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SESSION 2.1 INNOVATIVE MATERIALS – 2.1.3
This session focuses on progress in thermal insulation, both materials and systems

Single and double layered vacuum insulation panels of the same thickness in comparison

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Abstract:
The thickness of VIP used in the building envelope of primarily 20 mm in 2004 has reached a value of up to 60 mm in 2010. Hence a VIP double layer represents an alternative to thick single layers. The presented study on staggered, non-staggered and thick single VIP layer compares these alternatives with respect to thermal bridge and aging effects. These effects are both dependent on VIP thickness.

Keywords:
Vacuum insulation panels, VIP, aging, pressure increase, moisture uptake, thermal bridge effect

1. INTRODUCTION

Double layers of vacuum insulation panels (VIP) are used more and more, as low energy houses, passive houses, or even energy plus houses are built in an increasing number.
The situation of a double layered VIP shall be looked at in the perspective of the procedure described in RAL-GZ 960 [RAL2009] or the Swiss Quality assurance and declaration procedure [Brunner2009]. RAL is a private Quality Mark based in Germany.
Specific requirements pertinent to this study are that the aging due to pressure increase as well as moisture uptake over the commonly regarded 25 years shall be calculated. Secondly that 90% fractile of the production statistic as well as the edge effect shall be considered for the calculation of the 25 years predicted value.

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Vacuum insulation panels of a major manufacturer are considered. Figure 1 shows such a VIPs. The edges of almost all VIPs nowadays on the European market have 2 edges without seam and 2 edges with seam. Edges without seam are optimal regarding the thermal bridge effect; edges with seam are needed for production reasons.

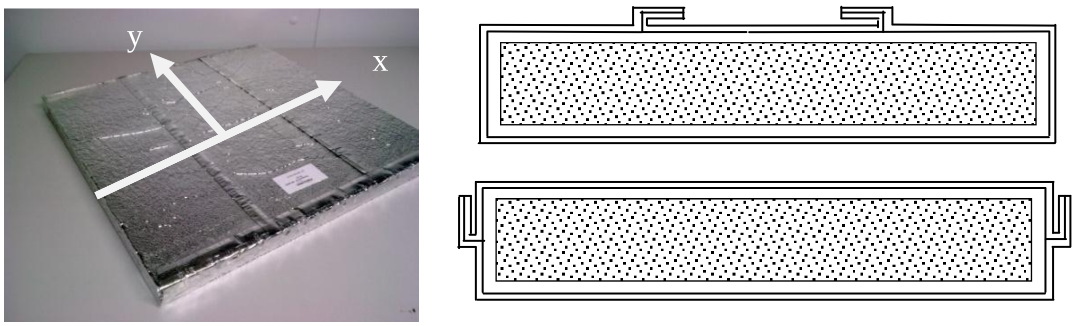

FIGURE 1: Left: Picture of a vacuum insulation panel (VIP), right top: schematic cross-section through this VIP along the x-axis. Right bottom the cross-section along the y-axis. The initial thermal performance data for these VIPs are λ_{cop} 4.1± 0.2 mW/m•K for the center-of-panels. The 90% fractile values $\lambda_{cop,\ 90\%}$ 4.4 mW/m•K is used later in the paper, when aging data are calculated.

2. EXPERIMENTAL SET-UP

All thermal resistance measurements were carried out in a guarded hot plate with a two-specimen symmetrical assembly in accordance with the international standard ISO 8302 (1991). The guarded hot plate is an absolute test method requiring no calibration. The apparatus used had an overall samples size of 500 x 500 mm with a metering area of 250 x 250 mm. The measurements were done at a mean temperature of 10°C with a gradient of 10°C. The accuracies of the measured thermal conductivities were within 5%.

3. SINGLE LAYER

A single layer will be considered before looking at double layered VIPs.

A gap of 3 to 4mm was seen to be typical for installations of VIPs on flat roof constructions [Brunner2008a], due to length and width tolerances.

Intermediate note 1:

So higher edge effect values are now considered, other than in Empa's publication 2004 until 2008, where the ideal potential of VIP was searched. (Not forced together anymore as in [GhaziWakili2004], where also rubber sheets had been used, because the aluminum thickness investigated there ranged up to 8 µm. Now a laminate with 3 by 100 nm is used with a total thickness including polymeric layers of measured 94 to 98 µm. This laminate type was already investigated in [Brunner2006] and [Brunner2008b] *and is called there Laminate L1. The Laminate L1 is called MF2 in [Simmler2005a], and MF4 in [Simmler2005b].*

VIPs as in Figure 1 have edges with seam as well as edges without seam. When placing them on an area, there can be joints without seam (called here Psi 1) as well as joints with seam on both adjacent VIPs. The last one will be called here Psi 2. (The mixed situation in a joint with a VIP edge without seam and the other with seam is seldom on flat roof application described in [Brunner2008a] and also called a terrace application.

Edge effect type Psi 1 Edge effect type Psi 2

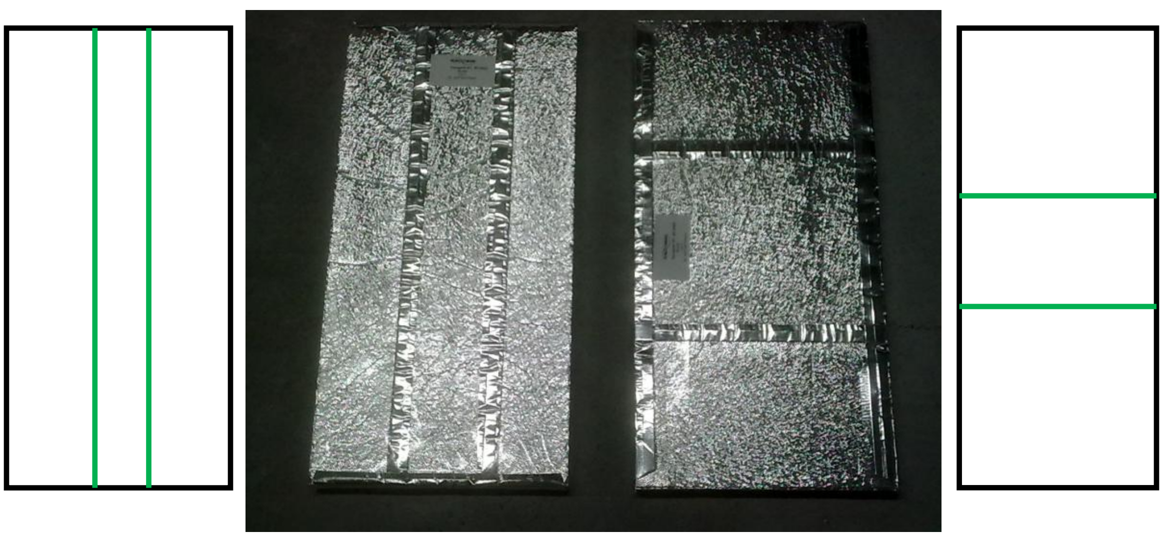

FIGURE 2: Picture of the VIP for thermal bridge determination. Two of each of these VIP types, were joined for the measurements in the guarded hot plate device.

