Monitoring of VIP in Building Applications

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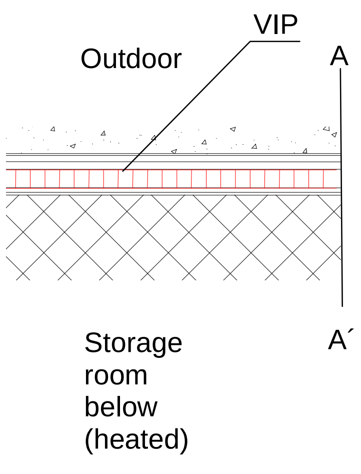
1 Introduction

Conservation of the initial low pressure and dry state inside of a high performance vacuum insulation panel (VIP) is a major requirement for a long-term application in construction assemblies. Laboratory based aging experiments and service life prediction models suggest a service life of several decades for VIP with fumed silica core and multiple metallised polymer laminate barrier in building applications [Simmler 2005a, Simmler 2005b, Schwab 2005a].

Since there is no long-term experience with installed VIP there is a need to verify laboratory based service life projection by means of data from real applications. In the following paragraphs we present measurements on a VIP-insulated flat roof construction (Fig. 1) that has been monitored from June 2004 till present. The results are compared with values obtained by laboratory aging measurements under defined temperature und humidity conditions. A simplified time dependence of the centre-of-panel thermal conductivity is given that allows an estimation of the long-term thermal performance. It is shown that a service life of several decades can be expected for this VIP construction, provided that aging in terms of a continuous increment of the thermal conductivity is taken into account.

The work was done within Annex 39 “High Performance Thermal Insulation” of the International Energy Agency (IEA), see [IEA 2005a] and [IEA 2005b].

Figure 1: Sketch of a flat roof with VIP insulation (left), layer structure of the construction (right).



Layer (AA´ from top to bottom)	d [mm]
Crushed gravel	30
Bituminous water barrier (3 layers)	10
Protective layer	7
VIP	20
Protective layer	5
Water barrier (previous construction)	10
Porous concrete (previous construction)	200

2 Experimental set-up

An existing flat roof construction as illustrated in figure 1, located near Zurich (Switzerland), was chosen for investigation. This is a favourite application of VIP in Switzerland in the last view years, since the indoor and outdoor floor level in a terrace or penthouse apartment can be kept equal, despite of the low U-value required for the outdoor roof area with heated space in the subjacent storey.

SiO_2-VIP with a 3-fold metallised polymer laminate barrier, dimensions 25 x 25 cm^2 or 50 x 50 cm^2 and a thickness 20 mm were installed in two square areas of about 200 x 200 cm^2. One area was equipped with temperature and humidity sensors on the indoor and the outdoor VIP surfaces near the centre of the panels and at the cross joints (Fig. 2). The other area was not equipped with sensors but prepared for repeated opening, because the internal pressure and moisture content had to be determined in the laboratory. It shall be mentioned at this point that none of these specimens was damaged by the repeated installation and de-installation procedure. This shows that non-protected VIP can be handled on site without damage.

As often in Swiss climate there were some rain drops shortly before the initial installation, so that the underlying protective PE foam layer was slightly wetted. It was dried as far as possible before the installation of the VIP. After the installation the test areas were sealed by a bituminous water barrier. Photographs of the installation are shown in figure 3.

Figure 2: Schematic outline of the in-situ monitored test area with location and labelling of the sensors. Outside and inside surface positions are indicated by x / y. T stands for temperature, F for humidity. The surrounding panels were installed to shield the monitored panels.

