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Vacuum insulation panels for building application Basic properties, aging mechanisms and service life

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Abstract

The vacuum insulation panel (VIP) is a high performance thermal insulation component recently introduced into building technology. Its high thermal resistivity provides new solutions for slim but still energy efficient building envelopes. One of the key issues for building application is to minimize failure in service and to ensure a service life in the order of several decades under typical stress conditions especially thermal and hygric effects. However, little experience exists up to now on the long-term properties and the durability of VIPs. This article describes aging mechanisms and reports experimental results for different temperature and humidity induced deteriorations. A functional representation of the measured data at steady state conditions is introduced. For specific VIP applications the internal pressure increase is calculated on the basis of a dynamic thermal model. End-of-life criteria and respective service life estimates are discussed as well.

Keywords: Vacuum insulation panel; High performance thermal insulation; Building envelope; Accelerated aging; Service life prediction

1. Introduction

In the last few years a novel type of a thermal insulation board for building envelope application, the so-called vacuum insulation panel (VIP), has been introduced to the construction technology [1]. Since the thermal resistivity for heat flows perpendicular to the main faces is 5–10 times higher compared to a conventional thermal insulation board a new field is opened for slim, energy efficient building envelope design. As an example, insulation of a terrace roof of an apartment building is shown in Fig. 1. A VIP is basically made of a micro-porous core structure which is evacuated and sealed in a thin, virtually gas tight envelope bag (Fig. 2). While open cell polystyrene foam has been used as core material for a long time by the refrigeration industry, fumed silica powder (SiO_2 agglomerates) has become the main core component in VIP for building application. One of the reasons is the less stringent depressurization requirement for this material. Compressed to about 200 kg/m^3 the pore size between the SiO_2 grains is well below the mean free path of atmospheric gas molecules at internal pressures below 1 mbar. Thus, the molecular collision rate is strongly reduced, and the gaseous heat transfer becomes almost negligible. Heat transfer is limited to solid conduction (2–3 mW m^{-1} K^{-1}), and thermal radiation (reduced to about 1 mW m^{-1} K^{-1} by admixture of an opacifier). Thus, the total thermal conductivity of the evacuated pyrogenic SiO_2 core is about 4 mW m^{-1} K^{-1}. It is evident that the conservation of the initial low pressure and dry state inside a VIP is the main concern when thinking of a long-term application in buildings. A service life of 30, 50 or more years is expected from a built-in component because replacement is often expensive or almost impossible. It is well known that sustainable high barriers can be achieved with metal layers having a thickness of around 10 μm or more. In fact, in the first stage of their production, VIPs were produced with laminated aluminum foils of this thickness range. However, thermal resistivity measurements and numerical calculations [2] show that the heat flow through the edge of a metal foil envelope can be even larger than the heat flow through the VIP core material. In order to optimize the opposing requirements of thermal heat loss and gas

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Fig. 1. Section of a VIP. The nano-porous fumed silica material is pressed in a PE fleece and sealed in a three-fold metallized polymer envelope under vacuum (below 1 mbar).

permeation, three-fold metallized polymer films with a thickness of 30–100 nm for each metallization are now widely used. Although better performance compared to a single metallized film can be expected, there is little knowledge if these barriers achieve the stringent requirements to ensure a service life of about 50 years. In the present study, aging is discussed in terms of an irreversible degradation of relevant performance characteristics of the VIP assembly and its components. Further the set-up and the results of hygrothermal aging experiments on VIPs are reported. Based on these an analytical acceleration function is derived. Service life estimates were made for two VIP containing building assemblies: a terrace which is the primary VIP application up to now in Switzerland, and a hypothetic wall construction due to its energy saving potential. The VIPs therein are subjected to different temperature and moisture stresses when a design reference year (DRY) for Zurich Airport (Switzerland) is applied as the outdoor boundary condition.

2. Aging mechanisms

2.1. VIP assembly

For a high performance thermal insulation component such as VIP the long-term behavior of its heat resistance is the most important issue with respect to service life. Since the thermal conductivity of the SiO_2 core is increased by a factor about 5 between low pressure (1 mbar) and standard atmospheric pressure (Fig. 3), gas permeation through the envelope is clearly the most important aging mechanism. There are many possible failure modes, starting with ‘‘childhood’’ failures caused by imperfect production. This problem frequently appeared in the beginning of VIP production. Since then the early failure rate was clearly lowered due to improved process and quality control. Another cause for short-term failure is of course mechanical damage of the rather delicate envelope during installation. This was observed on several construction sites visited by EMPA. Therefore on-site installation of unprotected VIP cannot be recommended. To avoid this problem prefabricated assemblies protecting the VIP are favorable. Normally, pressure increase in a VIP will take place due to slow permeation of atmospheric molecules through the barrier layer. Yet, there is no standardized end-of-life criterion for this continuous aging process. Based on the thermal conductivity characteristics of SiO_2 (Fig. 3), the inner pressure of 100 mbar is frequently used as a threshold value neglecting hereby the influence of moisture. For a target service life of 50 years, this would mean a maximum pressure increase of around 2 mbar per year. For three-fold metallized films (MF) on polymer substrates, oxygen transmission rates (OTR) between 0.05 and as low as 0.0005 STD $cm^3\ m^{-2}\ d^{-1}$ at 23 °C and 50% r.H. are declared by manufacturers [3]. If the nitrogen transmission rate (NTR) is in the same order of magnitude – an often used estimation is NTR $\approx$ OTR/4 – a pressure increase in the order of 0.01–1 mbar per year could be expected in a panel

Fig. 2. VIP insulation of a terrace with heated rooms beneath. The panels are placed on a thin polystyrene foam layer for mechanical protection.