The results of the guarded hot plate measurements are in Table 1. Because the joint is in the measuring zone of 250 mm x 250mm of this device, it is called here the effective thermal conductivity. The joint length is 250 mm and edge length ℓ with 500 mm. There are two edges in a joint. The equation from [GhaziWakili2004] $\lambda_{eff} = \lambda_{cop} + \Delta_{edge} = \lambda_{cop} + \Psi(d) \cdot d \cdot p/A$ with p as the edge length of a VIP (p from perimeter) is used here in the form

$$\psi_{edge} = \frac{A}{d_{VIP} \cdot \ell} \left(\lambda_{eff} - \lambda_{cop} \right) \qquad \textit{(Eq. 1)}$$

where

A	=	area (of the measuring zone)
ℓ	=	length of the two edges in the measuring zone of the guarded hot plate
d_{VIP}	=	thickness of the VIP
λ_{eff}	=	effective thermal conductivity
λ_{cop}	=	center of panel thermal conductivity

Intermediate note 2:

- The unit of Ψ and λ is by chance the same. In this paper Ψ is given in W/m·K and λ in mW/m·K to raise the awareness until the end, not to compare the numbers directly.
- Further there had been a second device with measuring zone of 350 mm x 350 mm was used in the project when regarding 4 producers VIPs.
- Another way to write the thermal bridge effect of the edge would be

$$\Psi_{edge} = \frac{\dot{Q}_{joint} - \dot{Q}_{1-\dim}}{\Delta T\, \ell} = \left(\frac{1}{R_{joint}} - \frac{1}{R_{1-\dim}}\right)\frac{A}{\ell} \text{, in W/m•K} \qquad \text{(Eq.2)}$$

TABLE 1: Measured thermal bridge effect for single VIP layers with one joint. Results of thermal bridge measurements with single layer VIP.

VIP Thickness	Measured effective thermal conductivity λ_{Psi1} mW/m·K	Type	Ψ_{joint} W/m·K	**$\Psi_{edge,without\ sealing}$ W/m·K**
15 mm	5.5	Psi 1	0.022	**0.011**
20 mm				0.009 [1]
30 mm	5.5	Psi 1	0.016	**0.008**
40 mm	5.5	Psi 1	0.009	**0.005**
	± ca 0.1			
VIP Thickness	λ_{Psi2} mW/m·K	Type	Ψ_{joint} W/m•K	**$\Psi_{edge,\ with\ sealing}$ W/m•K**
15 mm	6.3	Psi 2	0.032	**0.016**
20 mm				0.0147 [1]
30 mm	6.7	Psi 2	0.023	**0.012**
40 mm	6.8	Psi 2	0.017	**0.009**
Thickness	$\lambda_{edge,\ average}$			**Ψ edge, average**
				W/m•K
10 mm	-			**0.020 [2]**
15 mm	-			**0.014**
20 mm	-			**0.012 [1]**
30 mm				**0.010**
40 mm	-			**0.007**

[1] Value obtained by interpolation

[2] Value obtained by nonlinear extrapolation using the theoretical curve in [GhaziWakili2004]

As average, e.g. without considering exact sealing situation, the following ψ-values are recommended to be used (in Switzerland) for this VIP-product. This includes a common gap of 3 mm between adjacent VIPs core, while the corners of the VIPs are in close contact.

The above value for the 20 mm panel is higher than the value 0.009 W/m•K in [GhaziWakili2004], as that one was a Psi 1 situation only. This value fits well with the results obtained for 15 and 30 mm VIPs (0.011 resp. 0.008) in Table 1 considering the deviation of ± 0.0016 W/m•K given in [GhaziWakili2004].

4. DOUBLE LAYERED VIPS – STAGGERED SITUATION

As described already in [GhaziWakili2011] published recently, different thermal bridge situations B to E do occur in double layered VIPs:

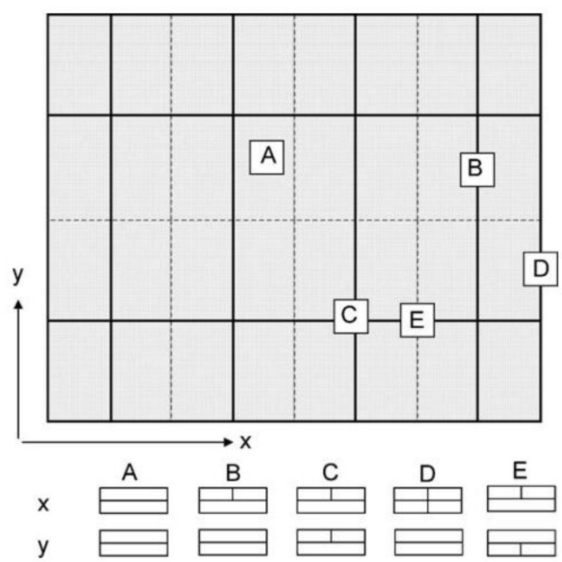

FIGURE. 3: Double layer of VIPs staggered in the x- and y-directions and the cross-sections of four different types of thermal bridges: [GhaziWakili2011].

Figure 3 describes (A) undisturbed double layer, (B) single joint in one layer, (C) cross joint in one layer, (D) single joint through both layers and (E) skew cross joint through both layers. Dashed lines indicate the lower VIP layer.

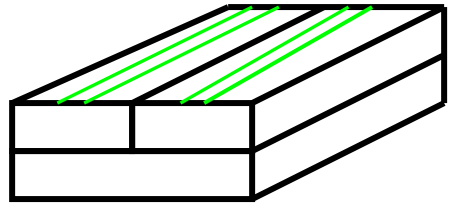

FIGURE 4: Situation B1, single joint in one layer with vertical projected measuring zone (yellow) of the guarded hot plate

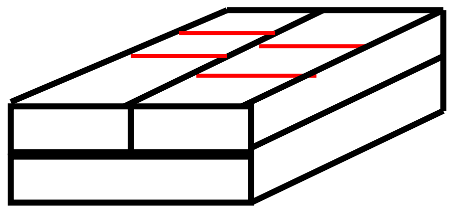

FIGURE 5: Situation B2
single joint with seal in one layer
A typical gap between the VIP cores can be seen at this 40 mm + 40 mm situation.

TABLE 2. Situation B.

