Aging and Service Life of VIP in Buildings

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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 concern when thinking of a long-term application in building [Caps 2001]. "Aging" in terms of an irreversible change of properties leading to a degradation of relevant performance characteristics will be present in a system like VIP. Up to now little experience exists on the aging behaviour and the "service life", i.e. the time between production and failure, which means approaching a certain end-of-life criterion related to a specific performance indicator. The service life of an individual specimen is clearly a random value. The service life of a population of individuals is often described by using a graphical representation called the bathtub curve (Fig. 1).

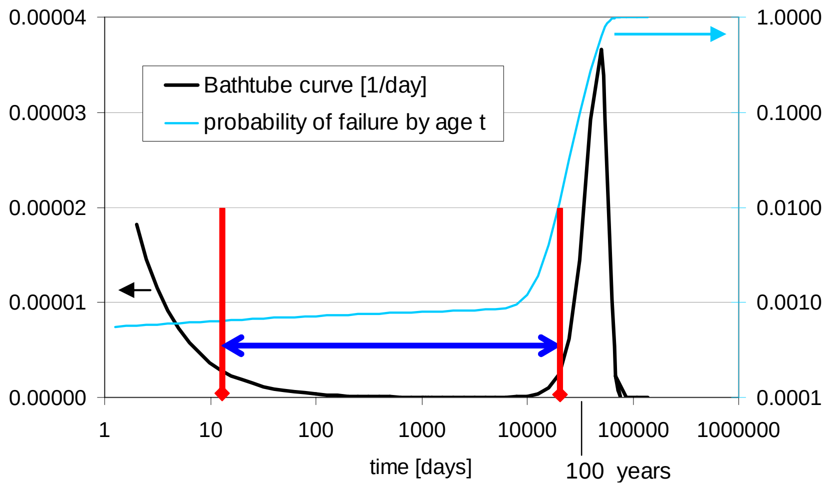
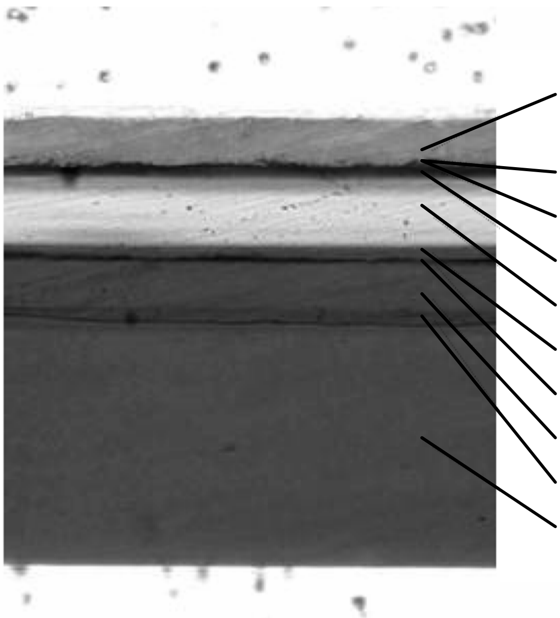


Figure 1: The bathtub curve describing the service life of a population

It consists of three periods: an infant mortality period with a decreasing failure rate followed by a normal life period (also known as "service life") with a low, relatively constant failure rate and concluding with a wear-out period that exhibits an increasing failure rate.

Infant failures are highly undesirable and typically caused by material defects, errors in production, etc. While with conventional thermal insulation products early failure almost does not exist, it appeared frequently in the first stage of VIP manufacture. Since then the early failure rate was strongly reduced due to improved process and quality control. Today the production failure rate for high quality products is presumably well below one percent. An effective counter measure is for instance the storage of freshly produced panels over a period of some 10 days before final control and shipping. Another cause of early failure is mechanical damage of the envelope during transport or installation, observed at several construction sites. Therefore on-site installation of unprotected VIP is really a challenging task requiring specialists and perfect quality management. Wear-out is a fact of life due to fatigue or deterioration of materials or – in the VIP context – inevitable increase of the thermal conductivity that brings a panel to an end-of-life criterion.

