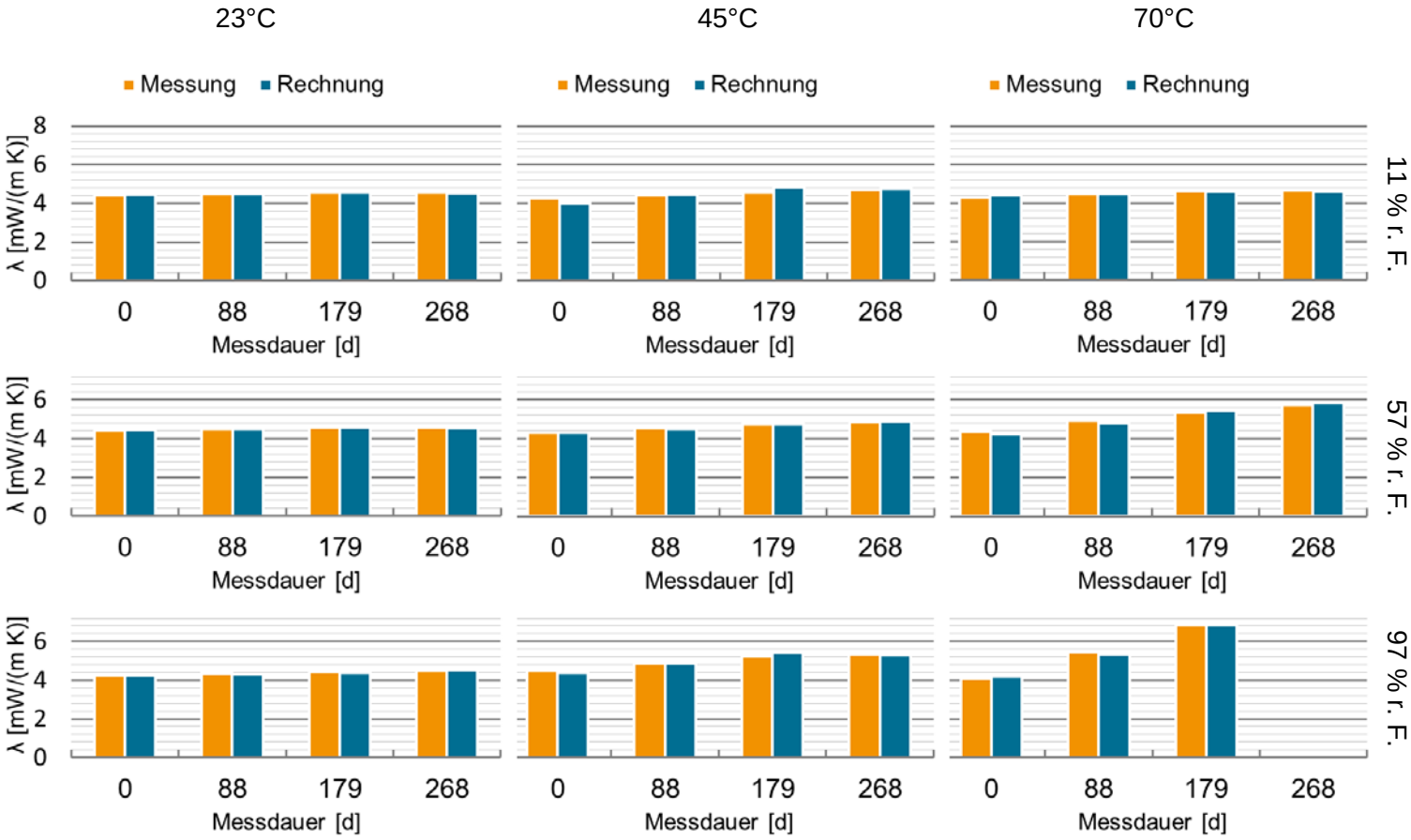
$$\lambda_G = \frac{\lambda_{G,frei}}{1 + \frac{p_{1/2}}{p_{G,part}}}$$

- $\Delta\lambda_F$: based on sorption behavior of the core

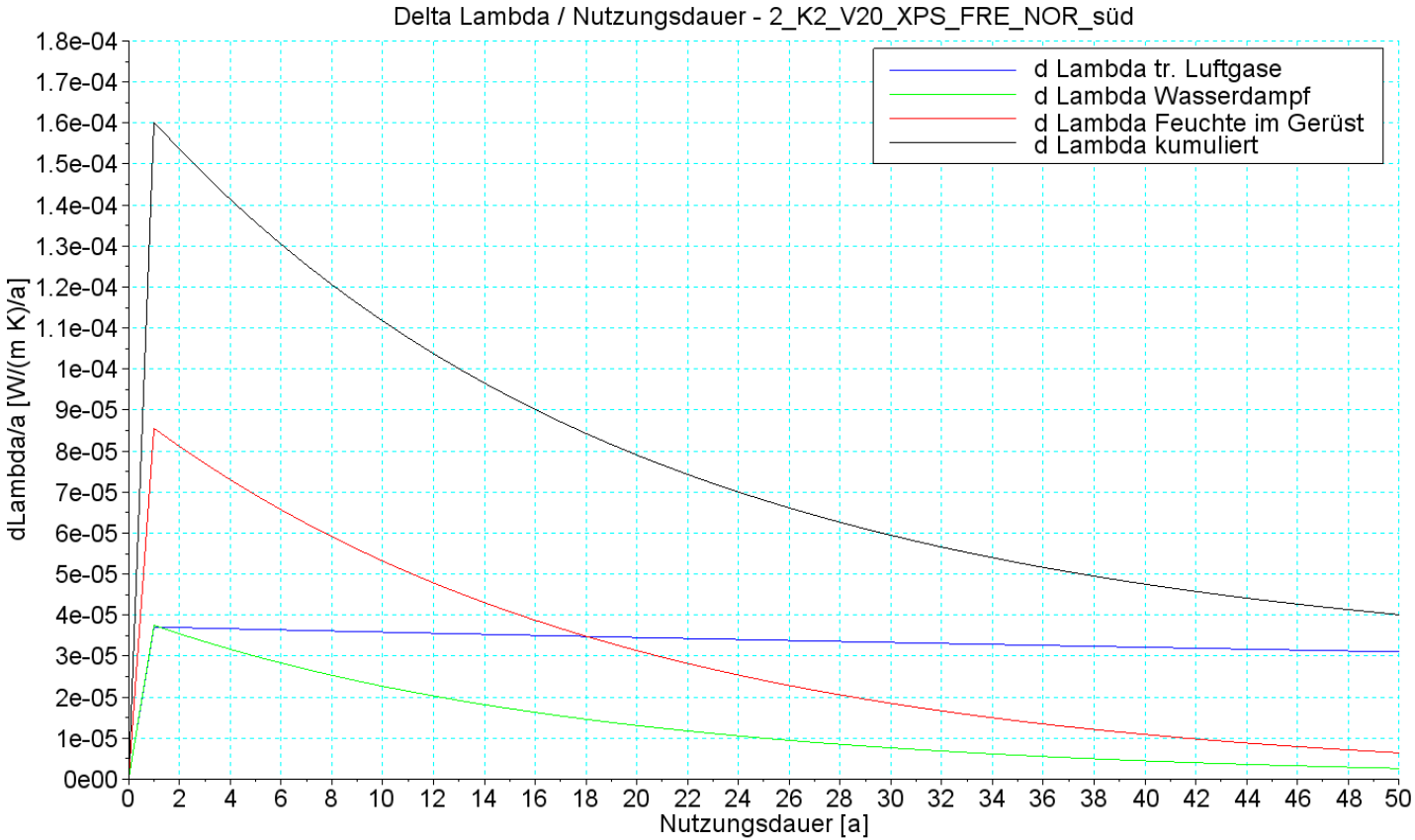
$$\lambda_F = \frac{\Delta\lambda}{\Delta u} \cdot \Delta u$$