Sample thickness [mm]	effective thermal conductivity $\lambda_{eff,}$ B [mW/m·K]	linear thermal transmittance ψ_B [W/m·K]	symmetrical sample situation on both side of guarded hot plate [mm]
Average all thicknesses	4.6 ± 0.2 [1]	**0.0025** ± 0.0015 [2]	2 pieces: 250 by 500 1 piece: 500 by 500

Intermediate note 3a:

[1] Value obtained by averaging the $\lambda_{eff,}$ B1 and $\lambda_{eff,}$ B2 in [GhaziWakili2011]

[2] Value obtained by averaging the ψ_B in [GhaziWakili2011] as described there.

Detailed results related to Table 2, the situation B with single joint in one layer are published in [GhaziWakili2011]. The difference between B1 and B2 could not be detected, due to production variation *(sigma($\lambda_{cop,\ single\ layer}$)) ± 0.2 [mW/m·K], a value measured in that paper for situation A for checked internal pressure (below 4mbar, average 1.8 mbar).*

Intermediate note 3b:
When looking in more detail at the B situation, the "with" and "without" seal had been distinguished in [GhaziWakili2011] as shown for B1 in Figure 4 and for B2 Figure 5). But other than in the single layer situation (Table 1), no significant thickness dependence could be determined experimentally. The deviations from the center-of-panel values (sigma(λ_{cop})= 0.2 mW/m•K) of nominal identical VIP with λ_{cop} 4.1± 0.2 mW/m•K in the single layer case, respective the related 90%-fractile $\lambda_{cop,\ 90\%}$ 4.4 mW/m•K, leads in the case of situation B as to too small differences to the $\lambda_{eff,}$ B, which had been between 4.3 and 4.9 mW/m•K for B1 and between 4.4 and 5.0 mW/m•K for B2 in [GhaziWakili2011]. Also the related reference situation A (Figure 3) had shown between 3.9 and 4.4 mW/m•K for the center-of-panel double layer case, which averages four nominal identical VIPs. In cases like the just mentioned 4.4 mW/m•K center-of-panel double layer case of four VIP with 500 mm by 500 mm by 20 mm, the internal pressure was checked after the thermal conductivity measurement and was below 4 mbar, so that the case of an higher value due to partial leakage is not the origin of the deviation. By the way, the average internal pressure was 1.8 mbar.

Situation D is equivalent to a non-staggered double layer situation, and the measured values reported in Table 3 are the same as in Table 1b, calculated for the average of single layer situations of the same thickness with and without seal at edge.

TABLE 3. Situation D with 4 pieces of 250 mm by 500 mm on each side [GhaziWakili2011]

Sample thickness d/2 [mm]	Effective thermal conductivity $\lambda_{eff;D}$ [mW/m·K]	Linear thermal transmittance ψ_D [W/m·K]
20	6.0 ± 0.2	0.013 ± 0.002
25	5.9 ± 0.2	0.008 ± 0.001
30	6.2 ± 0.2	0.010 ± 0.001

The thermal Bridge effect of a situation D is always to be divided by 2 for each single edge, as the measurement corresponds to 2 edges.

5. INFLUENCE OF THE SIZE OF THE AREA INSULATED WITH STAGGERED DOUBLE LAYER

Figure 6 show the sketch of a staggered double layer with upper and lower layer.

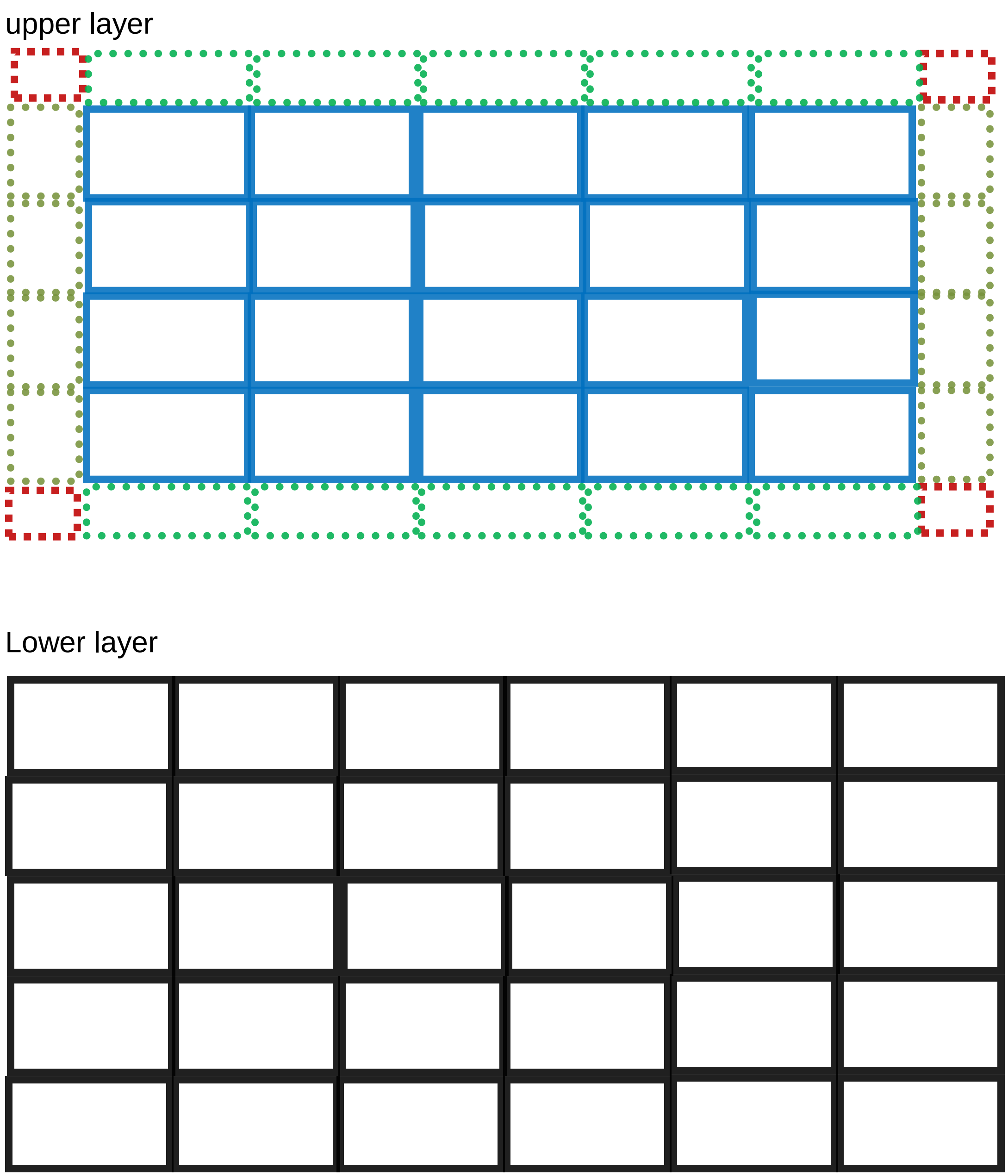

FIGURE 6: Sketch of a staggered double layer, where the upper layer is shifted with respect to the lower level. Full size (full line, blue), half size (dotted line, green and olive) and quarter size (dashed line, red). The lower layer is in full line and black.