In the "normal life" period, pressure increase as well as moisture accumulation will take place due to slow permeation of atmospheric molecules through the barrier surface. The permeation rates will depend on the environmental temperature and humidity conditions as well as on the barrier properties. It is well known that sustainable high barriers can be achieved with massive metal layers having a thickness ~ 10 μm. In fact, VIP were made with PE laminated aluminium foils in this thickness range in the first stage. However, thermal conductance measurements and numerical calculations [Ghazi 2004] show that the heat flow through the edge of a metal foil envelope can be much larger than the total heat flow through the VIP core. In order to reduce the thermal bridge problem, metallised polymer films are now widely used with a core made of fumed silica (SiO_2-VIP). To reduce the gas permeation problem specially developed laminated polymer based high barrier envelopes include up to three metallic layers with a thickness in the range of 50 - 100 nm each (Fig. 2).



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

Figure 2: Visualization of a laminated polymer based high barrier envelope containing three aluminium barrier layers with an optical microscope (top and bottom areas are embedding material)

In the following sections aging mechanisms, aging experiments and service life estimation of SiO_2-VIP will be presented. The work was done within Annex 39 “High Performance Thermal Insulation” of the International Energy Agency (IEA).

2 Aging mechanisms

Basically aging mechanisms are present on the materials level and with regard to the system properties of a VIP. In [Simmler 2005] a short review of aging potentials of barrier materials is given. In summary a laminated multi layer high barrier as shown in figure 2 should not be exposed regularly to temperatures above 60°C and high humidity. Only short-term temperatures of 80°C are acceptable for the most sensitive polymeric component PE (polyethylene) when stabilized by phenolic antioxidants. High humidity, in particular in parallel with high temperature, may induce oxidation of aluminium layers and cause degradation of the adhesive PUR layers by hydrolysis. The base level of moisture or water in the environment must be limited to pH-values less than 8.5, which should be considered particularly if concrete or other alkaline substances are present in the immediate vicinity. Protected from those impacts the service life of a VIP is not expected to be shortened due to aging of barrier materials and the silica core, which is very stable in the temperature range occurring in building applications.

However, as the thermal conductivity of the SiO_2 core is increased by about a factor 5 between initial pressure (1 mbar) and standard atmospheric pressure, gas permeation through the envelope is seen as the dominant aging mechanism of a VIP. Referring to the OTR of recent multi-layer metallised polymer barrier films (and a typical ratio OTR / NTR of approximately 4) a yearly pressure increase in the order of 0.01 to 0.1 mbar could be expected in a 1 x 1 x 0.02 m^3 panel. This seems to be sufficient compared to an acceptable pressure increase rate p_a of 1 to 2 mbar/yr [Simmler 2005]. However, this simple view has to be extended in several respects: i) Increase of the permeation rates at higher temperature and/or humidity will accelerate the pressure increase. The temperature dependence of a permeation rate for polymeric materials is often described in form of an Arrhenius acceleration factor:

$$P(T)/P(T_{ref}) = \exp\left(-\frac{E_a}{R(T-T_{ref})}\right) \qquad (1)$$

In an acceleration model, the combined effect of temperature and humidity has to be included.

Increased permeance of the edge area – mainly because of a higher defect density at wrinkles, edges, corners and the seal – may also result in higher panel permeance values than calculated just for the unstressed planar film. Therefore realistic aging data for VIP can hardly be derived from permeation properties of the envelope film, but must be investigated experimentally with assembled panels. As a consequence of different contributions from surface and perimeter size effects have to be taken into account.