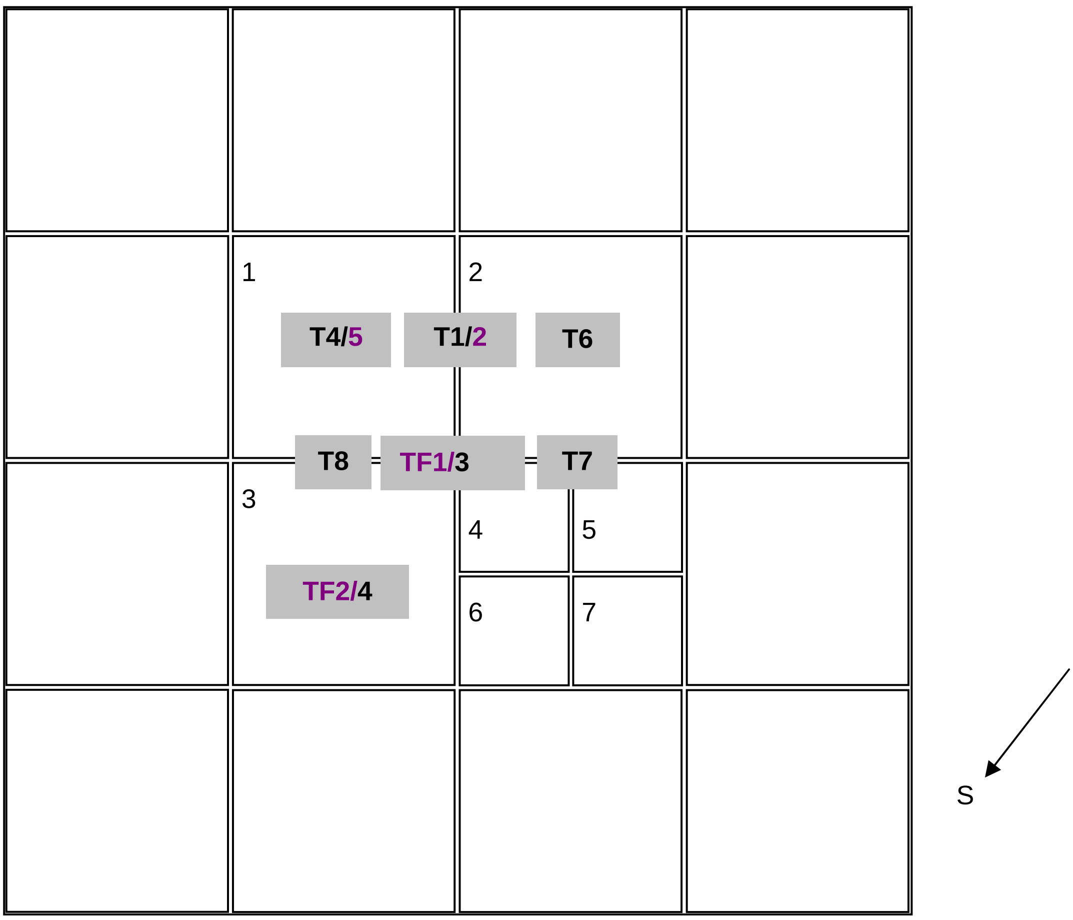
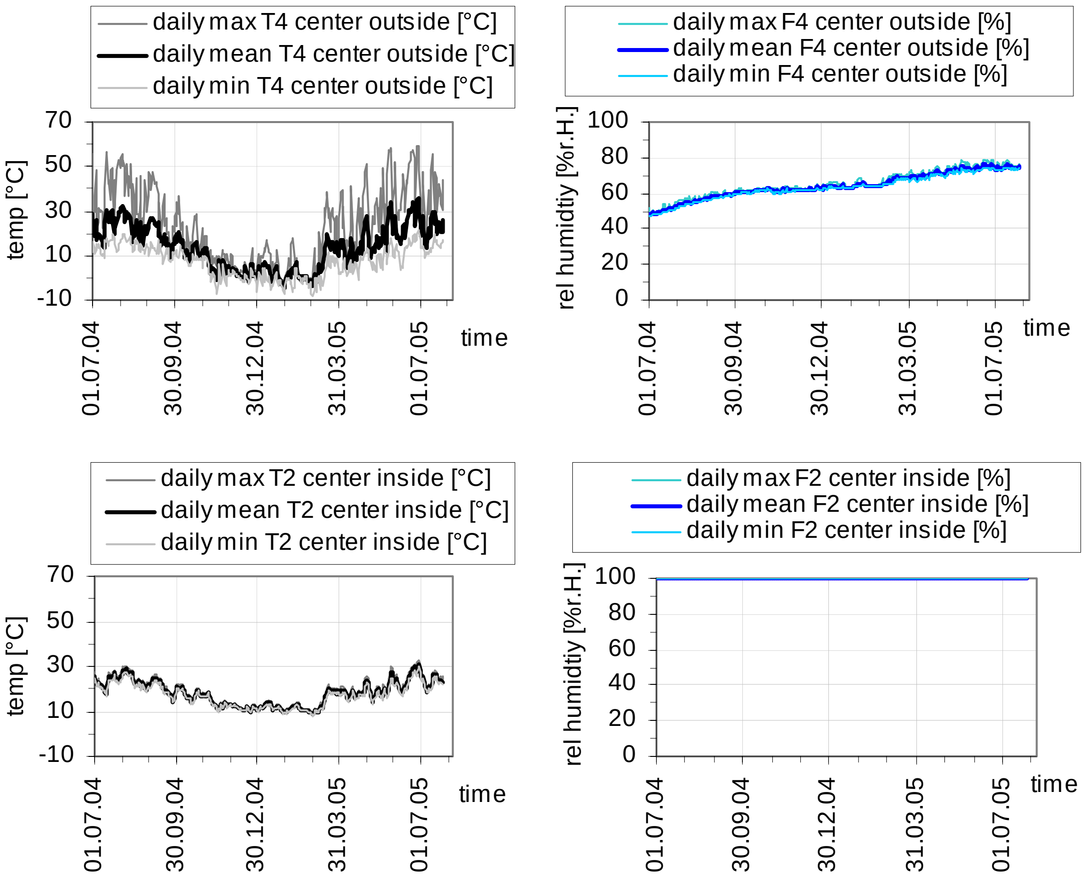