Depending on the size of the area, which shall be insulated, small VIPs needed to fill the area can influence the initial effective thermal performance due to the thermal bridge effect. While Example 1, sketched in Figure 6 is with the area of 6x3 m is a medium size example, extremely small ones would have a high relative contribution of the small VIP, which is not an advantage due to the thermal bridge effect. As example 1 the area of 6x3 m, which fits by chance exactly to the lower layer, was regarded.

Example 1	*Area 6 by 3 m = 18 m^2 with staggered double layer*		
	Lower Layer	*30 VIP with*	*1000 by 600 by 20 mm*
	Upper layer	*20 VIP with*	*1000 by 600 by 20 mm*
		+ 10 VIP with	*1000 by 300 by 20 mm*
		+ 8 VIP with	*500 by 600 by 20 mm*
		+ 4 VIP with	*500 by 300 by 20 mm*
	Psi D / 2	*0.00625 W/m·K*	*18 m (Perimeter of total area)*
	Psi B	*0.0025 W/m·K*	*87 m (Joints)*

Result: $\boldsymbol{\lambda_{eff.\ 25\ years}}$ ***= 6.0 mW/m·K***

for 20 + 20 mm VIP staggered double layer,

This result includes aged VIP data and thermal bridge effect, as well as the 90%-fractile and is for VIP, where Empa measured λ_{cop} 4.1± 0.2 mW/m•K in the single layer case,

Intermediate note 4a

The related 90%-fractile $\lambda_{cop,\ 90\%}$ = 4.4 mW/m•K is used above for this VIPs, where Empa measured λ_{cop} 4.1± 0.2 mW/m•K in the single layer case. As reported later in this paper, aging raises the value from 4.4 mW/m•K to e.g. 5.0 mW/m·K for VIPs with 1000 mm by 600 mm by 20 mm without considering thermal bridge yet. Small VIPs have a higher aging contribution. 500 by 300 by 20 mm is listed in Table 14 with 5.5 mW/m·K. The aging related increase is calculated to be 0.6 mW/m•K for most common used VIP size and 1.1 mW/m·K for smallest size used here.

Example 2: Very large area

A larger area e.g. 10 by 20 m with less type D thermal bridges results in $\lambda_{\textit{eff. 25 years, including edge effects}}$ = 5.9 mW/m·K for the staggered case. A non-staggered double layer on the other hand has 6.3 mW/m•K. Comparing staggered to non-staggered double layer, it can be concluded, when looking at thermal bridge effect only, that the staggering reduces the thermal bridge effect by about 30% for very large surface sizes. This is due to non-zero lateral heat flows.

6. COMPARISON OF STAGGERED DOUBLE LAYER (20 + 20 mm) WITH A CORRESPONDING SINGLE LAYER (40 mm)

The comparison of staggered double layer and a single layer depends on the sizes of the area to be insulated, as the weight of different thermal bridge types varies with size of the area (and the size of the single panel). The example above with area 6 by 3 m results to 6.0 mW/m·K *Intermediate note 5*

This includes aging and thermal bridge effect as well as the 90% fractile of the production statistic. The intention is to get in line with the European Standards EN 13162 to 13171 of factory made thermal insulation products.

Comparing a staggered double layer, with a single layer of the same total thickness, must consider two distinct effects: the thermal bridge effect and the aging effect. The information on aging effects is presented in Section 7 and 8. The result is results in 6.4 mW/m•K for the same total thickness (40 mm) for both area, the 6 by 3 m as well as for a very big one of 10 by 20 m.

Intermediate note 5a

This value is higher, due to higher measured thermal conductivity (Table 1 case Psi 2, and also in GhaziWakili2011).

Intermediate note 5b:

Lateral flow is the limited by the heat flow in the joint for increasing thickness. Energy is saved despite slightly rising lambda values, when the thickness increases. As shown for case Psi1 with same measured thermal conductivity in joint situation, clearly lower energy lost at the thermal bridge:

	with joint			
Thickness	Measured effective thermal conductivity mW/m·K	Ψ edge, without seal W/m·K	R-value joint K/W	1/R (near U-value) W/K
15 mm	5.5	0.016	2.7	0.37
30 mm	5.5	0.012	5.5	0.18
40 mm	5.5	0.009	7.3	0.14

	Centor of panel 4.1 mW/m•K		**lost energy due to thermal bridge effect**
Thickness	R-value COP K/W	1/R (near U- value) W/K	Delta of 1/R (near U-value) W/K
15 mm	3.7	0.27	**0.093**
30 mm	7.3	0.14	**0.047**
40 mm	9.8	0.10	**0.035**

By the way, both units in 1/R, the Watt and the temperature difference are primarily logged units. Other than in the thermal conductivity value, no error contribution from actual thickness is in 1/R. So 1/R is in the guarded hot plate more precisely known than λ_{cop}. The deviation of the thickness is normally the limiting factor regarding the precision of thermal conductivity value, not the ΔT or the electrical heat.

Intermediate note 5c:

The U-value, respective 1/R as the value to be minimized in the used of VIP as insulation, not Ψ or λ_{cop}. Adding additional layers out of foam to reduce Ψ increases the thickness of the regarded system. Lowering λ_{cop} by using e.g.by glass fiber cores affects the amount of edge effect and/or the aging.

Intermediate note 5d:

Besides the advantage of better performance of the thermal conductivity including aging and thermal bridge $\lambda_{\text{eff, 25 year, incl. thermal bridge effect}}$, a double layer of VIP has the advantage of better reliability regarding "Infant mortality", a term borrowed from reliability statistic, which describes the decreasing failure rate in the early part of the bath tub curve e.g. [Meeker1998].

Intermediate note 5e

The calculation for the example 1 and 2 is uses results from aging prediction for 25 years. These data shall are explained here in short, to enable recalculation.

TABLE 4: Values used above, based on results from chapter following later in this paper

VIP size *mm*	*Thermal conductivity* $\lambda_{cop,25y,\ 90\%}$ *mW/m•K* *without thermal bridge effect*	*Effective thermal conductivity* $\lambda_{eff,\ 25y,\ 90\%,}$ *mW/m•K* *incl. thermal bridge effect*
1000 by 600 by 40	*5.1*	*6.4*
1000 by 600 by 20	*5.0*	*6.3*
1000 by 300 by 20	*5.3*	*7.2*
500 by 600 by 20	*5.2*	*7.0*
500 by 300 by 20	*5.5*	*8.0*

TABLE 5: Thermal bridge parameters

	VIP thickness	*Interpolated Psi*
$\Psi_{edge,without\ seal}$	*20 mm*	*0.0100 W/m•K*
$\Psi_{edge,with\ seal}$	*20 mm*	*0.0147 W/m•K*

And equations 3 :

$$\lambda_{eff} = \lambda_{cop} + \Psi_{d,edge} \cdot d_{VIP} \cdot (perimeter_{VIP} / surface_{VIP}) \qquad (Eq.3)$$

7. AGING MEASUREMENTS

Data are needed for the equation

$$\lambda(t) = \lambda_0 + \Delta\lambda(t) \cong \lambda_{90\%} + \lambda_p \cdot p_a \cdot t + \lambda_{Xw} \cdot X_{w,eq} \left(1 - \exp\left(-t/\tau\right)\right) \quad \text{(Eq. 4)}$$

Core related parameters are $\lambda_{90\%}$ as received from production statistic collected by the manufacturer and checked for plausibility with 3 additional lab measurements.