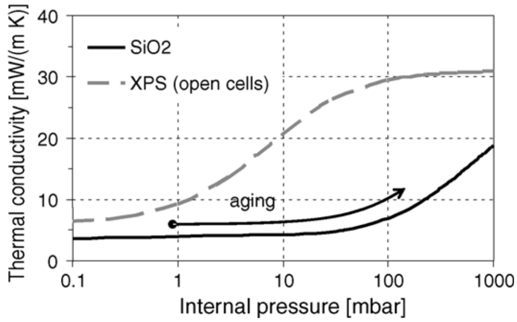


Fig. 3. Thermal conductivity of dry pyrogenic SiO_2 (full line) as a function of the internal pressure. For comparison, the similar function is shown for extruded polystyrene (XPS, dashed line). Vacuum requirements are much more demanding due to larger XPS cells.

of 1 m × 1 m × 0.02 m. 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:

$$\frac{P(T)}{P(T_{\mathrm{ref}})} = \exp\left(-\frac{E_{\mathrm{a}}}{R(T - T_{\mathrm{ref}})}\right) \quad (1)$$

In an acceleration model, the combined effect of temperature and humidity has to be included, e.g. by a parameterized Arrhenius function or in form of an Eyring model (e.g. Ref. [4]). Since these are the most relevant impact factors on a VIP, the temperature–humidity dependence of the pressure increase is a major field of investigation at EMPA.

(ii) The water vapor transmission rate (WVTR) can be 10^3 up to 10^6 times the values of OTR or NTR in equivalent units [5]. On a long-term basis, the internal water vapor pressure may reach equilibrium with the environment that is typically in the range of 10–20 mbar. On its own this would be a negligible contribution to the gas induced heat conduction in a SiO_2-VIP. However, moisture will be accumulated in the core according to the sorption isotherm (Fig. 4) [6,7], leading to an increase of the thermal conductivity of about 0.5 mW m^{-1} K^{-1} per mass% (Fig. 5) [8,9]. For example, if the moisture content approaches 4 mass% (equilibrium for normal indoor conditions 23 °C and 50% r.H.) the thermal conductivity will reach 6 mW m^{-1} K^{-1} compared to 4 mW m^{-1} K^{-1} in the dry state.

(iii) Due to a higher defect density at wrinkles, edges, corners and the seal, additional gas permeation and size dependent effects have to be taken into account. Since there is no obvious analytical model for those effects service life estimates must be extracted from the assembled VIP as a whole. Long-term behavior of other properties could be relevant as well. For instance requirements on dimensional stability apply for most applications. In load bearing constructions compression and compressive creep behavior have to be considered. In certain applications resistance to chemicals and/or UV is required too. On the other hand it is often possible to avoid those additional stress factors to a large extent by appropriate construction design.

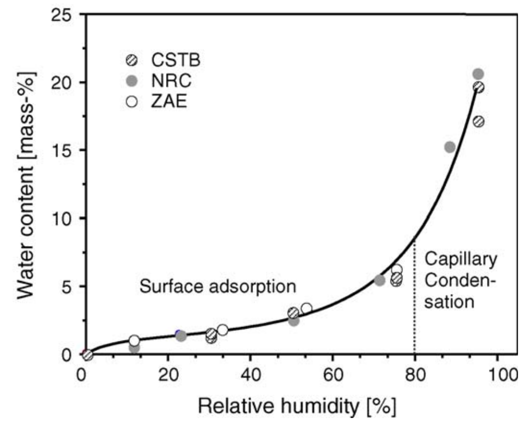


Fig. 4. Sorption isotherm of SiO_2 as determined by various labs within IEA Annex 39 [6]. A generally used linear approximation is 0.08 mass% per %r.H.