λ_F was fitted according to measured values at FIW during ageing

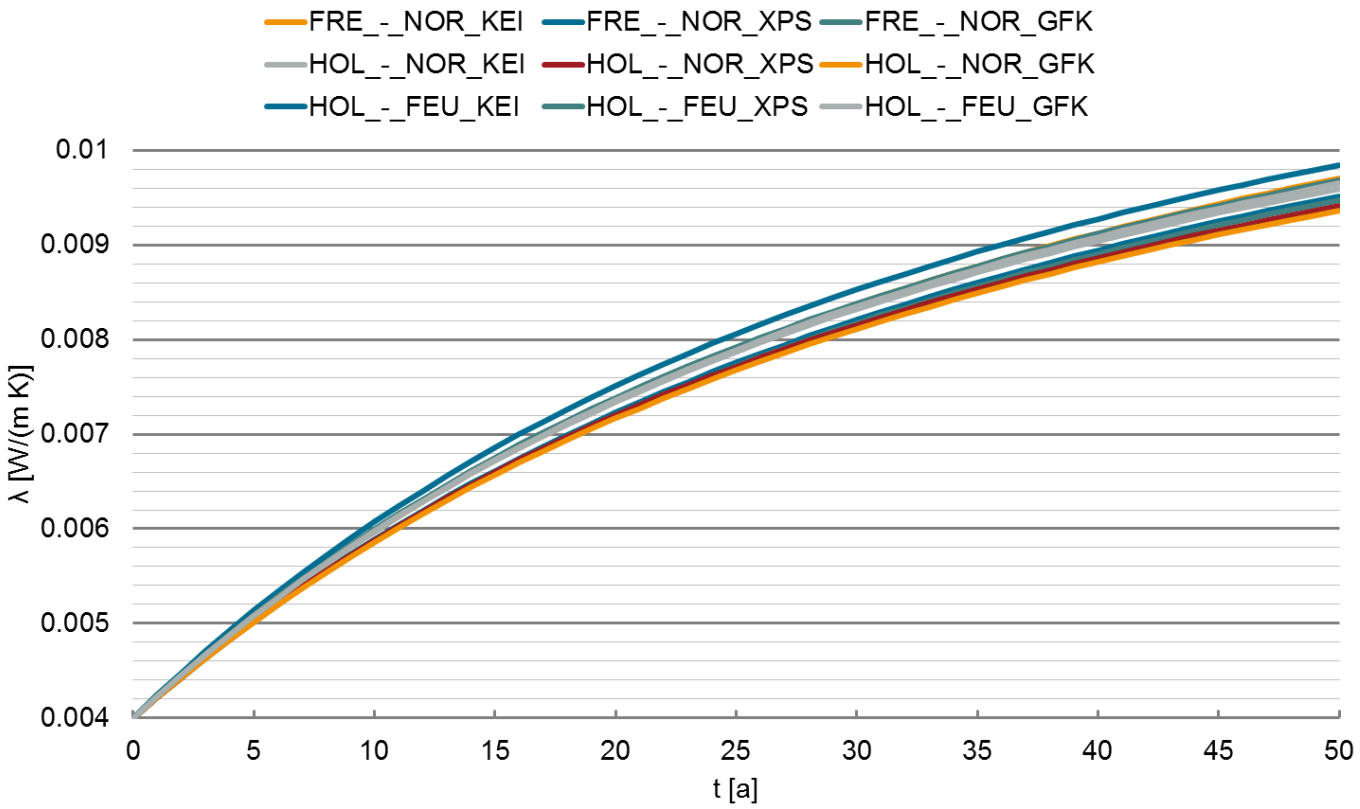
Validation and determination of λ_F



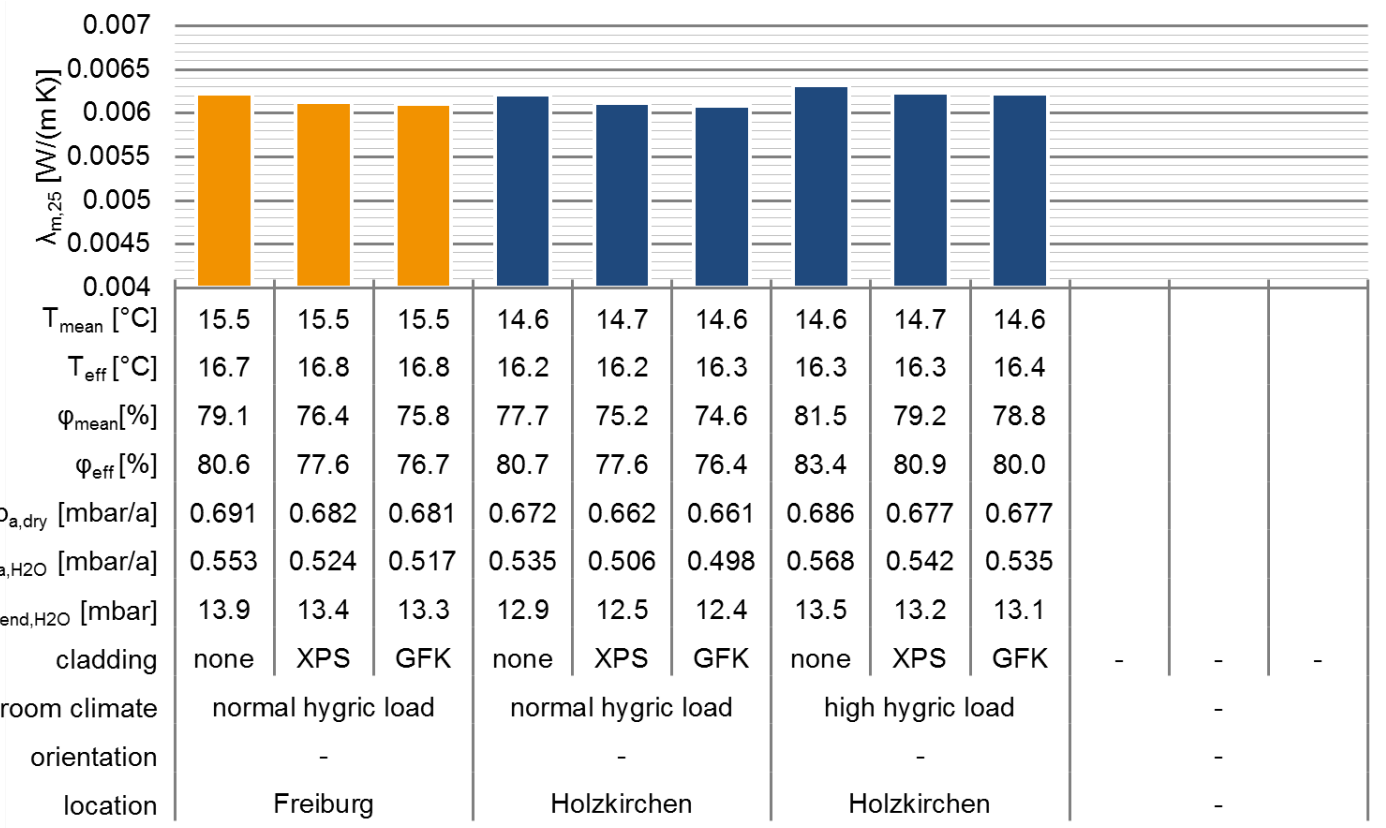
Δλ(t)


Delta Lambda / Nutzungsdauer - 2_K2_V20_XPS_FRE_NOR_süd
d Lambda tr. Luftgase
d Lambda Wasserdampf
d Lambda Feuchte im Gerüst
d Lambda kumuliert
dLambda/a [W/(m K)/a]
1.8e-04
1.7e-04
1.6e-04
1.5e-04
1.4e-04
1.3e-04
1.2e-04
1.1e-04
1e-04
9e-05
8e-05
7e-05
6e-05
5e-05
4e-05
3e-05
2e-05
1e-05
0e00
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34 36 38 40 42 44 46 48 50
Nutzungsdauer [a]