In addition moisture accumulation in the hygroscopic core due to the relatively large WVTR in the order of 0.01 g/(m^2 d) must be taken into account. With the assumption that the effects of pressure increase and moisture accumulation can be superimposed independently, the change of the thermal conductivity with time t (yr) may be estimated by means of the yearly rates of pressure increase p_a (mbar/yr) and moisture accumulation X_{wa} (%-mass/yr):

$$\Delta\lambda = \left(0.035 \cdot p_a + 0.50 \cdot X_{wa}\right) \cdot t \qquad (p < 100 \text{ mbar}) \qquad (2)$$

If moisture saturation is not negligible, equation (2) can be modified [IEA 2005]:

$$\Delta\lambda(t) = 0.035 \cdot p_a \cdot t + 0.50 \cdot X_{w,equi} \left(1 - \exp(-t/\tau)\right) \qquad (3)$$

with $X_{w,equi}$ equilibrium moisture content (≈ 0.08 %-mass x RH)

τ saturation time constant (= $X_{w,equi}$ / X_{wa})

For example, a pressure increase of 3 mbar/yr will give a thermal conductivity increase of ≈ $1 \cdot 10^{-3}$ W/(m K) after 10 years. Or, if an average moisture content of 4 %-mass is reached in equilibrium with air at 50 % RH, the thermal conductivity will be increased by about $2 \cdot 10^{-3}$ W/(m K).

3 Hygro-thermal aging experiments

Since heat and moisture are the most relevant and permanent impact factors on a VIP in any building application, (accelerated) aging experiments were focused on elevated temperature and humidity. The specimens, typically with a size of 250 x 250 mm^2 ("small") and 500 x 500 mm^2 ("large") and a thickness of 20 mm, were recent VIP products on the European market. Properties of the two investigated polymer based barriers are listed in Table 1.

Table 1: Polymer based laminates used in the aging tests (WVTR values converted from 38°C, 90% RH) at 23°C, 50% RH, as indicated by the manufacturers.

Layer sequence	OTR $cm^3(STP)/(m^2\ d)$	WVTR $g/(m^2\ d)$
12 μm PETmet / 18 μm PPmet / 12 μm PETmet / 60 μm PE-LD	< 0.05	< 0.025
12 μm PETmet / 12 μm PETmet / 12 μm PETmet / 50 μm PE-HD	0.0005	0.0025

To check the impact of a wide range of conditions, a first series was performed on small VIP at the manufacturer-declared maximum service temperature of 80 degree Celsius, applying a relative humidity of 80 percent at the same time (80 °C / 80 % r.H.). The barrier material was MF3, a threefold metallised polymer laminate produced in 2002. For comparison, cyclic conditions and 80°C exposure at ambient vapour pressure were also investigated. Subsequent tests were performed at 30 °C / 90 % r.H., considered to cover a reasonable range of applications. As the most direct aging indicators the mass (by weighing) and the internal pressure (by detection of the equilibrium pressure in a depressurization chamber) were determined in regular time intervals.

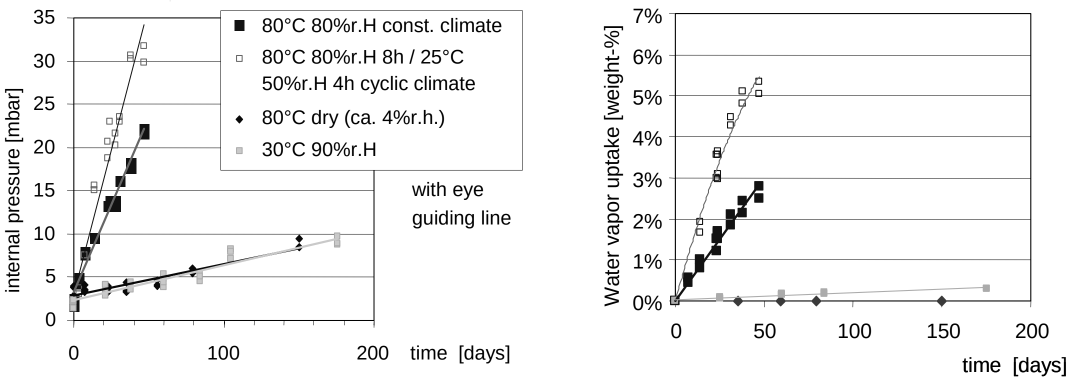


Figure 3: Increase of internal pressure (a) and moisture content (b) in "small" VIP at elevated temperature / humidity. The measurements were done at room temperature after cooling down the samples for some hours.