2.2. Polymer based barrier materials

As an example the layer sequence of a polymer based high barrier material with three metal layers is indicated in Fig. 6. It consists of three aluminized PET or PP films which are PU laminated. An additional PE layer towards the VIP inside is used to thermally weld two adjacent barrier sheets. On a long-term scale, aging of all envelope components has to be taken into account. Because the metal layer is extremely thin (e.g. 30 nm), a short check for the 50 years service life regarding the oxidation speed of aluminium is

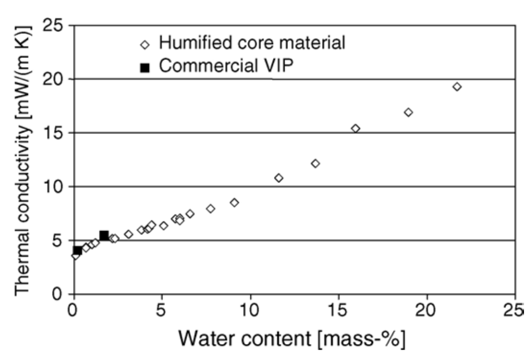
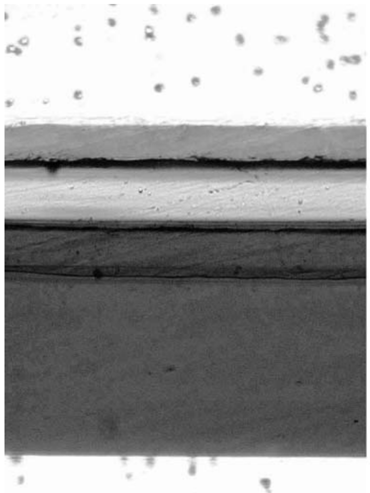


Fig. 5. Thermal conductivity of evacuated SiO_2 as a function of the moisture content. The humified core material data are from ZAE [8], where the specimens were water loaded before evacuation and sealing. The VIP data were determined on a commercial product, before and after exposure to high water vapor pressure.



Layer #	Material	Function	Thickness [μm]
1	PET	Protecting layer (substrate for 2)	12
2	AL	Barrier layer	0.03
3	PUR	Glue	2
4	AL	Barrier layer	0.03
5	PP	Substrate for 4	18
6	PUR	Glue	2
7	AL	Barrier layer	0.03
8	PET	Substrate for 7	12
9	PUR	Glue	2
10	PE-LD	Sealing layer	60

Fig. 6. Visualization of a laminated polymer based high barrier envelope containing three aluminum barrier layers with an optical microscope (top and bottom areas are embedding material).

needed. A fresh aluminum surface has a 1 nm oxide layer. This layer acts as an oxidation barrier and slows down further aluminum oxidation asymptotically up to a thickness of some tens of nm in contact with air [10]. Also, a fully oxidized first layer can act as a barrier, as Al_2O_3 is also used as a barrier material [11], so that the second and third metallic layers have much lower oxygen exposure. Moreover, accelerated aluminum surface oxidation is primarily observed at high air humidity above 60–80% r.H. [12] and temperatures in a range of 80 °C or above. Within these limitations, oxidation should not be critical in most building applications, as far as high humidity is not correlated with high temperature. Also the base level of moisture or water in the environment must be limited to pH-values between 3 and 8.5 [13,14], which should be considered particularly if concrete or other alkaline substances are present in the immediate vicinity. PU layers may be subject to degradation by hydrolysis in contact with hot water [15]. Subsequent delamination of the barrier would clearly cause premature failure of a VIP. Delamination could be accelerated by interfacial H_2O condensation as well as shear stress from different hygro-thermal expansion properties of metallic and polymeric layers.

Concerning the polyethylene layer used for sealing the envelope, maximum service temperatures of PE-LD are given as 80 °C for short-term and 60 °C for long-term application when stabilized by phenolic antioxidants. For PET 130 °C is permissible under long-term exposure [16]. Various stabilizers to prevent UV as well as thermal aging are available for each type of polymer [17]. PET is stated as quite UV resistant [16]. If regular exposure to solar radiation in the application is foreseen, specially stabilized types are required. It should be noticed that short high intensity UV irradiation does occur during the plasma-treatment before metallization [18]. For this reason O_2 or Ar plasma is favorable [19]. Also PE as the most sensitive polymeric material in the VIP envelope was proven to be stable in a long-term building application by means of appropriate stabilization [20]. For all those reasons barrier materials should be carefully protected against moisture or even water from the environment, as well as against temperatures above an approved maximum service temperature. Occasional condensation can be accepted if subsequent drying is ensured.

2.3. SiO_2 based core material

Generally it can be stated that besides compression forces no substantial stress appears on core components at least as long as the barrier is tight. Furthermore fumed silica as the main component is very stable in the temperature range of buildings. The same holds for additives such as fibers used for structural enhancement or opacifier added to reduce interstitial infrared radiation exchange. Therefore no significant aging of the core has to be taken into account. In case of a barrier break moisture equilibrium with the environment will be reached soon, but the core materials will still not degenerate in an unacceptable manner.

In summary, recent barrier materials and core components both do have the potential of a reasonable service life in building applications, provided the mentioned limitations are respected. In the remaining sections, the focus will be put on the long-term performance of the VIP assembly exposed to temperature and humidity.