Flatroof / roof terrace

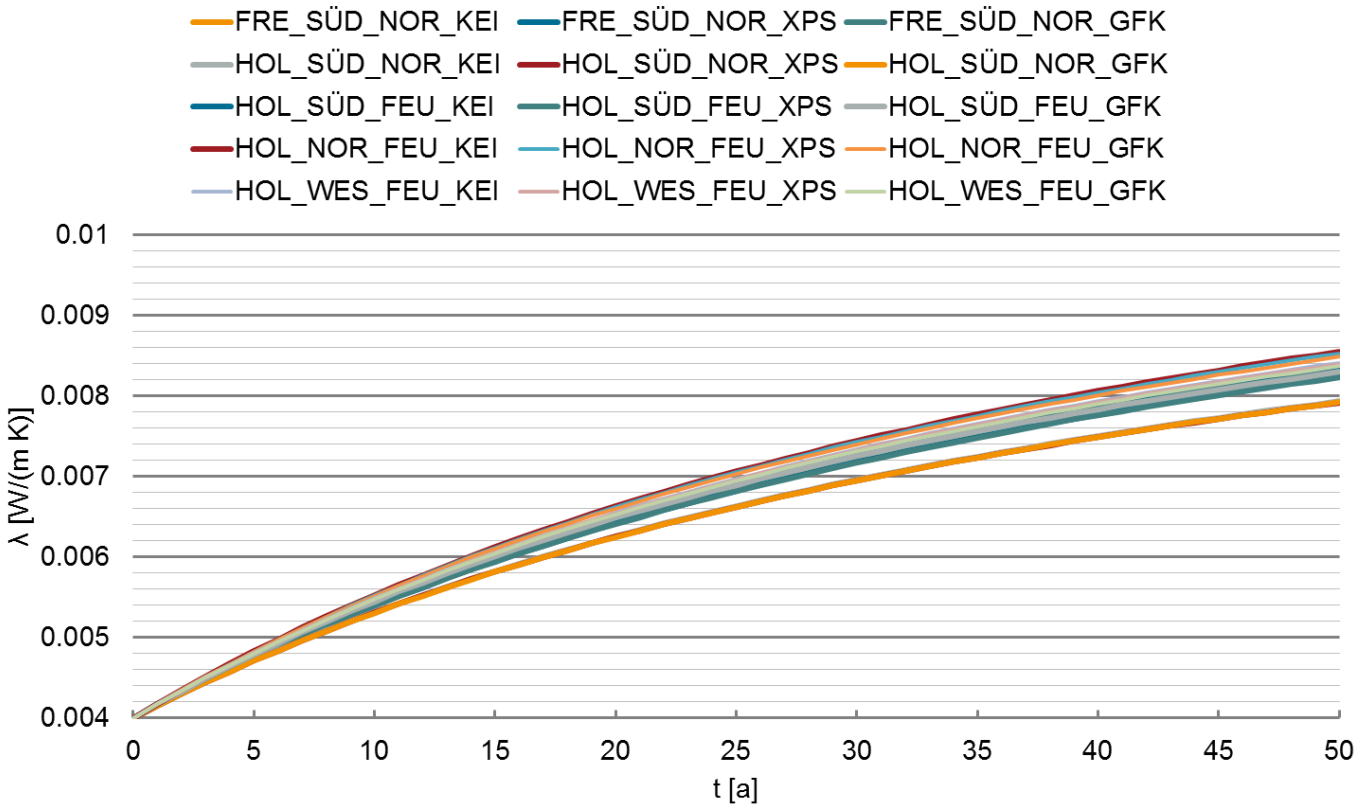


Flat roof / roof terrace

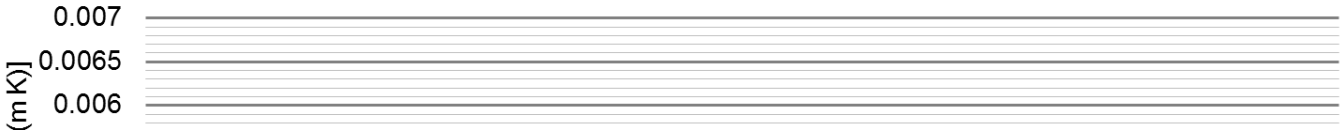


T_{mean} [°C]	15.5	15.5	15.5	14.6	14.7	14.6	14.6	14.7	14.6			
T_{eff} [°C]	16.7	16.8	16.8	16.2	16.2	16.3	16.3	16.3	16.4			
φ_{mean}[%]	79.1	76.4	75.8	77.7	75.2	74.6	81.5	79.2	78.8			
φ_{eff} [%]	80.6	77.6	76.7	80.7	77.6	76.4	83.4	80.9	80.0			
$p_{a,dry}$ [mbar/a]	0.691	0.682	0.681	0.672	0.662	0.661	0.686	0.677	0.677			
$p_{a,H2O}$ [mbar/a]	0.553	0.524	0.517	0.535	0.506	0.498	0.568	0.542	0.535			
$p_{end,H2O}$ [mbar]	13.9	13.4	13.3	12.9	12.5	12.4	13.5	13.2	13.1			
cladding	none	XPS	GFK	none	XPS	GFK	none	XPS	GFK	-	-	-
room climate	normal hygric load			normal hygric load			high hygric load				-	
orientation	-			-			-				-	
location	Freiburg			Holzkirchen			Holzkirchen				-	