Results are summarized in figure 3. At 80°C / 80% RH it is obvious that the pressure increase as well as the moisture accumulation is too fast for a long-term application. As can be seen in the figure cyclic conditions (8 hours at 80 °C / 80% RH ↔ 4 hours at 25 °C / 50% RH) are even harder than a constant 80 °C / 80% RH exposure. Pressure and moisture content increase rates are almost doubled. Higher permeance under cyclic conditions may arise either from shear strain between polymer and metal layers due to a mismatch of thermal expansion properties, and / or by cyclic condensation of water on the “cold” VIP surfaces being delayed in temperature - humidity rise periods by the thermal inertia of the core material.

A clear correlation exists between the external vapour pressure and the extrapolated yearly increase rates of internal pressure and moisture content, indicating that the vapour pressure is a major driving force for the degradation. Another indication of the high moisture sensitivity is the behaviour at 80 °C and low (ambient) vapour pressure: the pressure increase rate is much lower, but is still above 10 mbar/yr. The moisture content remains close to zero in this case. At 30 °C / 90% RH the pressure increase rate is (by occasion) quite similar.

The behaviour of 3 different products, each in two formats, was compared by continuous exposure to 23°C / 50% RH conditions (Table 2). Product AF1 with a massive 6 μm aluminium barrier is very stable, regarding both the moisture content and the internal pressure. Product MF3 and product MF4 have basically a similar barrier, namely a 3-fold laminate of metallised polymer film. Looking at the "large" format of those products the moisture accumulation rate X_a (about 0.1 %-mass) is quite similar, whereas the pressure increase rate p_a with MF3 (about 2 mbar/yr) is significantly higher than with MF4 (about 1 mbar/yr). Edge effects are also apparent from Table 2, as the rates depend on the format of the specimens.

Table 2: Moisture content and internal pressure increase rates of VIP specimens in two sizes at standard conditions 23°C, 50% RH with different barrier materials

	Size *[cm]*	**X_a, %-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

Calculated format dependent yearly rates, extracted from the experimental data, are indicated in figure 4 for 2 cm thick VIP with the formats 0.25 x 0.25 m^2, 0.25 x 0.50 m^2, 0.5 x 0.5 m^2, 0.5 x 1.0 m^2, and 1.0 x 1.0 m^2. There is a clear trend toward higher pressure increase rates for smaller formats due to the perimeter contribution. The format dependence is less significant regarding moisture accumulation, since the surface contribution is more dominant. For formats 0.5 x 1.0 m^2 or larger these products show sufficiently low leakage rates for a long term application at typical ambient conditions.