3. Experimental characterization methods

Rise of the internal pressure and accumulation of moisture in the core material are the two basic aging effects influencing the long-term heat resistance and hence the service life of VIP. Whereas moisture permeation can easily be measured just by weighing, a common method for the measurement of the internal pressure does not exist. A

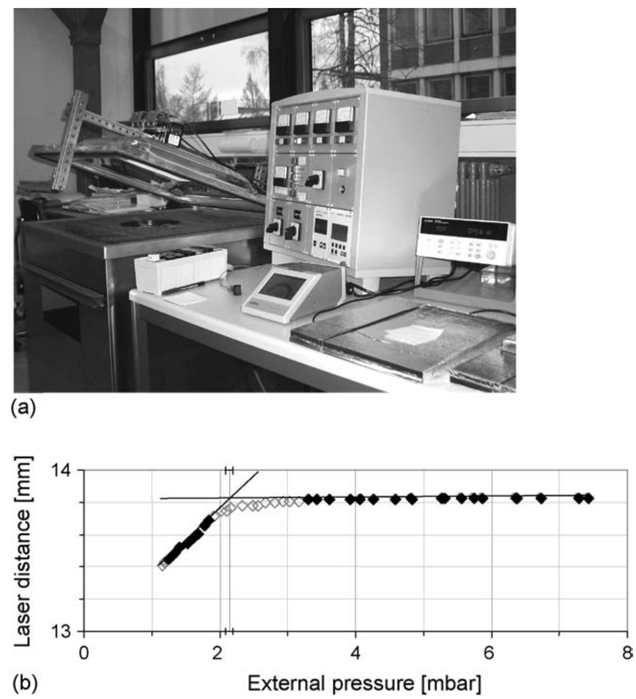


Fig. 7. Depressurization apparatus for the determination of the internal pressure at EMPA (a). The pressure of detachment is identified in the distance–pressure diagram (b) as the intersection of the two linear portions (filled diamonds) of the distance function. Below the intersection the VIP is expanding.

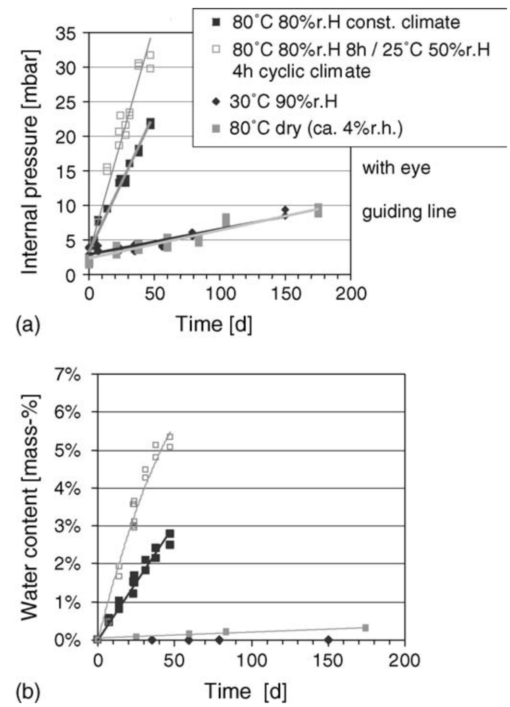


Fig. 8. Increase of internal pressure (a) and moisture content (b) in ''small'' VIP at elevated temperature/humidity. The measurements were carried out at room temperature after cooling down the samples for at least 2 h.

depressurization based method has been successfully applied by various laboratories: the pressure around a VIP specimen is continuously reduced in a vacuum chamber. If the chamber pressure reaches the internal pressure of the VIP, the flexible barrier film starts moving away from the core board. At EMPA the distance of the envelope surface is measured continuously with one or more laser distance meters at fixed locations on the VIP surface as a function of the chamber pressure (Fig. 7). Thus, the ''critical pressure'' of detachment can be determined with an accuracy of about 0.3 mbar plus 5%, taking into account that the detachment behavior may be influenced to some extent by local effect. An important measure is of course the thermal resistance to be determined, e.g. with a guarded hot plate [21]. However, since the sensitivity of the thermal conductivity to slight pressure changes (Fig. 3) is weak, this method is rather inappropriate to quantify gas permeation effects on an undamaged VIP. Furthermore, a change of the thermal resistance can be caused either by pressure increase and/or moisture accumulation in the silica core.

4. Hygro-thermal VIP aging behavior

As varying temperature and moisture conditions are always present in buildings, (accelerated) aging experiments at EMPA were focused on elevated temperature and humidity. The specimens, typically 250 mm × 250 mm (''small'') and 500 mm × 500 mm (''large'') with a thickness of 20 mm, represent recent VIP products on the European market. To check the impact of a wide range of conditions, a first series of measurements were performed on small specimens at the manufacturer-declared maximum service temperature of 80 °C, applying a relative humidity of 80% at the same time (80 °C/80% r.H.). For comparison, cyclic conditions and 80 °C exposure at ambient vapor pressure were also investigated. Subsequent tests were performed at 30 °C/90% r.H., considered to cover a reasonable range of applications.

Results are summarized in Fig. 8. At 80 °C/80% r.H., 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 Fig. 8 cyclic conditions (8 h at 80 °C/80% r.H. ↔ 4 h at 25 °C/50% r.H.) are even more severe than a constant 80 °C/80% r.H. 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 between internal pressure and moisture content exists, indicating that water vapor is a major reason for the pressure increase. Another indication of the high moisture sensitivity is the behavior at 80 °C and low (ambient) vapor pressure: the pressure increase rate is much lower, but is still above 10 mbar per year (remember an acceptance range of about 2 mbar per year).