Pitched roof

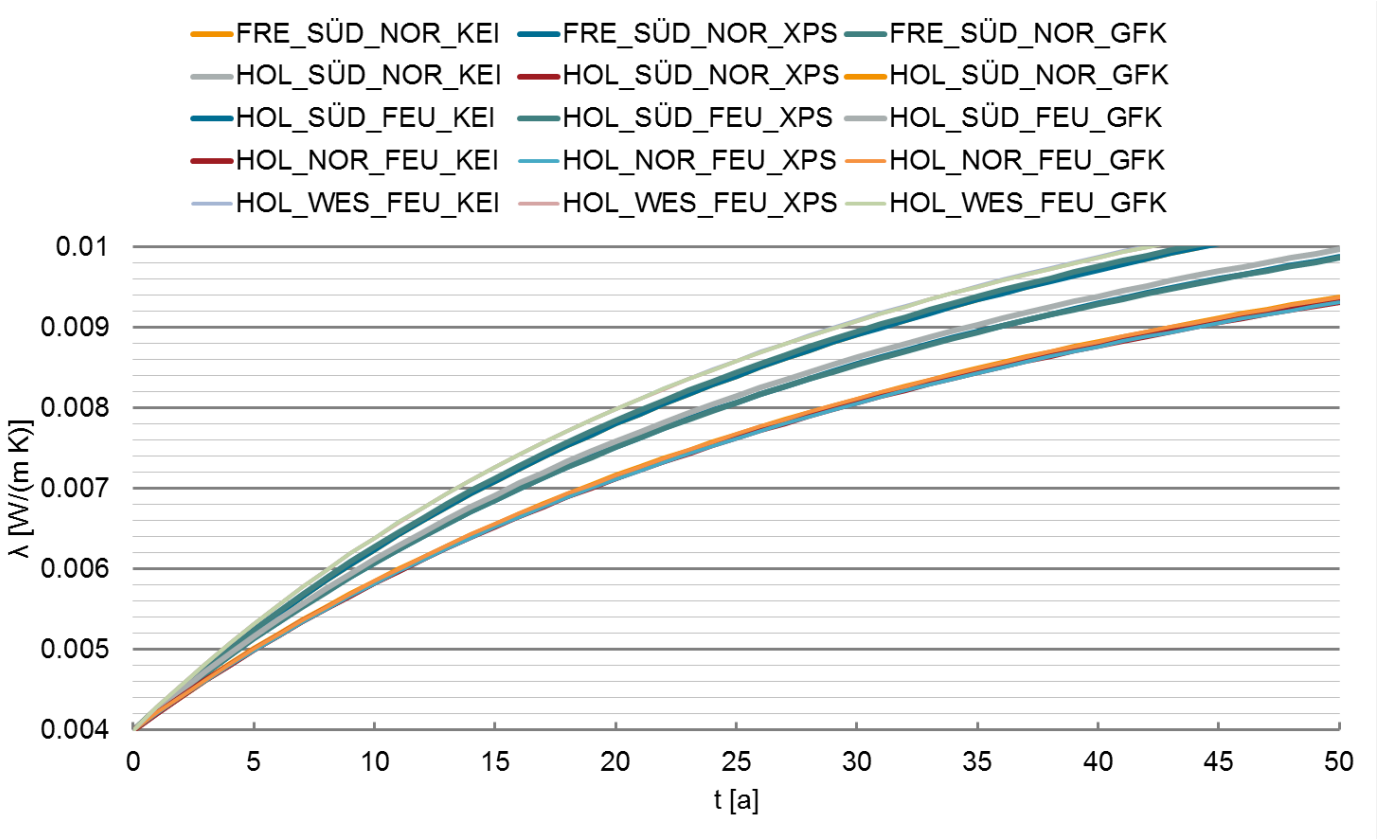


Pitched roof

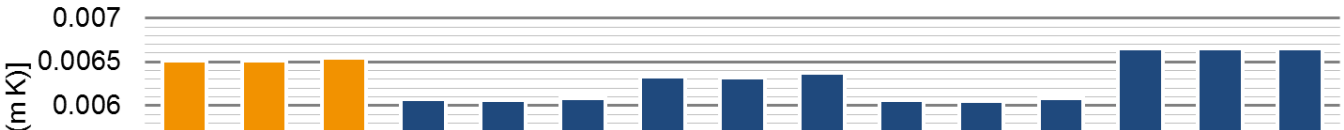


T_{mean} [°C]	16.4	16.4	16.4	15.8	15.8	15.8	15.8	15.8	15.8	14.6	14.7	14.6	15.3	15.3	15.3
T_{eff} [°C]	18.2	18.1	18.1	18.3	18.2	18.1	18.2	18.1	18.1	16.6	16.5	16.5	17.5	17.5	17.4
φ_{mean}[%]	54.2	54.0	53.7	48.5	48.2	48.4	54.6	54.4	54.3	61.7	61.3	60.3	57.5	57.2	56.7
φ_{eff} [%]	55.6	55.8	55.7	50.5	50.7	50.7	57.2	57.4	57.3	62.9	63.0	62.8	59.5	59.7	59.6
$p_{a,dry}$ [mbar/a]	0.661	0.658	0.658	0.645	0.642	0.641	0.666	0.663	0.662	0.627	0.625	0.625	0.649	0.647	0.646
$p_{a,H2O}$ [mbar/a]	0.384	0.383	0.383	0.350	0.350	0.349	0.396	0.395	0.393	0.396	0.395	0.394	0.395	0.394	0.393
$p_{end,H2O}$ [mbar]	10.1	10.1	10.0	8.7	8.7	8.7	9.8	9.8	9.7	10.3	10.2	10.0	10.0	9.9	9.8
cladding	none	XPS	GFK	none	XPS	GFK	none	XPS	GFK	none	XPS	GFK	Keine	XPS	GFK
room climate	normal hygric load			normal hygric load			high hygric load			high hygric load			high hygric load		
orientation	south			south			south			north			west		
location	Freiburg			Holzkirchen			Holzkirchen			Holzkirchen			Holzkirchen		

Exterior insulation system

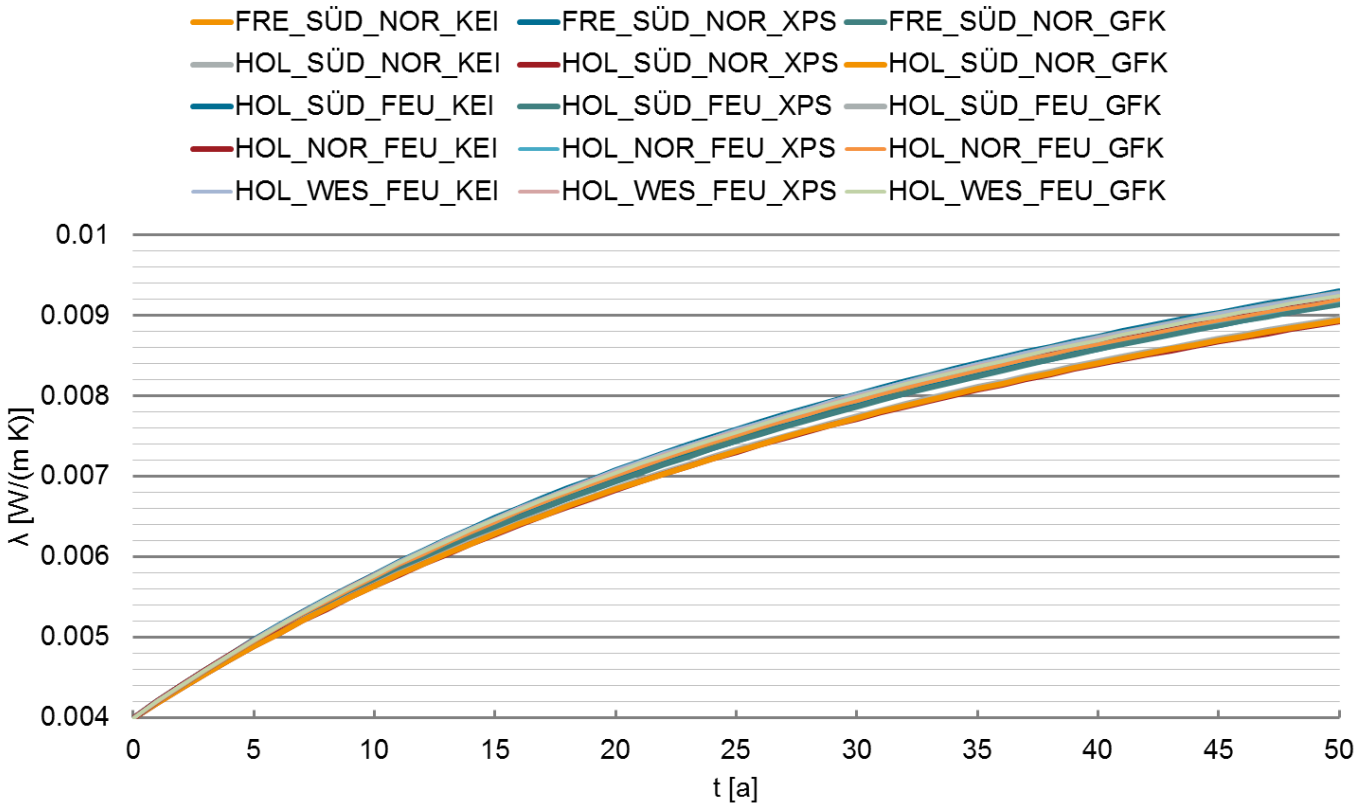


Exterior insulation system



T_{mean} [°C]	15.4	15.4	15.4	14.3	14.3	14.3	14.3	14.3	14.3	13.4	13.5	13.4	13.8	13.8	13.8
T_{eff} [°C]	16.6	16.6	16.6	15.9	15.8	15.9	16.0	15.9	16.0	15.1	15.0	15.1	15.6	15.5	15.6
φ_{mean} [%]	88.9	88.7	88.8	75.5	75.2	76.2	83.1	82.9	84.4	77.7	77.2	78.0	91.7	91.4	91.3
φ_{eff} [%]	88.9	89.2	90.0	76.2	76.3	76.5	83.7	84.1	85.2	76.6	76.7	77.4	93.2	93.7	93.3
$p_{a,dry}$ [mbar/a]	0.717	0.716	0.720	0.645	0.642	0.646	0.674	0.672	0.678	0.617	0.615	0.620	0.692	0.690	0.692
$p_{a,H2O}$ [mbar/a]	0.640	0.641	0.652	0.482	0.481	0.485	0.558	0.558	0.572	0.460	0.459	0.467	0.647	0.649	0.648
$p_{end,H2O}$ [mbar]	15.5	15.5	15.5	12.3	12.3	12.4	13.5	13.5	13.7	11.9	11.9	12.0	14.4	14.4	14.4
cladding	none	XPS	GFK	none	XPS	GFK	none	XPS	GFK	none	XPS	GFK	Keine	XPS	GFK
room climate	normal hygric load			normal hygric load			high hygric load			high hygric load			high hygric load		
orientation	south			south			south			north			west		
location	Freiburg			Holzkirchen			Holzkirchen			Holzkirchen			Holzkirchen		