The 90% fractile value of production statistic as received from the manufacturer is $\lambda_{90\%}$ = **4.4 mW/m•K**. The mean 4.1, min. 3.2, max 4.8 .

Intermediate note 6

In future QS documents $\lambda_{90\%}$ shall to be changed to 90% with 90% confidence, which would add often another 0.1 mW/m•K.

TABLE 6: **Measurement on VIPs as delivered with 500 mm by 500 mm and nominal thickness 15, 20, 30 mm ***

Measurement number	Sample number	Internal pressure mbar	Thickness mm	**Thermal conductivity Lambda mW/m•K**	$R_{1\text{-dim}}$ (m^2 K)/W
1	78 / 80	1.8 / 2.4	16.1 / 16.1	**4.1**	3.9
2	86 / 88	1.2 / 1.3	21.7 / 21.7	**4.0**	5.4
3	94 / 96	1.7 / 1.2	31.5 / 31.6	**3.9**	8.1

*which is a single layer measurement in the symmetrical guarded hot plate.

TABLE 7: **VIPs resealed with higher internal pressure,**

Measurement number	**Internal pressure mbar**	**Lambda mW/m•K**
4	**58**	**5.3**

$\lambda_p = d\lambda / dp \approx ((5.3 - 4.1)/(58 - 0.97))$ is about 0,021 mW/m•K•mbar for this VIP with 500 mm by 500 mm by 30 mm

TABLE 8: ***VIP resealed to get the moisture dependence***

Measurement number .	**Moisture increase (du)** **M-%**	Internal pressure mbar	**lambda** **mW/m•K**
5	**3.06**	16	**4.8**

$d\lambda / du \approx ((4.8-4.1)/(3.06-0))$ is about 0,23 mW/m•K•M-% for this VIP with 500 mm by 500 mm by 30 mm. (opened, ice added and resealed, leading to a weight increase of 45 g water. Weight of addition envelope considered)

TABLE 9: VIP vented (opened)

Measurement number	lambda mW/m•K
6	19

Within the QA Procedure 3 data points of the sorption isotherm have to be measured:

TABLE 10: Measurements for the sorption isotherm (3 samples)

Climate	Moisture Content (m-%)
23°C 35% r.H.	0.77 ± 0.08
23°C 50% r.H.	1.40 ± 0.08
23°C 80% r.H.	5.28 ± 0.05

The QA-procedure to calculate the 25 year prediction simplifies here with a linearization shown in the next Figure:

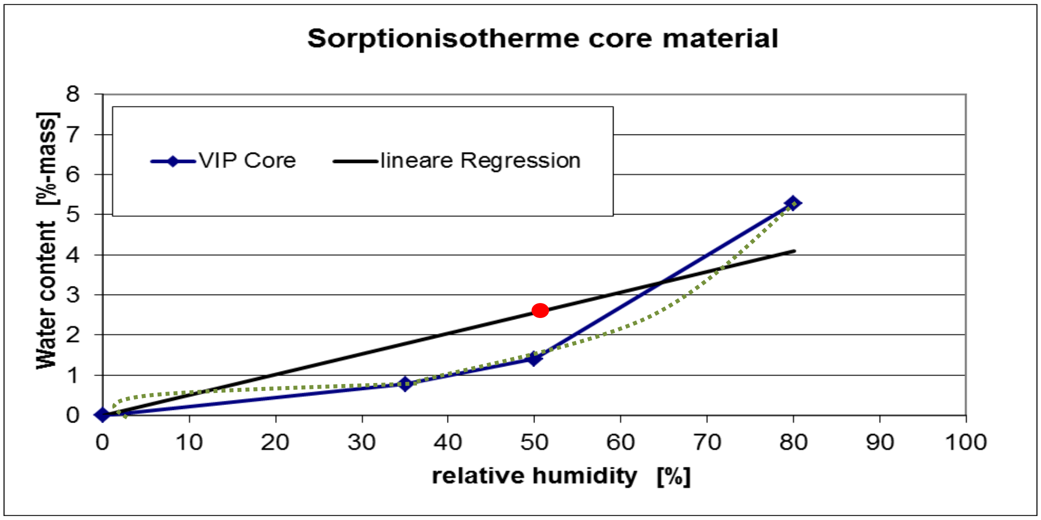

FIGURE 7: Sorption isotherm of core mixture based mainly on pyrogenic silica

The value used here for further calculations is 2.6 %-mass, and not the measured 1.4, because the condition of using a VIP is different from 23°C 50%r.h for the cold side of the VIP, but often similar to the warm side for most building applications..

Intermediate note 6a:

The value is linearized from 3 point measured on the sorption isotherm with given relative humidity from the procedure. This simplifying linearization has in this case only a minor influence, as the dry gases dominate (by 90% for most VIP sizes)), while for other VIP Types used in Building applications, the simplified analysis gives dominating influence of water vapor on the pressure increase. But a more detailed analysis has to be done, as this could be only due to the simplifications.
For this case here with small $\Delta\lambda_{25years}$, and bigger $\Delta\lambda_{thermal\ bridge}$, the $\lambda_{25years,\ eff}$ is good enough predictable based on this SLP model. (With big $\Delta\lambda_{25years}$ the model is less good, but building application do no longer make sense then.)

Intermediate note 6b:

Also for VIPs in refrigerators the warm side is near 23°C 50%r.h when of used in moderate climate zones. The other side is cold, resp. most time colder on building envelope application in moderate climatic zone, (an argumentation for at least Europe, or the northern part of North America.).

TABLE 11: Measured internal pressure, with start about 1 month after production.