Table 1
Moisture accumulation and internal pressure increase rates of VIP specimens in two sizes at accelerated conditions 65 °C, 75% r.H. with different barrier materials, based on an exposure of 103 d

Type	Size (cm)	Moisture accumulation (mass%/a)	Pressure increase (mbar/a)
AF	25 × 25 × 2	0.04 ± 0.01	*
	50 × 50 × 2	0.02 ± 0.02	*
MF1	25 × 25 × 2	7.1 ± 0.3	63 ± 3
	50 × 50 × 2	5.5 ± 0.1	38 ± 1
MF2	25 × 25 × 2	5.3 ± 0.5	34 ± 5
	50 × 50 × 2	4.0 ± 0.4[b]	19[a]

[a] Four samples of 25 cm × 25 cm × 2 cm, two samples of 50 cm × 50 cm × 2 cm the only sample having stress on middle seam failed near 4% at 29 and 73 d.
[b] Higher value than small size is hint to coming leakage at the middle seam, which occurred about 3 weeks after the 103 d while stored at lab conditions on the MF2.
* Value had been still below detectable level.

The moisture content remains close to zero in this case. At 30 °C/90% r.H., the pressure increase rate is (by accident) quite similar. The behavior of three different products, each in two sizes, was compared by continuous exposure to 65 °C/75% r.H. conditions (Table 1). Product AF with a massive 6 μm aluminum barrier is very stable, regarding both the moisture content and the internal pressure. Product MF1 and product MF2 have basically a similar barrier, namely a laminated three-fold metallized polymer film. Each metal layer thickness is about 30 nm (MF1) and 100 nm (MF2). While MF2 is more resistant to N_2 and O_2, both polymer based products are rather open to water vapor. The almost tripled aluminum thickness in MF2 does not block H_2O permeation much better. Edge effects are also apparent from Table 1, as the rates are not independent from the size of the specimens. Less severe, but non-negligible effects are detectable also for the more typical conditions 23 °C, 50% r.H., regarding both water uptake and pressure increase (Table 2). For those conditions, the moisture accumulation rate $\dot{u}$ is in the order of 0.1 mass% per year, and the pressure increase rate $\dot{p}$ in the range of 1.5 mbar per year for the ‘‘large’’ specimen size. It can be concluded from the data that the area and edge contribution to the moisture permeance are about equal, while the pressure increase is dominated by the edge contribution.

Table 2
Moisture content and internal pressure increase rates of VIP specimens in two sizes at standard conditions 23 °C, 50% r.H. with different barrier materials, based on an exposure of ca. 180 d

Type	Size (cm)	Moisture accumulation (mass%/a)[a]	Pressure increase (mbar/a)[b]
AF	25 × 25 × 2	0.02	0.7
	50 × 50 × 2	0.03	0.6
MF1	25 × 25 × 2	0.15	3.3
	50 × 50 × 2	0.10	1.8
MF2	25 × 25 × 2	0.16	1.4
	50 × 50 × 2	0.12	1.0

[a] Estimated uncertainty ±0.02%.
[b] Estimated uncertainty ±0.6.

Combining these panel aging results with average core properties derived from Figs. 3 and 5 the change rate of the thermal conductivity, which may be expressed as

$$\dot{\lambda} = \frac{\partial \lambda}{\partial p}\dot{p}(T,\varphi) + \frac{\partial \lambda}{\partial u}\dot{u}(T,\varphi) \tag{2}$$

is estimated as

$$\dot{\lambda} = 0.035 \times 1.5 + 0.5 \times 0.1 \approx 0.1\,\mathrm{mW\,m^{-1}\,K^{-1}\,a^{-1}} \tag{3}$$

for constant rates and conditions 23 °C, 50% r.H. Hence, for instance during a 25 years exposure, the thermal conductivity is expected to change approximately from 4.0 to 6.5 mW m^{-1} K^{-1}. The effects of moisture accumulation and ‘‘dry’’ gas pressure increase are roughly equal in this case. A general expression for the pressure increase rate is

$$\dot{p} = \frac{p_0 Q_{N_2,O_2}(T,\varphi,A,\ell)}{V_i}\Delta p \tag{4}$$

where the dry air permeance Q_{N_2,O_2} depends on temperature and humidity as well as on surface area A and edge length ℓ, V_i is the free volume in the porous core, p_0 the standard air pressure and Δp the pressure difference between outside and panel inside. For low inside pressure Δp is approximately the ambient pressure p_{ambient}.