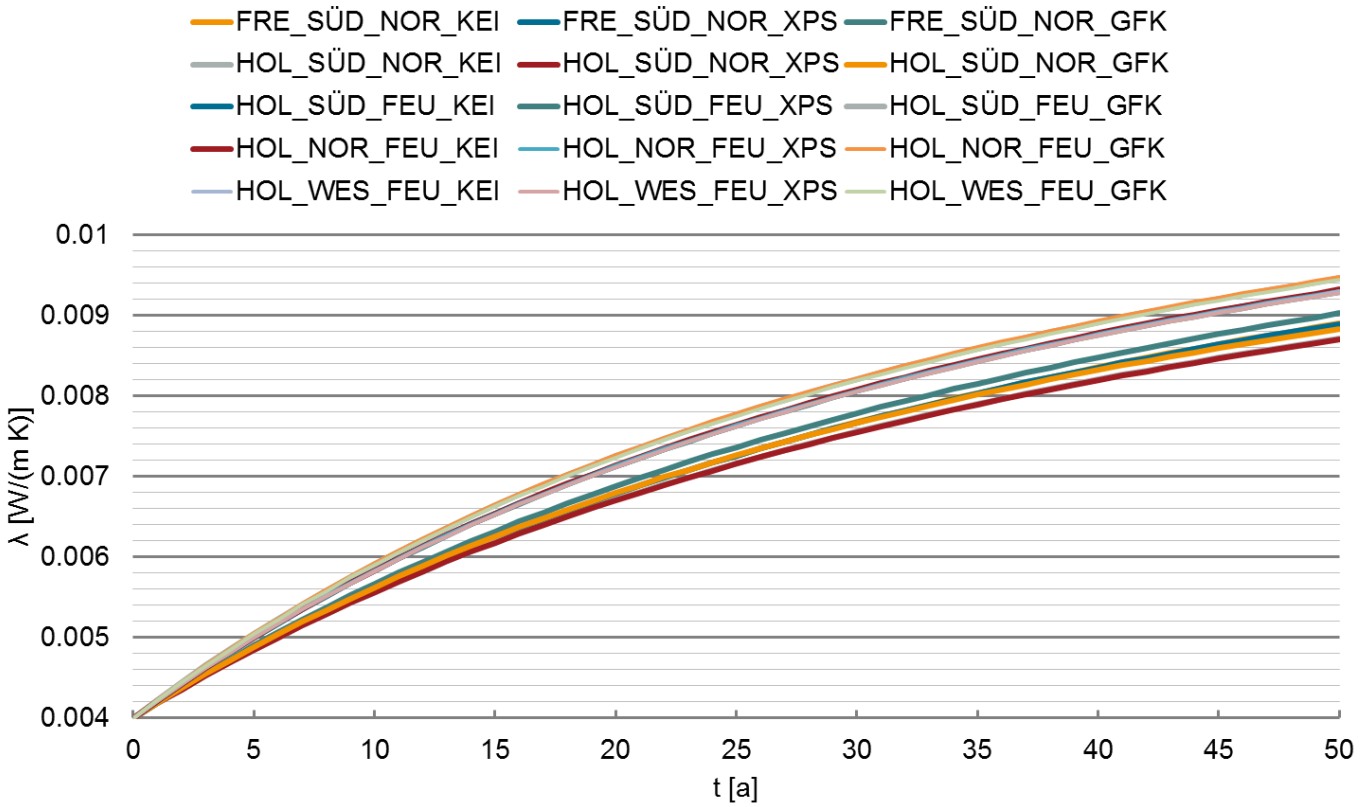
Interior insulation system



Interior insulation system

T_{mean} [°C]	15.7	15.7	15.7	14.6	14.6	14.6	14.6	14.6	14.6	13.8	13.8	13.8	14.2	14.2	14.2
T_{eff} [°C]	16.4	16.4	16.4	15.5	15.5	15.5	15.7	15.7	15.7	15.1	15.0	15.1	15.4	15.3	15.4
φ_{mean}[%]	72.6	72.2	72.3	70.6	69.9	70.3	75.7	75.2	75.5	75.8	75.2	75.5	76.0	75.4	75.7
φ_{eff} [%]	73.1	72.8	72.5	71.5	71.1	70.9	75.9	75.5	75.3	75.3	75.0	74.5	75.8	75.6	75.2
$p_{a,dry}$ [mbar/a]	0.652	0.651	0.650	0.618	0.616	0.617	0.637	0.635	0.636	0.614	0.612	0.612	0.626	0.624	0.625
$p_{a,H2O}$ [mbar/a]	0.470	0.468	0.465	0.433	0.429	0.429	0.474	0.470	0.469	0.450	0.447	0.445	0.464	0.461	0.459
$p_{end,H2O}$ [mbar]	12.9	12.8	12.8	11.7	11.6	11.7	12.6	12.5	12.5	11.9	11.9	11.9	12.3	12.2	12.2
cladding	none	XPS	GFK	none	XPS	GFK	none	XPS	GFK	none	XPS	GFK	Keine	XPS	GFK
room climate	normal hygric load			normal hygric load			high hygric load			high hygric load			high hygric load		
orientation	south			south			south			north			west		
location	Freiburg			Holzkirchen			Holzkirchen			Holzkirchen			Holzkirchen		