VIP Size mm	Internal pressure start [1] p , mbar	Internal pressure 131 days p , mbar	Internal pressure 187 days p , mbar
250 by 250 by 10	2.41	3.45	3.97
250 by 250 by 10	2.07	3.30	3.58
250 by 250 by 10	2.09	3.19	3.56
deviation*	± 0.07	± 0.09	± 0.09
500 by 500 by 15	2.27	2.88	3.18
500 by 500 by 15	1.83	2.36	2.64
500 by 500 by 15	1.32	1.92	2.20
deviation*	± 0.04	± 0.07	± 0.06
500 by 500 by 20	1.20	1.87	2.02
500 by 500 by 20	1.34	2.05	2.20
deviation*	± 0.01	± 0.03	± 0.03
500 by 500 by 30	1.80	2.54	2.71
500 by 500 by 30	1.29	2.04	2.21
deviation*	± 0.03	± 0.05	± 0.03

[1] at start the VIPs have about a month or more since their production to avoid effects from the very first days on the measured pressure chance.
* Deviation of 3 blowing repetitions with 3 or 4 lasers distance measuring units

Laminate and folding type related values are

TABLE 12: Increase in internal pressure and moisture at 23°C 50%.r.H. as well as the moisture increase related time constant.

VIP size mm	Increase in internal pressure $\dot{p}$ **, mbar / year**	Moisture related weight increase $\dot{u}$ **, %-mass / year**	Time constant moisture equilibration τ, years
250 by 250 by 10	3.0	0.04	
250 by 250 by 10	2.9	0.05	
250 by 250 by 10	2.9	0.06	
Mean :	**2.9**	**0.05**	51
500 by 500 by 15	1.8	0.04	
500 by 500 by 15	1.6	0.03	
500 by 500 by 15	1.7	0.03	
Mean :	**1.7**	**0.03**	85
500 by 500 by 20	1.6	0.027	
500 by 500 by 20	1.6	0.017	
Mean :	**1.6**	**0.022**	117
500 by 500 by 30	1.7	0.018	
500 by 500 by 30	1.7	0.021	
Mean :	**1.7**	**0.020**	128

Thickness rule* is not followed as expected: neither pressure nor moisture increase is inversely proportional to thickness.

Intermediate note 7:

Thickness rule: At 30 mm thickness a value of half of 1.7 mbar / year for 15mm is expected (IEA Annex39-project [Simmler2005b]), but the measured value was 1.7 mbar / year. 0.020 %-mass / year was measured and not half of 0.03 %-mass / year. Within 4 VIP-types from 4 manufactures, 1 followed the thickness rule within the measurements deviation.

TABLE 13: **Predicted values for climate 23°C / 50% r.H. for a single layer**

VIP Size [mm]	250x250x10	500x500x15	500x500x20	500x500x30
Predicted values for 25 years Internal pressure p_{total} [mbar] Moisture content u [%-mass]	 76 1.0	 45 0.7	 42 0.5	 44 0.5
Thermal conductivity $\lambda_{cop,25y}$ [mW/m·K] without thermal bridge effect for this pyrogenic SiO_2 based core	6.0	5.3	5.3	5.3
Ψ – value (with resp. without sealing) [mW/m·K]	25 resp 15	16 resp 11	14.7 resp. 10	12 resp 8
Effective thermal conductivity $\lambda_{eff,\ 25yaers}$ [mW/m·K] incl. thermal bridge effect	**9.2**	**6.9**	**7.2**	**7.7**

The last row in Table 13 represented in a Figure as function of time:

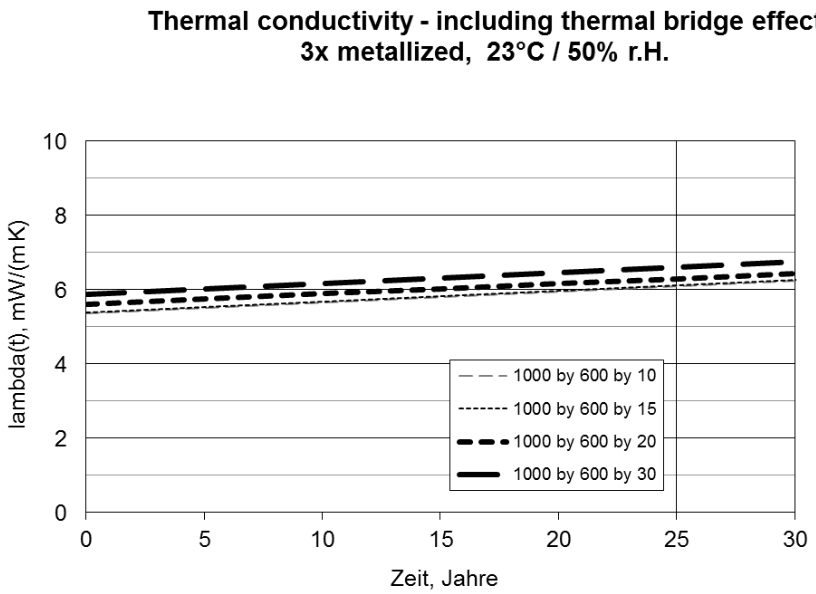

FIGURE 8: Aging prediction for measured VIP sizes

For other sizes, using 250 mm by 250 mm by 10 mm for size extrapolation, and assuming the same low thickness dependence also for 500 mm by 500 mm by 10 mm, it is possible to extrapolate to larger sizes:

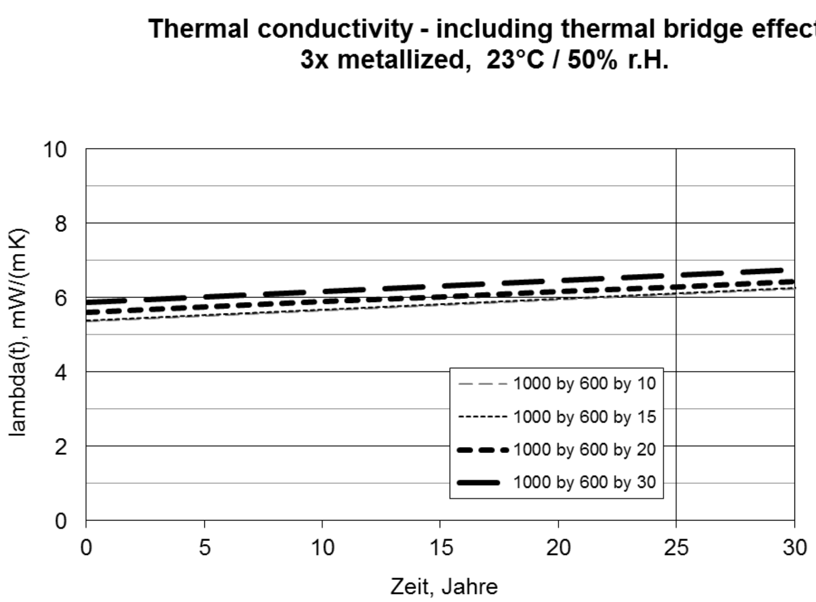

FIGURE 9: Aging prediction for larger VIP sizes
(both time and size extrapolated)

To do this the thickness rule for the measured thickness had to be adapted.