Since ambient water vapor pressure is rather low in most applications moisture saturation effects or equilibrium may occur on a long-term scale. With a linear approximation of the sorption isotherm $u(\varphi) = s\varphi$ in the hygroscopic range the moisture accumulation rate equation is

$$\dot{u} = \frac{Q_{H_2O}(T,\varphi,A,\ell)}{m_{\mathrm{dry}}}(p_{H_2O,\mathrm{ambient}} - p_{H_2O}) = \frac{1}{\tau}(u_{\mathrm{equilibrium}} - u) \tag{5}$$

under steady state conditions, with

$$\tau = \frac{u_{\mathrm{equilibrium}}}{\dot{u}_{\mathrm{initial}}}, \qquad u_{\mathrm{equilibrium}} = s\varphi_{\mathrm{ambient}} \tag{6}$$

The water vapor permeance Q_{H_2O} depends on similar parameters as Q_{N_2,O_2}. With constant parameters the solution of Eq. (5) is

$$u(t) = u_{\mathrm{equilibrium}}\left(1 - \exp\left(\frac{-t}{\tau}\right)\right) \tag{7}$$

If Eqs. (6) and (7) are used instead of a constant moisture accumulation rate in Eq. (3) the time constant τ is 40 years and the (asymptotic) equilibrium moisture content $u_{\mathrm{equilibrium}}$ is 4 mass%. The moisture related change of the thermal conductivity after 25 years is 0.93 mW m^{-1} K^{-1} compared to 1.25 mW m^{-1} K^{-1} obtained without accounting for saturation.

5. Service life estimates in building applications

In order to estimate the service life in an application, a direct approach is the integration of Eq. (2), taking into account the appropriate core characteristics, the temperature and humidity dependent permeation rates and the dynamic boundary conditions in the environment of a built-in VIP. Furthermore, transport and storage of heat and moisture within the VIP core must be considered in a detailed model of gas and moisture exchange between a VIP and its environment. Due to the complexity of this task a simplified approach was chosen to get service life estimates on the safe side. Yearly values of pressure increase and moisture accumulation have been determined at a constant relative humidity of about 80% for various temperatures. They are indicated in Fig. 9 in direct units and in a log(y) versus $1/T$ plot. The linear shape of the curves clearly indicates an Arrhenius-like behavior (cf. Eq. (1)) of the acceleration functions. Under the assumption that the yearly pressure increase can be superimposed by the time weighted increase at a given temperature and humidity, the Arrhenius fit parameters A and E_a can be used to estimate the yearly pressure increase rate p_a with respect to dynamic boundary conditions as follows:

$$p_a = \frac{\sum_i A \exp\left(-\frac{E_a}{RT_i}\right)\Delta t_i}{\sum_i \Delta t_i} = A\exp\left(-\frac{E_a}{RT_{\text{effective}}}\right) \quad (8)$$

Due to the Arrhenius temperature weighting factor the effective temperature $T_{\text{effective}}$ is always higher than the time average temperature. A similar approach is applicable to evaluate the yearly moisture accumulation rate u_a. A rather high relative humidity being effective at all temperatures is a cautious assumption in building applications. However, frequent contact with liquid water is not covered by the acceleration function.

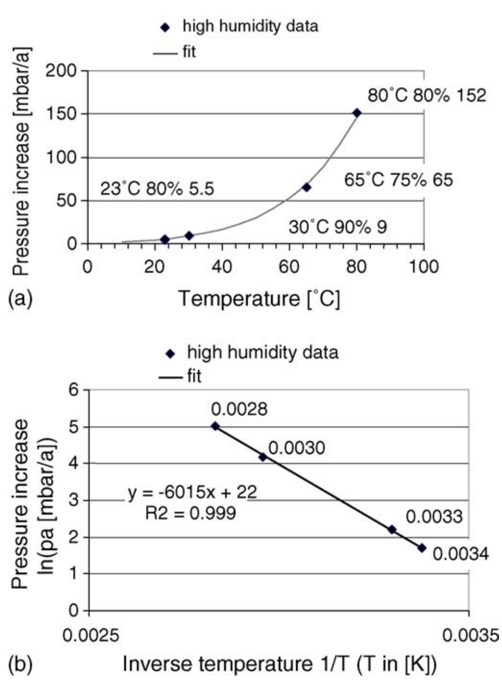
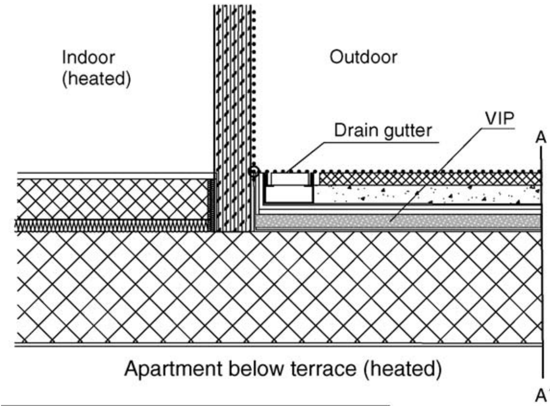


Fig. 9. Temperature dependence of the pressure increase rate in the high humidity range (a) and Arrhenius plot of the same data set (b).



Layer (AA´ from top to bottom)	d [mm]
Concrete plate	20
Crushed gravel	30
Fleece	2
Bituminous water barrier	7
Protective layer	8
VIP	20
Protective layer	5
Water barrier	3
Concrete	180
Interior plaster	5

Fig. 10. Building details and material layers of a walkable VIP insulated terrace. A solar absorptance of 65% on the outside surface was assumed in the thermal calculation.