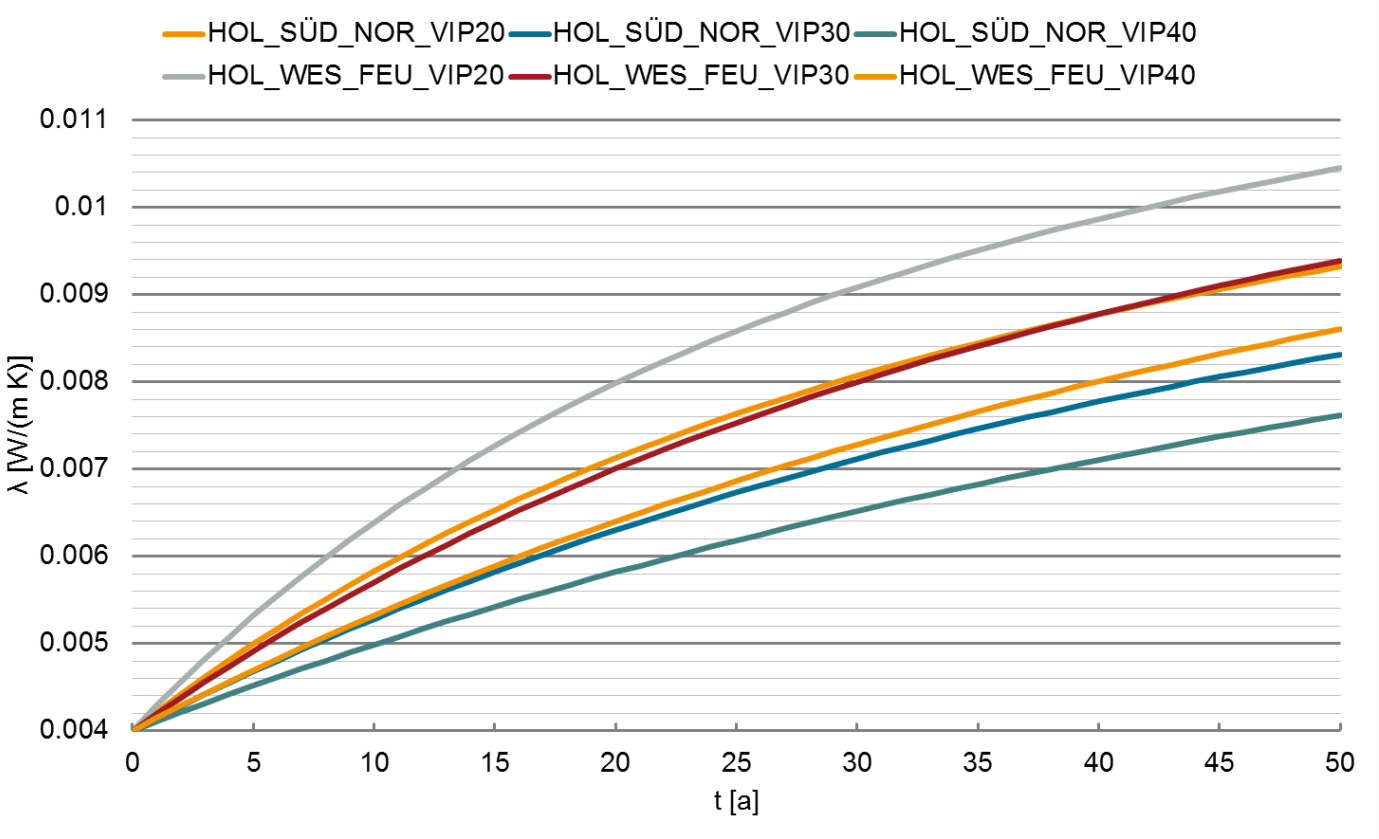
Ventilated facade system



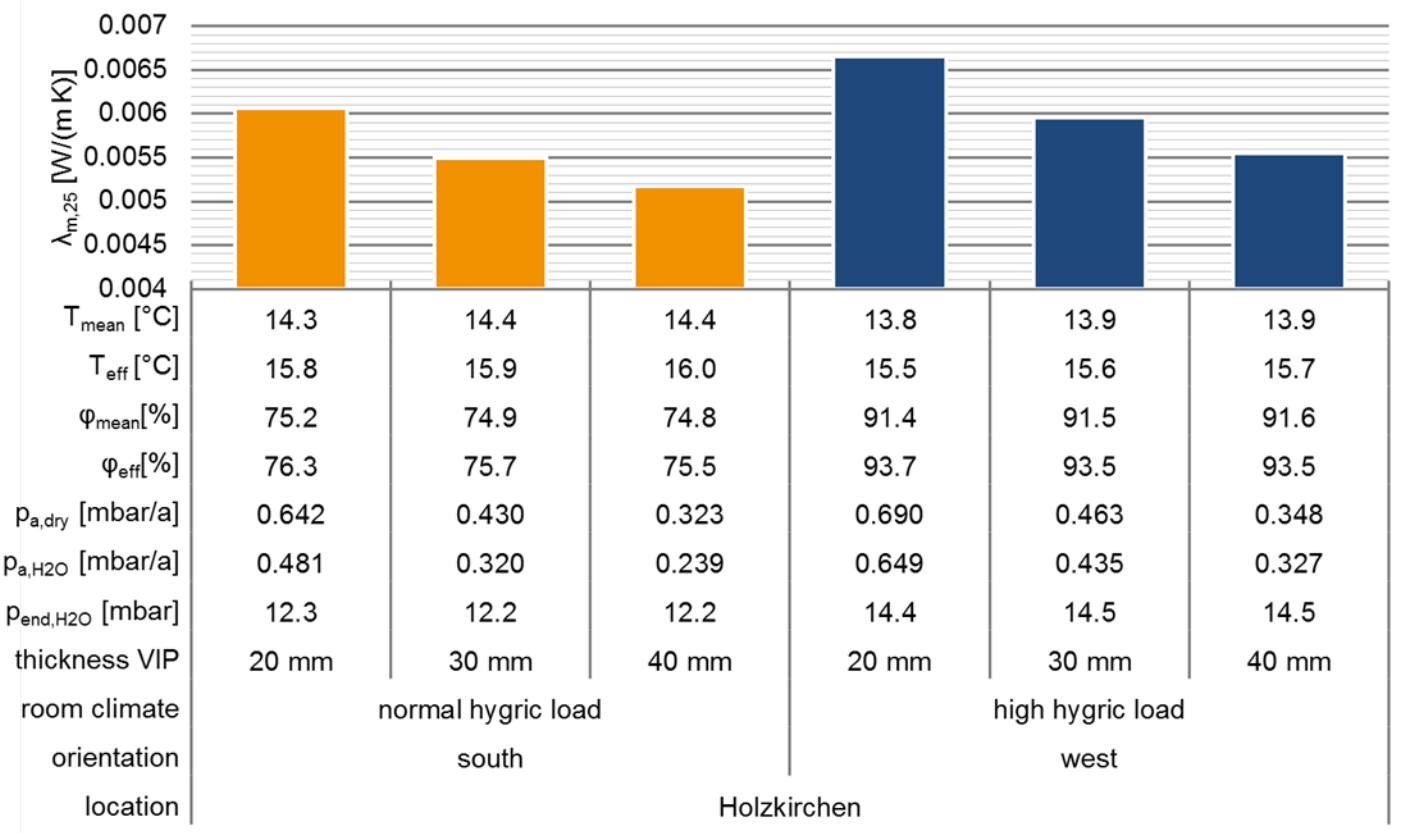
Ventilated facade system

T_{mean} [°C]	15.9	15.9	15.9	13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7
T_{eff} [°C]	16.8	16.7	16.8	15.1	15.0	15.1	15.1	15.0	15.1	15.1	15.1	15.1	15.1	15.0	15.1
φ_{mean}[%]	67.9	67.6	69.3	67.9	67.6	69.5	76.2	75.9	78.0	76.3	76.0	78.2	76.1	75.8	77.8
φ_{eff} [%]	67.8	68.1	70.4	67.3	67.6	69.8	77.4	77.8	80.4	77.6	78.0	80.7	77.1	77.6	80.1
$p_{a,dry}$ [mbar/a]	0.649	0.649	0.658	0.590	0.589	0.597	0.623	0.621	0.631	0.624	0.622	0.633	0.621	0.620	0.630
$p_{a,H2O}$ [mbar/a]	0.438	0.439	0.459	0.389	0.390	0.407	0.470	0.471	0.496	0.472	0.473	0.499	0.467	0.468	0.492
$p_{end,H2O}$ [mbar]	12.2	12.2	12.5	10.6	10.6	10.9	11.9	11.9	12.2	12.0	11.9	12.2	11.9	11.9	12.2
cladding	none	XPS	GFK	none	XPS	GFK	none	XPS	GFK	none	XPS	GFK	Keine	XPS	GFK
room climate	normal hygric load			normal hygric load			high hygric load			high hygric load			high hygric load		
orientation	south			south			south			north			west		
location	Freiburg			Holzkirchen			Holzkirchen			Holzkirchen			Holzkirchen		