TABLE 14: Predicted values for other VIP size (as Table 4) starting with $\lambda_{90\%}$ = 4.4 mW/m•K

VIP size **mm**	Thermal conductivity $\lambda_{cop,25y}$ mW/m•K without thermal bridge effect	**Effective thermal conductivity** $\boldsymbol{\lambda_{eff,25y}}$ **mW/m•K** **incl. thermal bridge effect**
1000 by 600 by 40	5.1	**6.4**
1000 by 600 by 20	5.0	**6.3**
1000 by 600 by 10	5.1	**6.1**
1000 by 300 by 20	5.3	**7.2**
500 by 600 by 20	5.2	**7.0**
500 by 300 by 20	5.5	**8.0**

For larger sizes values between 6 and 7 mW/m·K are calculated. So declaration values of 7 and 8 mW/m·K are for this VIP used in Switzerland, depending on the VIP size, and no longer on the VIP thickness, as before. With continuous increase expected for the average of service life of other insulation systems such as External Thermal Insulation Composite Systems (ETICS), listed with 30 t0 40 years.

8. LESSONS LEARNED

Only about 1/3 of the edge effect can be reduced by staggering the VIP.

VIP size [mm]	$\lambda_{eff,\ 25\ year}$
1000 by 600 by 20 staggered double layer	5.9 mW/m•K
1000 by 600 by 40 single layer	6.4 mW/m•K

Intermediate note 8 regarding links to work of others:

Beside the advantage of a better performance regarding $\lambda_{eff,\ 25\ year,\ incl.\ thermal\ bridge\ effect}$, a double layer of VIP has the advantage of better reliability regarding "Infant mortality", related to the production as well as *related to installation or damage with reasons occurring later during the service life. The occurrence of "childhood failure" has been shown by Heinemann et al. [Heinemann2009, Heinemann2010].*

The above prediction is based on permeation of dry gases (O2, N2, and few amounts of noble gases) as well as water vapor, which is treated separately. The work of Heinemann [Heinemann2009, Heinemann2010] gives good hint's, that the prediction will be valid for about 87% resp. 95% of the "population", i.e. the number of VIPs.

Reliability will increase, with increasing emphasis on production QA and installation experience, as long as the market is willing to pay for it. From the energy saving point of view, this reliability level is already attractive. It is realistic to take into account a small number of vented VIPs, which will result in lower surface temperature on the room side of the construction. The thickness of the VIP should be chosen, so that even if vented this surface temperature reduction does not cause condensation risk nor mold grow.

Due to higher psi –value than published by several other authors (based often on simulation only), and secondly the very small reduction of measured aging data with thickness, the former recommendation to use preferred thick VIP is no longer valid for many manufactures. At least, if we trust measurements more than theory. On the other hand, I got one series, where the thickness rule might be valid.

Aging related parameters are improved by several VIP producers since the IEA Annex39 report data [Simmler2005b]. On other hand we also had seen failures despite QA, some could be solved within weeks with identifying laminate problems, while for another case there was a step back in the way of folding applied to raise reliability back to low level as might be expected.

9. OUTLOOK

As the aging related contribution to effective thermal conductivity is below 1 mW/m•K over the required 25 years, there is potential to investigate the possibility of longer life times and the occurrence of other deterioration mechanisms. It would also be interesting, to quantify the dependence of VIP lifetime at a somewhat warmer environment.

Aging data give room for discussion on thickness related permeation or outgassing. Thickness related permeation could be, where the laminate is 180° folded, but a third tested series is against this hypothesis.

10. DISCUSSION

VIP Service Life Prediction as discussed in literature is in the often cited paper of Schwab et al. [Schwab2005], an elaborate investigation with a two times metallized laminate, with still the best dataset $d\lambda / du$ with 0.3 mW/m•K•M-% regarding used a quite unique device. Two times metallized laminate are an option for non-building application with lower durability requirements from my point of view, as long as they are from the required high quality. Quality problems had been seen with some producers, but not the leading one nowadays.

Also $d\lambda / dp$ is here lower than 0.035 mW/m•K•mbar used in [Simmler2005a]. There are several producers of VIPs, who reach lower values, but there is also the temptation to use cheaper core / envelope material and the RAL, resp. the Swiss procedure gives them the feedback Interested parties can ask producers for Empa's test reports. RAL is a Quality label [RAL2009].

Request for very long Service Life of 100 years like e.g. in the very recent review paper of Alam et al [Alam2011] are hard to show with organic materials. The well-established External Thermal Insulation Composite Systems (ETICS) has in building planning documents of the Swiss home owner association [HEV2009] an average service of 30 years (with 25 to 45 year band) and for 100 years requirements foamed glass granulates or foamglass would be the option, listed with 120 years (with 100 to 150 years band). This is used e.g. beneath the ground plate of new buildings. It would be interesting to see the potential service life of other insulation material including polymeric materials like EPS (expanded Polystyrene) as used External Thermal Insulation Composite Systems (ETICS), to just name the most frequently used one. There are of course hint's for longer potential service life, especially for a minority of the "population", that will not see changes due to reasons independent of the insulation aging. On vented facades, animals (e.g. mice, wasps) can damage, if not installed and maintained properly, e.g. maintenance after storm events. A distinction between the physical service life and the above mentioned economical service life of 30 years is done in newest version of [Kasser2011] for the application in a "warm roof", with the argument of accepted difference in service life for this specific application. EPS, XPS, PUR/PIR is there with 50 years physical service life, mineral wool and glass wool with 60 years and foamed glass with 100 years. Such a roof is comparable to the roof described in [Simmler2005a] for the predicted aging of VIP and [Brunner2008a] for the measured pressure and moisture increase. Reference [Kasser2011] uses no service life for other insulation application. Life times do of course depend on the specific application. In [Heinemann2010] only one application type showed detectable rising failure, a type of application, that was now aware of the limitations mentioned in [Simmler2005a], that the pH has to be in the stable range of aluminum, as aluminum is exposed at the cutting edge of the laminate to the environment, which was in that case an alkaline render. Beside this wrong selected application, only 1 out of thousand was detected to fail after the first IR-imaging [Heinemann2010], so there is already quite a good database of about 2400 m^2 available to assume a continuation of a very low failure rate after the first winter, resp. after the installation.

Reference [Gudmundsson2011] on other hand used too short life times for his argumentations about using VIPs on buildings or not. e.g. the 25 years are not the end of the service life time, but just the age to declared insulation materials according to the standards. More insights in the stabilization package used in Polyethylene would be helpful for application of VIPs in hot desert locations. As well as more detail on the polyurethane glue for application of VIPs in tropic locations, especially for required lifetime beyond 25 years.