Figure 3: Pictures from the installation of the two VIP test areas

3 Results

The data recording was started in June 2004 and is continued presumably for three or more years. The temperature and humidity progression for one year is shown in figure 4.

Fig. 4: Monitored temperature and humidity conditions around the VIP (positions see Fig. 2)



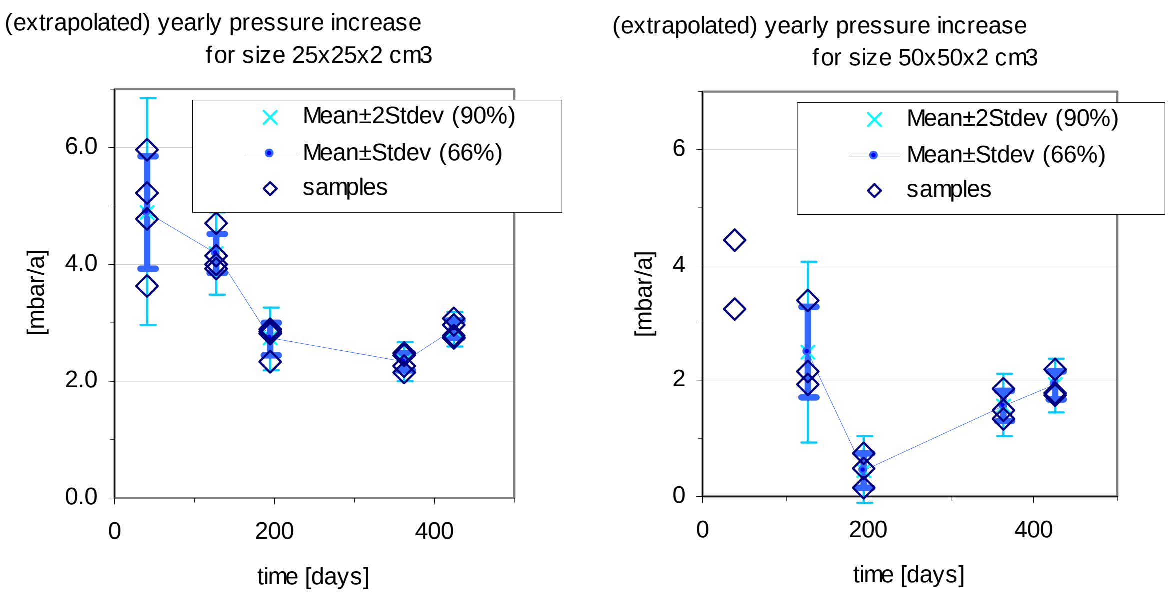
Temperatures up to 60°C are observed at the outside centre position on the VIP surface, in spite of the heat buffering capacity of the gravel layer. The temperature variation on the inside surface is much smaller. The inside temperature is relatively low in winter because the subjacent room was not fully heated. The relative humidity (RH) on both sides of the VIP is almost independent from the outdoor climate, as can be expected for a cavity containing moisture buffering materials. Below the inside VIP surface even saturation occurs, which is a consequence of the slight wetting during the installation. The slow RH increase on the outside may be due to moisture transfer from the other side. The overall average for both sides over a one year period is in the range of 80 % RH.