Influence of panel thickness (20 – 40 mm) e. g. exterior insulation system



Influence of panel thickness (20 – 40 mm) e. g. exterior insulation system

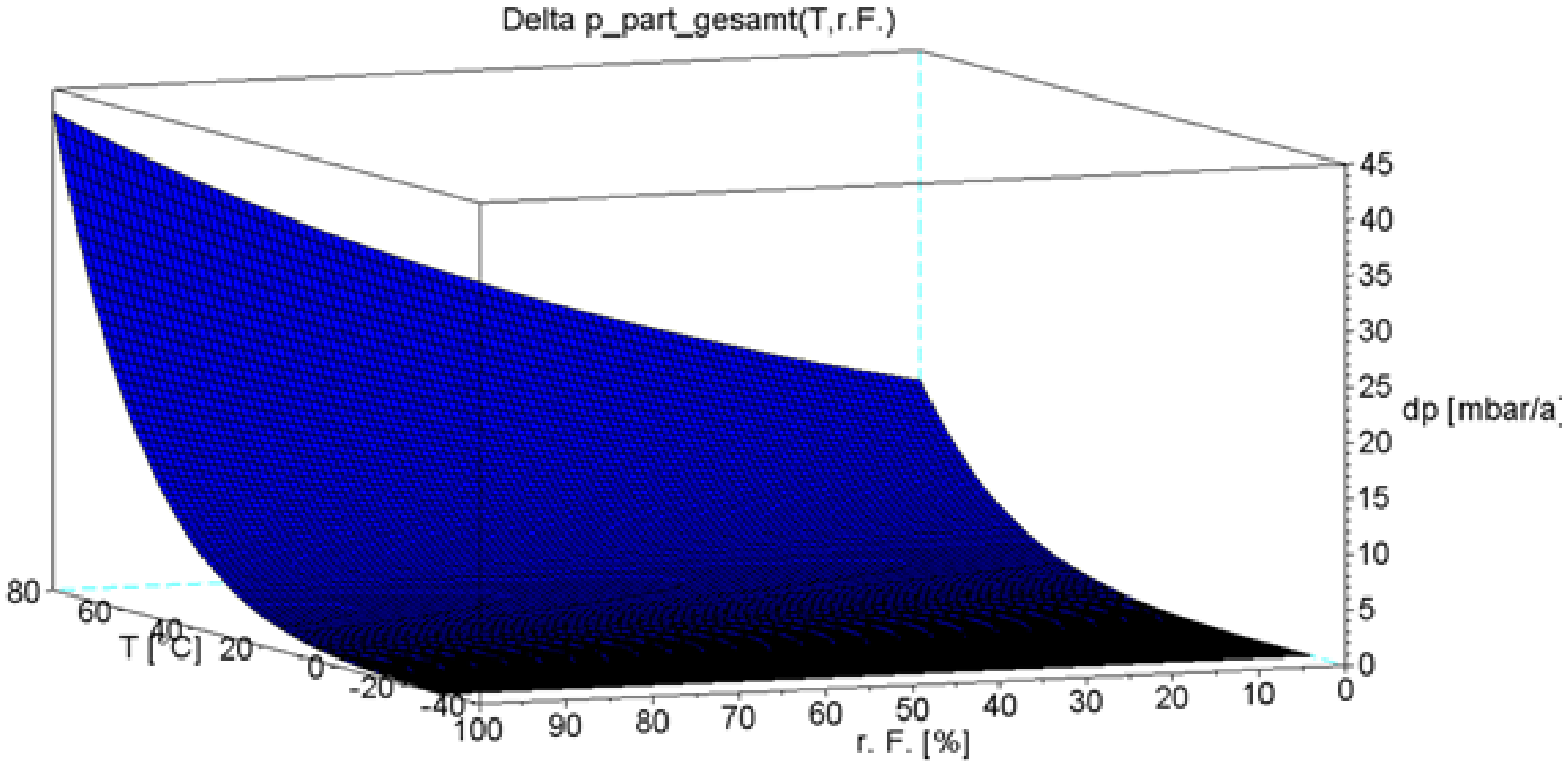


T_{mean} [°C]	14.3	14.4	14.4	13.8	13.9	13.9
T_{eff} [°C]	15.8	15.9	16.0	15.5	15.6	15.7
φ_{mean}[%]	75.2	74.9	74.8	91.4	91.5	91.6
φ_{eff}[%]	76.3	75.7	75.5	93.7	93.5	93.5
$p_{a,dry}$ [mbar/a]	0.642	0.430	0.323	0.690	0.463	0.348
$p_{a,H2O}$ [mbar/a]	0.481	0.320	0.239	0.649	0.435	0.327
$p_{end,H2O}$ [mbar]	12.3	12.2	12.2	14.4	14.5	14.5
thickness VIP	20 mm	30 mm	40 mm	20 mm	30 mm	40 mm
room climate		normal hygric load			high hygric load	
orientation		south			west	
location		Holzkirchen				

Adequate reference conditions?

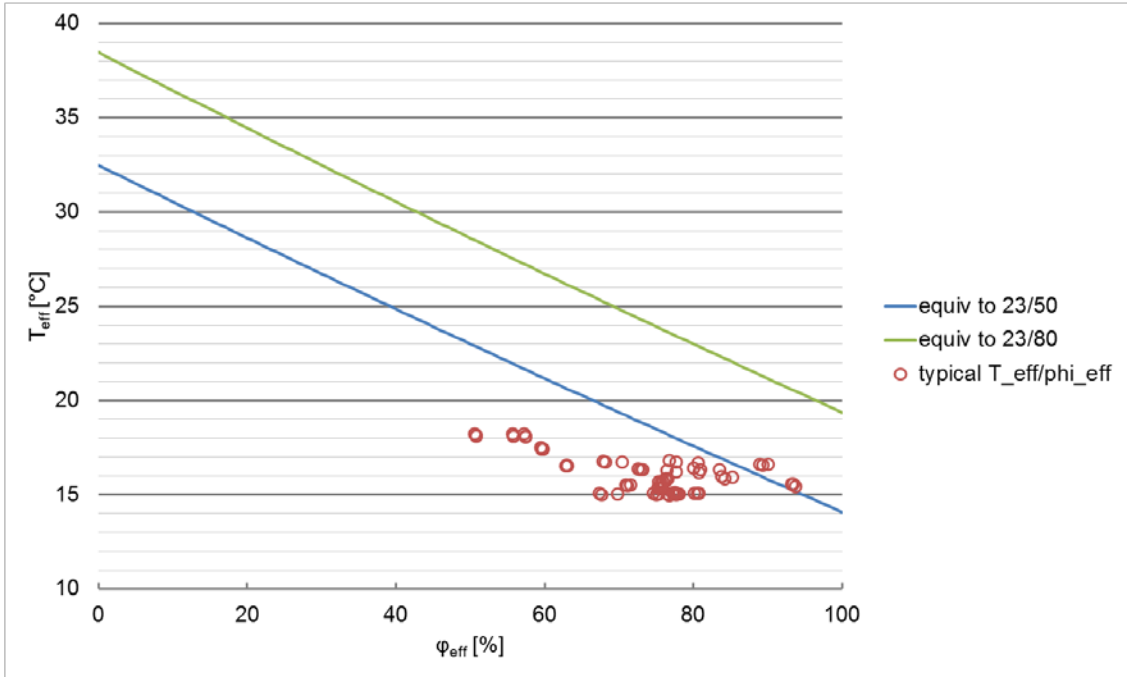
- According to draft standard ageing with 50°C/70 % r. h.
- Determination of pressure increase / thermal conductivity
- Conversion of these values to 23°C / 50 % r. h.
- Calculation of mean thermal conductivity over the first 25 years
- Are these reference conditions (23/50) adequate?

Increase of internal pressure as a function of temperature and r.h.