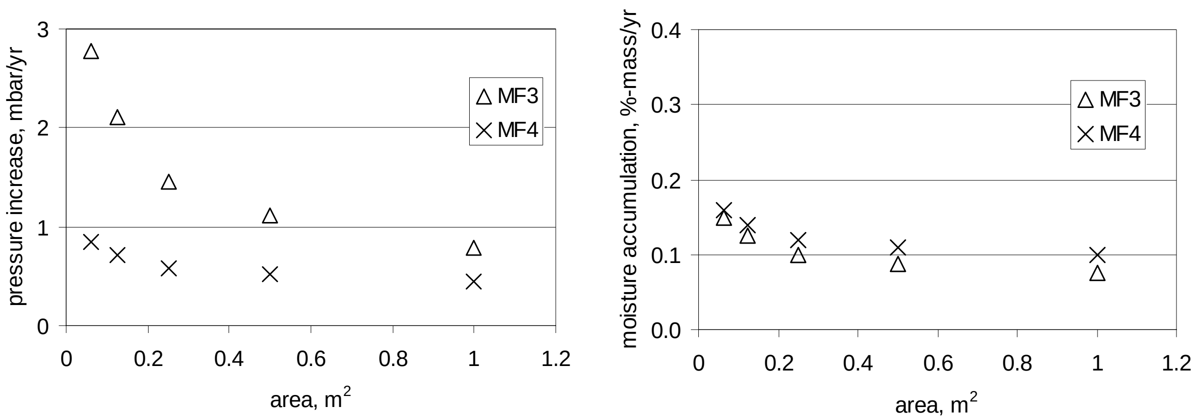


Figure 4: Moisture accumulation and pressure increase rates at 23°C, 50% RH (1 bar) for various VIP formats, based on the values in Table 2 (uncertainty 10 to 15%)

4 Service life estimates in building applications

In building applications the boundary conditions are mostly dynamic. Due to the complexity of a real transient heat and moisture transfer model for the VIP system rather simplified methods are discussed here to estimate the long-term changes of VIP. The first step is always the calculation (or measurement) of the temperature and humidity conditions around the VIP, which have a strong influence on the internal pressure and the moisture content changes as seen before. This task is not easy, as coupled heat and moisture transport in the building element containing VIP is involved. The situation is often simplified by a one-dimensional (centre-of-panel) model. It may be further simplified if one of the following assumptions can be made:

- Constant relative humidity: In an (almost) vapour tight cavity containing hygroscopic materials besides VIP a constant relative humidity may be assumed. The problem is then reduced to a transient temperature calculation for the main faces.
- Ambient vapour pressure: In diffusion open environment that is in direct contact with room or outside air the vapour pressure corresponding to the air temperature and relative humidity may be used.

Once the time dependent boundaries (e.g. one-hour steps) are known there are various options to calculate an approximate yearly increment of the internal pressure and moisture content [IEA 2005]. They all include the assumption that a yearly increment may be calculated by superposition of changes with stationary temperature – moisture boundary conditions.

i) A time step model can be realized by integration of a balance model over the time steps. It is described in more detail in [Schwab 2005].

ii) The most simple approach is the calculation of the time average values of temperature and humidity conditions around the VIP. The corresponding permeation properties for dry air and moisture as determined by laboratory experiments for constant boundary conditions are then applied. Obviously the observed non-linearity of the transmission rates is thus neglected.

iii) The non-linearity of transmission rates may be taken into account by including e.g. a known Arrhenius-like temperature dependence of the pressure increase rate in the averaging process. The procedure is illustrated by means of permeation data determined for VIP at various temperatures and a constant relative humidity of about 80 %, which corresponds to a cavity situation as described before. The pressure increase rate p_a is indicated in figure 5 in a log (p_a) versus 1/T plot. The linear shape of the curve clearly indicates an Arrhenius-like behaviour of the acceleration function. The Arrhenius fit parameters A and E_a can be used to estimate the yearly pressure increase rate with respect to dynamic boundary conditions with a weighted average:

$$p_a = \sum_i A \exp\left(-\frac{E_a}{RT_i}\right)\Delta t_i \Big/ \sum_i \Delta t_i = A \exp\left(-\frac{E_a}{RT_{effective}}\right) \qquad (4)$$

Due to the exponential temperature weighting factor the effective temperature $T_{effective}$ is always higher than the time average temperature. A similar approach is applicable to evaluate the yearly moisture accumulation rate X_a, which is due to the exponential temperature dependence of the external vapour pressure. In diffusion open applications the time average of the environmental vapour pressure would be sufficient to select the corresponding yearly moisture accumulation rate.