As a remark the occurrence of 60°C combined with high humidity must be considered in the development of laminated barrier materials, as PUR glue is not necessarily stable against hydrolysis and subsequent delamination of the barrier at these conditions.

The second test area was opened repeatedly in order to determine the moisture content and the internal pressure of test specimens at the laboratory. Condensation below the VIP was observed upon the first removal of the bituminous barrier as indicated in the RH measurements of the in-situ monitored test area.

Yearly pressure increase rates p_a are shown in figure 5 for the two formats. The 40 d, 126 d, 194 d data are extrapolated to one year. As indicated in the figure the uncertainty decreases with increasing time because of a measuring uncertainty of $p_a \approx 0.5$ mbar (2 σ interval). There is also a transient effect which may be related to seasonal variation of the boundary conditions. The final evaluation based on data after 424 days gives the average values 2.9 mbar/yr for the format 25x25 cm^2, and 1.9 mbar/yr for the format 50x50 cm^2. The statistical uncertainty is 0.2 mbar/yr. Respective average values of the yearly moisture content increase X_{wa} are 0.22 %-mass/yr and 0.13 %-mass, with a relative uncertainty of 15 to 20 %.

Figure 5: Yearly pressure increase rates



4 Comparison with laboratory aging data

To compare the monitoring results with laboratory-based aging data the procedure of calculating an Arrhenius weighted effective temperature $T_{effective}$ to determine expected yearly rates p_a and X_{wa} was applied to the measured data [Simmler 2005a,b]. The permeation data were determined in the laboratory at various temperatures and 80 % RH, which corresponds to the cavity situation in the application. The pressure increase rate p_a is indicated in figure 6 in a log (p_a) versus 1/T plot.

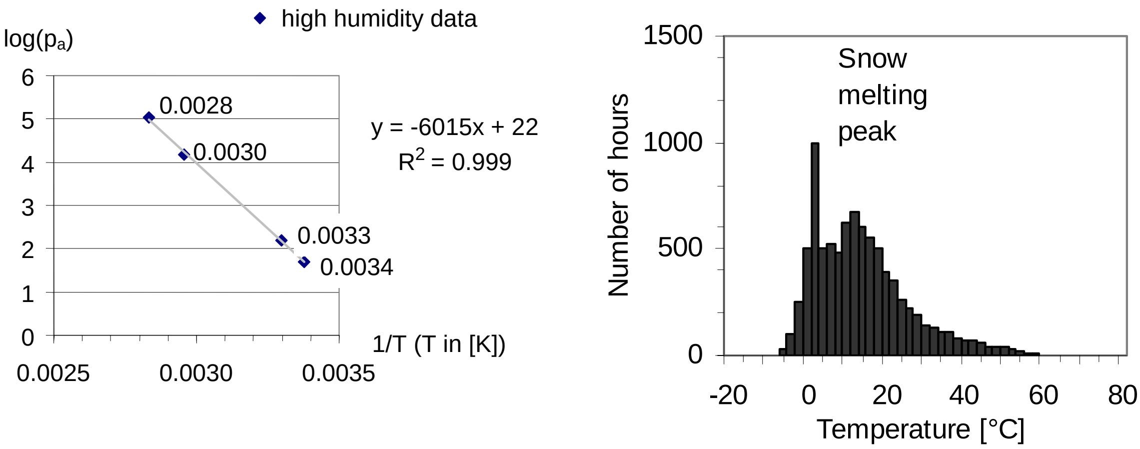
The linear shape of the plotted data clearly indicates an Arrhenius-like behaviour of the acceleration function. The Arrhenius fit parameters A and E_a are used to determine an effective temperature $T_{effective}$ and to estimate the pressure increase rate with respect to dynamic boundary conditions according to the following exponential weighting:

$$p_a = \sum_i A\exp\left(-\frac{E_a}{RT_i}\right)\Delta t_i \Big/ \sum_i \Delta t_i \equiv A\exp\left(-\frac{E_a}{RT_{effective}}\right) \qquad (1)$$

A similar approach is applicable to the yearly moisture content increase rate X_{wa}, which is due to the exponential temperature dependence of the vapour pressure at constant RH.

The temperature histogram obtained from the monitoring data is shown for the outside surface is shown in figure 6. A frequency peak is caused by the melting temperature of snow, which has however no important influence on the results. The effective temperatures are 18.8°C (inside) and 19.5°C (outside). A comparison with the average temperatures 17.6°C (inside) and 12.9°C (outside) shows that the non-linearity of the exponential weighting has a bigger influence on the outside. There, the high temperature peaks shift the value by about 7 K.

Figure 6: Arrhenius plot of the temperature dependence of the yearly pressure increase rate p_a in the high humidity range (80% RH) (left). Frequency histogram of the outside surface temperature obtained from the monitoring data (right).



Calculated pressure and moisture content increase rates are summarized in table 1 together with the measured values for the two panel formats installed in the application. The pressure increase rates based on the effective temperatures are in good correspondence with the measured values, keeping in mind that several assumptions and simplifications were made in the calculation. Actually the uncertainty of the calculated value is thought to be significantly higher than that of the measurement. If the average temperature is used, the result is lower compared to the measured value, thus underestimating the non-linear impact of high temperatures.

Table 1: Comparison of measured and calculated aging data for the inside and outside surface of a 20 mm VIP layer in a flat roof construction.

Panel size	Quantity	Calculation based on the temperature data (1 year)			Measurement after 424 d	
	[mbar/yr]	Inside	Outside	Mean		
25 x 25 x 2 cm^3	p_a ($T_{effective}$)	2.72	2.89	2.8	2.9	±0.2
	p_a ($T_{average}$)	2.48	1.70	2.1		
50 x 50 x 2 cm^3	p_a ($T_{effective}$)	2.04	2.17	2.1	1.9	±0.2
	p_a ($T_{average}$)	1.86	1.27	1.6		
	[%-mass/yr]					
25 x 25 x 2 cm^3	X_{wa} ($T_{effective}$)	0.26%	0.29%	0.28%	0.22%	±0.04%
	X_{wa} ($T_{average}$)	0.23%	0.16%	0.19%		
50 x 50 x 2 cm^3	X_{wa} ($T_{effective}$)	0.15%	0.17%	0.16%	0.13%	±0.02%
	X_{wa} ($T_{average}$)	0.14%	0.09%	0.11%		

The results for the moisture content increase rate are less unambiguous. Qualitatively the overall agreement is not bad, but the non-linear weighting seems to give a somewhat too high rate. One reason for the too high result may be an observed drying effect due to the repeated opening of the test area (no more condensate upon the second opening). That is, the relative humidity might have been decreasing to some extent, in contrast to the assumptions in the calculation. With arithmetic averaging the result is again below the experimental value. It should be noted however that the humidity related rates are small at all, so a rather large uncertainty has to be accepted for all results.