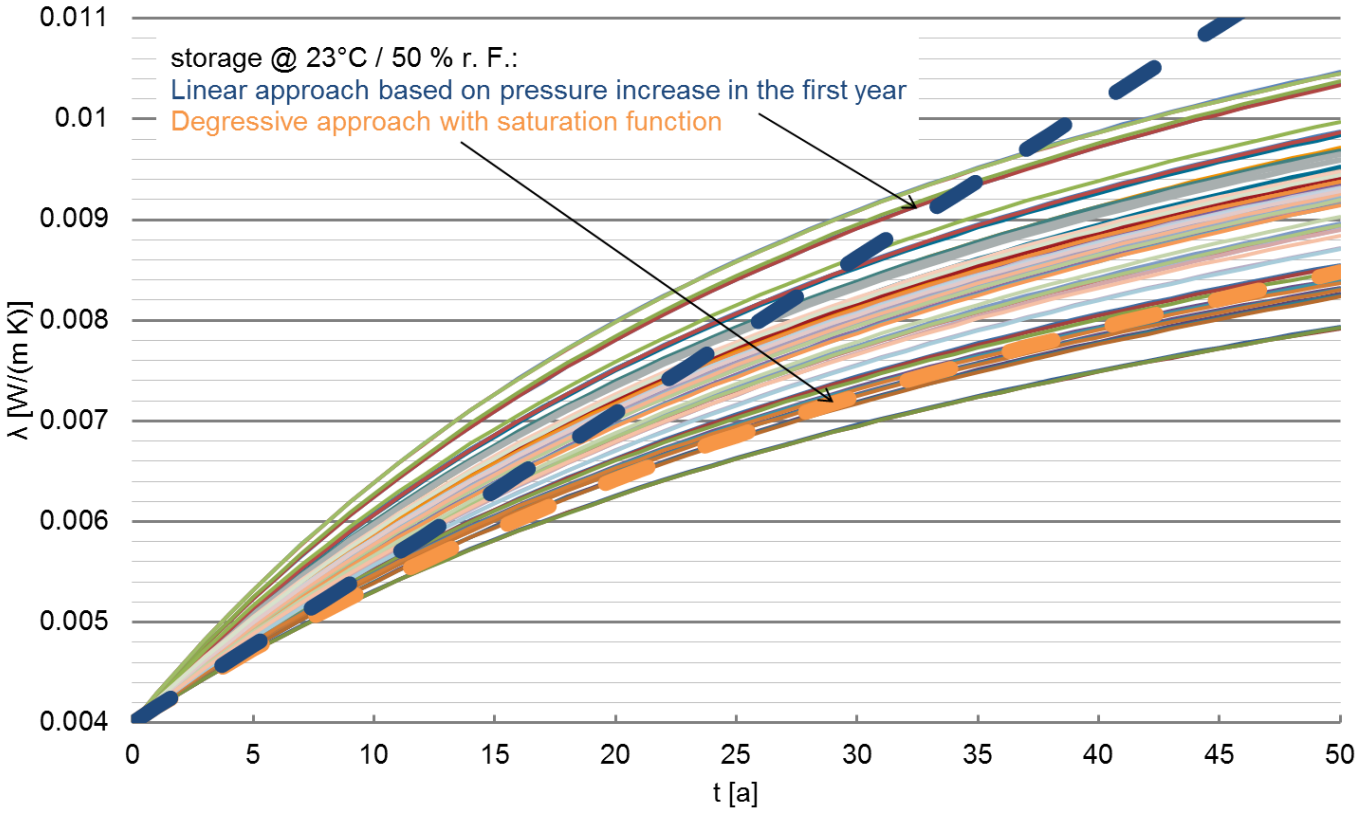


Adequate reference conditions?

- Isolines with $p_{increase,tot}$ = $p_{increase,tot}$ (23/50) and $p_{increase,tot}$ (23/80)
- Compare with effective temperature and r.h. of modelled applications
- 23/50 seems to be adequate
- 23/80 is on the safe side



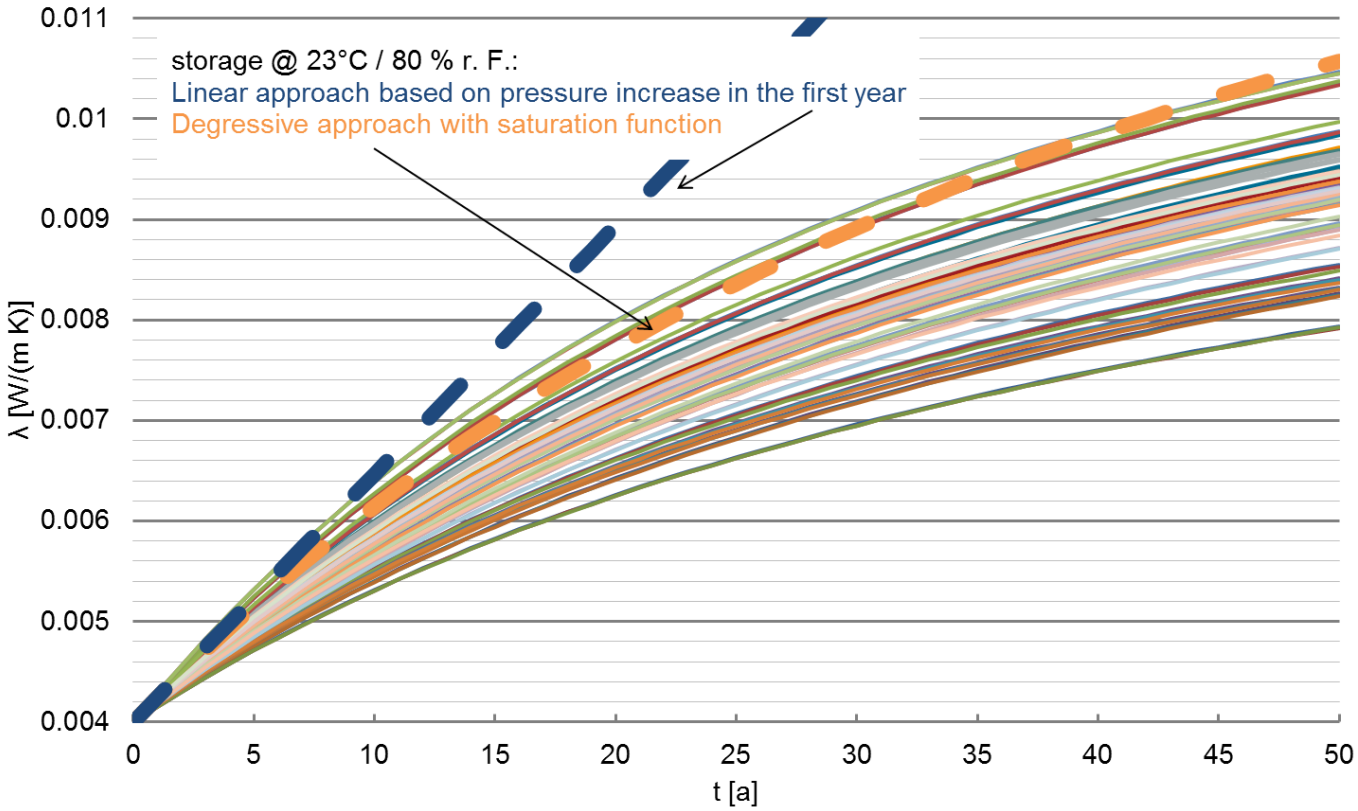
Constant 23/50 storage vs. detailled ageing model



Adequate reference conditions?

- 23°C / 50 % r.h. as reference condition looks good for the pressure increase
- However, it underestimates the increase of thermal conductivity
- Reason: $\Delta\lambda_F$ becomes higher with higher moisture content of the core (that is dependent on adjacent r.h.)
- Calculation of increase of thermal conductivity for constant conditions with 23°C / 80 % r.h. show…

Constant 23/80 storage vs. detailled ageing model



Conclusions

- Application, location of the building, orientation and interior climate are of influence on the specific ageing behavior
- The chosen model gives realistic results – estimation of the increase of thermal conductivity of VIP is possible
- Mean thermal conductivity for the first 25 years is in the range of actual declared values
- With ongoing time (> 25 Jahre) the annual rates of increase of thermal conductivity become lower (saturation function)
- Thicker panels show an improved ageing behavior with lower increases of thermal conductivity (larger volume inside the foil)

Conclusions

- With respect to pressure increase only, the calculation of $\lambda_{mean,25a}$ based on constant storage at 23/50 seems to reflect the behavior in real life conditions adequately
- However, moisture increase of the core is higher in real life applications – therefore 23/80 as reference conditions seems more appropriate
- Occurs on the dependency of λ as a function of moisture content, herein determined with 2.77 mw/%MC (seems to be relatively high)
- This value has to be double checked to valid the findings

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