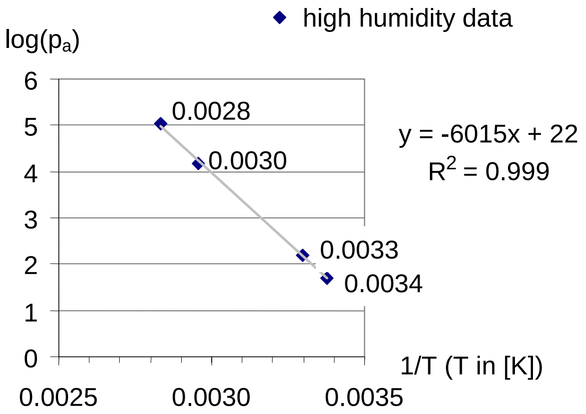


Figure 5: Arrhenius plot of the temperature dependence of the yearly pressure increase rate per annum in the high humidity range (80% RH)

The procedure was applied to a VIP insulated flat roof of a terrace building on a hill side, which is a typical construction in densely populated areas in Switzerland. The climate data from the Design Reference Year (DRY) for Zurich Airport (Switzerland) were chosen. Details of the construction and of the calculation of the boundary conditions are described in another VIS contribution [Brunner 2005]. Calculated results which show the influence of the different averaging methods are shown in Table 3. It can be seen that on the interior VIP surface the arithmetic and the Arrhenius weighted average are the same because of the small range of temperatures (interior air temperature fixed at 22°C). On the exterior surface with more dynamic conditions (from -18 to 44°C) the difference between the weighted and the normal average is about 4 K, giving a significant increase of the transmission rates compared to the non-weighted average. On the other hand, the average load at the interior surface is obviously higher than on the exterior surface, irrespective of the averaging method.

Table 3: Results of the thermal and aging calculation for the inside and outside surface of a 20 mm VIP layer (size 50 x 50 cm^2) in a terrace construction

		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

Averaging the rates in Table 3 for both sides of the VIP Equation (3) with $X_{w,equi}$ = 6.4 %-mass at 80 % RH gives a time constant τ = 35.6 yr and thus the thermal conductivity increase function

$$\Delta\lambda(t) = 0.035 \cdot 2.1 \cdot t + 0.50 \cdot 6.4\left(1 - \exp(-t/35.6)\right) \quad (5)$$

The predicted change of the thermal conductivity after 25 years is $3.5{\cdot}10^{-3}$ W/(m K). A comparison of calculated and monitored data from a flat roof construction on the basis of this model can be found in [Brunner 2005]. Other examples of monitored construction assemblies and a comparison with time step calculations are shown in [Schwab 2005]. A general observation is that the pressure increase calculated by those models is in reasonable agreement with the measured data, while the moisture content increase is normally overestimated. One reason for this may be the assumption of steady state behaviour for the moisture transfer, whereas it may take several days until stationary H_2O permeation through those types of barriers films is reached in permeability measurements [IEA 2005]. Furthermore the temperature and humidity dependence of the water vapour permeability must be taken into account for an improved prediction.

5 Conclusions

The investigations at Empa and other laboratories show that the new high performance thermal insulation panels based on evacuated fumed silica sealed in a multiple metallised laminated polymer barrier have the potential to meet the requirements both for long-term building application and minimal thermal bridge effects through the edge zone. A service life in the range of several decades may be expected in suitable constructions, provided that moderate temperature and humidity conditions can be maintained in the environment of VIP, and no other significant (mechanical, chemical) stresses are present. First monitoring data seem to justify the application of simple service life prediction models available to date. However they give just a rough estimate of gas intrusion, and experimental aging data from panels in at least two dimensions are required as input.

Improvements of barrier materials are still needed, both to reduce the degradation speed and respective increments on thermal conductivity design values and to increase the range of acceptable hygro-thermal conditions or other stresses on VIP.

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6 References

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