From a practical point of view an important question is the long-term progression of the thermal conductivity. To get realistic data, the measured data in table 1 were up-scaled to a standard panel format 100 x 60 cm^2. For this dimensions the rates become p_a = 1.5 mbar/yr and X_{wa} = 0.10 %-mass/yr. Following the calculation scheme described in [Simmler 2005b] the time constant for moisture saturation is

$$\tau = X_{w,equilibrium} / X_{wa} = 64.0 \text{ yr, with } X_{w,equilibrium} \approx 6.4 \text{ \%-mass at 80 \% RH} \quad (2)$$

The predicted thermal conductivity increase as function of time t (in years) is then

$$\Delta\lambda(t) \approx 0.035 \cdot 1.5 \cdot t + 0.50 \cdot 6.4\left(1 - \exp(-t/64.0)\right) \text{, in } 10^{-3} \text{ W/(m K)} \quad (3)$$

The expected change of the thermal conductivity is $2.3 \cdot 10^{-3}$ W/(m K) after 25 years, which is the standard period for the specification of long-term properties of thermal insulation products in Europe [EN 2001]. Assuming an initial value of $4.5 \cdot 10^{-3}$ W/(m K) the thermal conductivity after 25 years is approximately $7 \cdot 10^{-3}$ W/(m K). At present there are no verified means to quantify the uncertainty of this prediction. An error propagation analysis on the influence of parameter deviations gives a relative uncertainty of about 15 % for the predicted value.

In the described application mechanical or chemical stresses have not significantly influenced the aging behaviour in the first year. In other applications the occurrence of additional stresses might be relevant. A general recommendation is to minimize any temperature, humidity, mechanical and chemical impacts by constructive means. More examples of monitored construction assemblies and comparison with calculated temperature – moisture related aging can be found in [Schwab 2005b].

5 Conclusions

Monitoring data from a flat roof with VIP insulation show aging effects of the panels that can be quantified with reasonable accuracy after a period of one year. Aging characteristics derived from laboratory based aging of specimens at defined temperature and humidity conditions can be related to the in-situ behaviour by linear or non-linear weighting of the experimental boundary conditions. The pressure increase rate obtained by non-linear weighting is in good correspondence to the experimental data. The moisture content increase seems to be overestimated to some extent. Linear weighting gives lower values than observed for both quantities.

Basically in-situ as well as laboratory based aging results suggest a service life in the range of several decades. A long-term increase of the thermal conductivity must be taken into account in building applications. The increment depends on barrier properties, panel dimensions and boundary conditions. For the described flat roof application a long-term value of $7 \cdot 10^{-3}$ W/(m K) may be appropriate for actual SiO_2–VIP with polymer-based barrier.

Monitoring results from periods of several years are still needed to clarify existing uncertainties, to quantify additional aging effects not taken into account so far, and to further strengthen confidence in vacuum insulation.

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6 References

[EN 2001] see e.g. European standard EN 13165 (2001): ***Thermal insulation products for buildings - Factory made rigid polyurethane foam (PUR) products – Specification***

[Ghazi 2004] Ghazi Wakili, K., Bundi, R. (2004), ***Effective thermal conductivity of VIP used in building constructions,*** Building Research & Information **32** (4), 293 – 299

[IEA 2005a] IEA/ECBCS Annex 39 (2005), ***VIP - Study on VIP-components and Panels for Service Life Prediction of VIP in Building Applications***, Subtask A report (in press)

[IEA 2005b] IEA/ECBCS Annex 39 (2005), ***Vacuum Insulation in the Building Sector - Systems and Applications***, Subtask B report (in press)

[Schwab 2005a] Schwab H. et al. (2005), ***Prediction for Service Life for VIP with Fumed Silica Kernel and Foil Cover,*** Thermal Envelope & Building Science, **28** (4), 357 – 374

[Schwab 2005b] Schwab H. et al. (2005), ***Predictions for the Increase in Pressure and Water Content of VP,*** Thermal Envelope & Building Science, **28** (4), 327 – 344

[Simmler 2005a] Simmler, H., Brunner, S. (2005), ***VIP for building application – basic properties, aging mechanisms and service life,*** Energy & Buildings (in press)

[Simmler 2005b] Simmler, H., Brunner, S. (2005), ***Aging and Service Life of VIP in Buildings***, see present VIS 2005 proceedings