The procedure was applied to a terrace building on a hill side, which is a typical construction in densely populated areas in Switzerland (Fig. 10). Underneath the VIP insulated accessible flat roof are heated rooms of the apartment below. In spite of potential risks with water penetration some ten thousand square meters of VIP are installed in this type of roof construction by now. The reason for the trend to slim VIP insulation is that the floor height inside and outside can be made equal, even under the stringent heat resistance requirements for the outside part of terrace roof. Surface temperatures on both sides of the VIP layer were calculated by means of the building simulation tool HELIOS [22]. The program calculates hourly values of temperatures and heat fluxes in a single zone and on the surrounding wall surfaces depending on the indoor temperature control strategy and outdoor climate data like air and sky temperature, wind speed and solar irradiance and absorption on outer surfaces. In the calculation, a constant indoor temperature of 22 °C was assumed for simplicity. For the outdoor climate, the design reference year for Zurich Airport (Switzerland) was chosen. The solar absorptance of the outside surface was set to 65% (weathered concrete). In Fig. 11a, temperatures on the two main faces of the 20 mm VIP are shown from the beginning of October until the end of September. On the inside surface, the temperature is quite constant according to

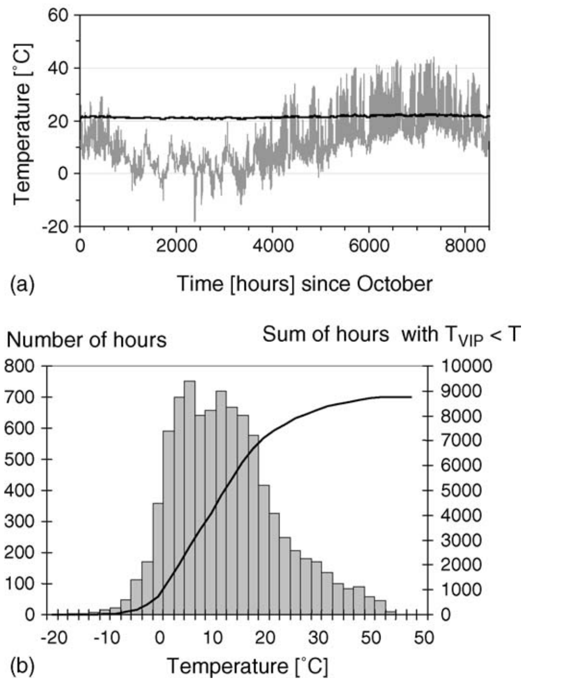


Fig. 11. Surface temperatures of a VIP in a terrace insulation application for a Swiss design reference year (Zurich Airport) starting on 1 October (a) and cumulative histogram of hourly temperature values on the outside surface of the VIP (b).

the boundary condition, while the temperature on the outside varies between −18 up to +44 °C. The temperature histogram in 2°-steps is indicated in Fig. 11b. The temperatures and the respective number of hours of occurrence were fed into Eq. (8), along with the parameters obtained from the Arrhenius fits. A panel size of 50 cm × 50 cm was modeled by scaling parameter A according to the size dependent results in Table 2. The results of the thermal and the aging evaluation are given in Table 3. The effective temperature at the inside surface, close to the time average value, is about 21.5 °C. On the outside surface, the effective temperature of 16.0 °C is clearly higher than the time average of 11.9 °C due to the temperature peaks in summertime as consequence of the non-linearity of the Arrhenius function. Nevertheless, the high-temperature periods are short enough to keep the average stress lower on the outside than on the inside surface for climatic zones similar to Zurich or colder. Averaging the results of both sides, the mean pressure increase rate p_a is

Table 3
Results of the thermal and aging calculation for the inside and outside surface of a 20 mm VIP layer (panel size 50 cm × 50 cm) in a terrace construction for high humidity condition (80% r.H.)

Quantity	VIP inside	VIP outside
Maximum temperature (°C)	22.5	44.1
Average temperature (°C)	21.5	11.9
Effective temperature (Arrhenius) (°C)	21.5	16.0
Pressure increase rate (mbar/a)	2.5	1.7
Moisture accumulation rate (mass%/a)	0.21	0.14

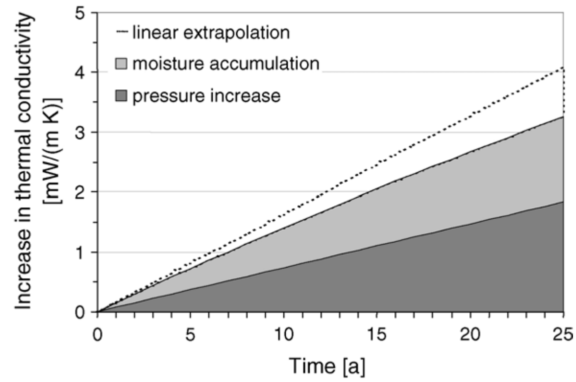


Fig. 12. Increase of the thermal conductivity of a VIP terrace insulation due to pressure increase and moisture accumulation (panel size 50 cm × 50 cm, see text for details).