Another approach for the 25 year declaration developed in Germany for the DIBt values by1999, is based on accelerated testing. A 2011 Compendium written in German, gives an overview over practical and legal details of VIPs [Herr2011]. This accelerated test procedure was used also by Wegger et al [Wegger2011], and is there compared with literature data. The comment there “it seems that the CUAP falls a little short of covering an aging period of 25 years.” is no longer true, when the scaling factor of 15.3 in reference [Sprengard2011a] is considered. (resp. 1 / 15.3 /0.5 year*25 years =3.27) as used by DIBt and FIW in Germany. This accelerated test gets quite reasonable results, as the dry gas permeation is accelerated. But in case of new type of envelopes, like non-metallic ones, the scaling factor has to be determined again.

VIP size dependency (as in Table 13) is to my knowledge unique for this procedure developed at ZAE and Empa for VIPs to be used in building applications. VIP types with aerogel-core are not yet tested by an independent lab to my knowledge regarding the above parameters. VIP types with fiber or foam core do need added getters, not only the desiccant, whose behavior is determined in the sorption curve. Durability approach for VIPs with getters where presented at previous IVIS meetings, called VIA in 1998 to 2003, (Vacuum Insulation Association). Such types of VIPs are widely used outside Europe, and there are also companies advertising their VIPs for Building application. In the available English written literature, no durability related testing could be found for VIPs with getters since 2003 [Celik2003], despite quite an effort done for searching. Getters, as described there, likely to identify by pressure testing over half a year, due to the very low pressure.

Psi-values are discussed critically in [VanDenBossche2010]. Several publications have lower Psi-values, some from my point of view with too air gaps. While some look at new optimized façade application, this approach likes to include less optimal adjacent materials. A thin foam insulation layer is reasonable, but not all time the case, [Gyrinning2010] had even air as adjacent layer. The staggered layer in Gyrinning et al. [Gyrinning2010] show there only a small reduction on the U-value, what is due the very low lower edge effects under that conditions with adjacent layer as air layer. In general, these values are quite low for Psi-values, especially, when considering, that that envelope is with an additional 0.1mm protection layer.

Since Sept 2011 there are proposals from Germany and Korea for an ISO standard of VIP in ISO TC 163 SC 03 to work out a prEN ISO 16478 “Thermal insulation products - Vacuum insulation panels(VIPs) Specification”. Regarding the aging consideration, there is the pressure and moisture uptake method as presented here as well as accelerated testing. Accelerated testing leads to discussions about the acceleration factor to link to the 25 years. For an accelerated test procedure used in Germany acceleration factors are discussed in [Sprengard2011b; Sprengard2011c]. The pressure and moisture uptake method presented in this paper has the advantage to consider both pressure and moisture related aging at condition relevant for most VIP as used nowadays in buildings as shown in [Simmler2005a], where the inside temperature profile over the years domination over the outside for climates like Switzerland or colder.

11. CONCLUSION

Staggered VIPs are recommendable option regarding thermal bridge effects as well as aging for areas above a certain size. There are VIPs from leading European producers that show an attractive aging behavior for using them in the building envelope to insulate against the cold outside.

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NOMENCLATURE

λ_{cop}	center of panel thermal conductivity
$\lambda_{cop,90\%}$	90% fractile values of the center of panel thermal conductivity statistic

ℓ	length of the two edges in the measuring zone of the guarded hot plate
λ_{eff}	effective thermal conductivity
Δ_{edge}	edge effect on thermal conductivity
Ψ	linear thermal transmittance
d_{VIP}	thickness of the VIP
p	perimeter (the sum of the edge length of one or several VIPs)
A	area (of the measuring zone)
$\dot{Q}_{joint}$	heat flux through the metering zone with a joint of two VIPs
$\dot{Q}_{1-\dim}$	heat flux through the metering zone in a guarded hot plate device with 1-dimensional ideal case (one VIP above and another below the plate)
R_{joint}	R-value of two VIP in a joint
$R_{1-\dim}$	R-value of VIPs (without considering edge effect, aging nor 90% percentile)
λ_{Psi1}	effective thermal conductivity of a VIPs joint without sealing
λ_{Psi2}	effective thermal conductivity of a VIPs joint with sealing
$\Psi_{\text{edge,without sealing}}$	linear thermal transmittance of an VIP edge without sealing
$\Psi_{\text{edge,with sealing}}$	linear thermal transmittance of an VIP edge with sealing
$\lambda_{\text{eff, B}}$	effective thermal conductivity in case (B) edges in one layer (see Figure 3)
Ψ_B	linear thermal transmittance in case (B) edges joint in one layer (see Fig. 3)
$\lambda_{\text{eff, D}}$	effective thermal conductivity in case (D) edges in both layers (see Figure 3)
Ψ_D	linear thermal transmittance in case (D) edges in both layers (see Figure 3)
$\lambda_{eff.\ 25\ years}$	effective thermal conductivity including edge effect, aging and 90% percentile
$\lambda_{cop,25y,90\%}$	center-of panel thermal conductivity aging and 90% percentile, but not including edge effect (these are the values to be checked in future in a guarded hot plate device)
$perimeter_{VIP}$	edge length of a VIP
$surface_{VIP}$	surface area of a VIP
t	time [years] respective [a]
$\lambda(t)$	time-dependent thermal conductivity value, format-dependent [W/(m·K)]
λ_0	initial value of thermal conductivity, 90 % fractile value factory statistics (not aged), at least 10 measuring values [W/(m·K)]
$\Delta\lambda(t)$	aging related increase of thermal conductivity

p	internal pressure [mbar]
$\lambda_p = d\lambda / dp$	pressure-dependent increase of thermal conductivity [(W/(m·K))/mbar]
p_a	internal pressure per annum due to dry gas permeation (according to Swiss definition 2011 with $p_a = p_{total} - p_{H20}$ and if $p_{H20} > 0.5 \cdot p_{total}$,then $p_a = 0.5 \cdot p_{total}$ shall be used in the simplified case. in ISO-TC163 German proposal ISO (E) VIP 2011-08-01: annual increase of internal pressure of VIP [mbar/a] (simpler and on the good side for the customer)
$\dot{p}$	internal pressure increase per annum as measured
$\lambda_u = d\lambda / du$	moisture-dependent increase of thermal conductivity [(W/(m·K))/mass-%]
u	moisture content of the VIP core [%-mass]
$\dot{u}$	moisture related weight increase = u_a
u_a	moisture increase per annum = $\dot{u}$
u_{eq}	equilibrium moisture content at 23°C, 50 % relative humidity [mass-%]
τ	Time constant moisture equilibration = $u_{,eq} / u_a$, [mass-%/(mass-%/a)]
$Xwa = u_a$	moisture content of the VIP core (other way of writing) annual increase of humidity inside VIP [mass-%/a]
$Xw, eq = u_{eq}$	equilibrium moisture content at 23°C, 50 % relative humidity [mass-%]
	compensation humidity 23°C, 50 % relative humidity [mass-%] or
φ	humidity
$u(\varphi) = s \cdot \varphi$	linearized sorption isotherm

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