about 2.1 mbar per year, the initial moisture accumulation rate u_a is 0.18 mass% per year, and the saturation time constant τ is 35.6 years for the equilibrium moisture content $u_{equilibrium}$ of about 6.4 mass% at 80% r.H. (Eq. (6)). According to Eq. (7), the thermal conductivity increase by integration of Eq. (2) is

$$\Delta\lambda(t) = 0.035 \times 2.1 \times t + 0.5 \times 6.4\left(1 - \exp\left(\frac{-t}{35.6}\right)\right) \quad (9)$$

in mW m^{-1} K^{-1}, with time, t, in years (Fig. 12). If for instance an increase of 4.0 mW m^{-1} K^{-1} is considered the time span is 31.6 years under these rather unfavorable assumptions.

A similar calculation was made for an external thermal insulation compound system (ETICS) often applied on concrete or masonry walls in Central Europe. Thick mineral wool or polystyrene foam boards are normally used. The standard thermal insulation board was replaced by a 20 mm VIP covered by a 10 mm polystyrene layer on both sides. Of importance for the dynamic behavior is a sufficient heat buffering capacity of the outside rendering. With a 3 cm mortar layer, the yearly effective temperature – dependent on the wall orientation – does not exceed 15 °C for similar boundary conditions as in the terrace calculation (solar absorptance 35%). Consequently, reasonable service life can be expected also in this application. However, it shall be pointed out again that no other aging mechanisms but temperature and humidity are included in the aging consideration so far. For instance, frequent occurrence of condensation on surfaces or along joints between VIP boards could cause aging effects not covered by the underlying acceleration function. Therefore, laboratory work will be extended to aging behavior under hygro-thermal cycling including surface condensation. More detailed construction performance calculations will have to include heat and moisture transport in order to evaluate condensation risks on VIP surfaces or joints. The relevance of other stresses, e.g. of mechanical and/or chemical origin, and the correlation between laboratory based service life prediction and real world behavior can be assessed only by comparison of laboratory data with real long-term performance data from installed VIP. Set-up and evaluation of this kind of measurements is in progress.

6. Thermal design values

Similar to conventional thermal insulation products, aging effects covering a time period of 25 years have to be taken into account for product specification and building design (see, e.g. Ref. [23]). As product specific aging procedures are not yet established, it is reasonable to use approximate thermal design values for the VIP core which include performance characteristics of different envelope materials in usual applications. As shown before, aging of VIP with aluminum foil (AF) and metallized polymer film (MF) barrier is clearly different. Using $\mathrm{W\,m^{-1}\,K^{-1}}$ units, increments of 0.001 (moisture uptake) plus 0.001 (pressure increase) seem to be sufficient for the AF type. The results on the MF type suggest applying increments of about $0.002\ \mathrm{W\,m^{-1}\,K^{-1}}$ both for moisture uptake and pressure increase effects at standard conditions. Thus, starting with $0.004\ \mathrm{W\,m^{-1}\,K^{-1}}$ for the dry low-pressure SiO_2-VIP, suggested preliminary design values λ_{core} are $0.006\ \mathrm{W\,m^{-1}\,K^{-1}}$ for the AF and $0.008\ \mathrm{W\,m^{-1}\,K^{-1}}$ for the MF product group with a thickness of at least 20 mm and width of 250 mm or more.

In addition to those core design values, thermal bridge effects at the VIP edges or other components of a VIP construction have to be considered carefully, since thermal bridge and condensation risks are much more pronounced in an assembly containing a high heat and moisture barrier. In Ref. [2], it is shown that an equivalent thermal conductivity:

$$\lambda_{\mathrm{equivalent}} = \lambda_{\mathrm{core}} + \Psi(d)\frac{d\ell}{A} \tag{10}$$

can be used for a large area VIP insulation layer if other thermal bridges are negligible. The edge contribution depends on a linear thermal transmittance $\Psi(d)$, the thickness d, the total edge length ℓ, and is the total area A. Design values on the safe side for the linear thermal transmittance, $\Psi = 0.07\ \mathrm{W\,m^{-1}\,K^{-1}}$ for AF and $\Psi = 0.01\ \mathrm{W\,m^{-1}\,K^{-1}}$ for MF envelopes, were calculated and experimentally verified at Empa.

7. Conclusions

The recent VIP technology in building offers new solutions for highly insulated constructions with just a fraction of the required insulation thickness compared to conventional thermal insulation materials. New high barrier materials on the basis of multi-layer metallized polymer films have the potential to meet the requirements both for long-term building application and minimal thermal bridge effects through the edge zone. In general, moisture permeance is still a weak-point of those barriers compared to massive aluminum foil. In particular, wet or alkaline environment in combination with high temperature should be avoided in any application. According to the observed Arrhenius-like temperature aging behavior in humid environment, a service life in the range of several decades may be achieved in suitable constructions, provided no regular surface condensation or other significant stresses are present. More data from real world and laboratory assessment are necessary to get more reliable service life prediction for an arbitrary combination of temperature, moisture, mechanical and chemical aging mechanisms.

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