



HiPTI - High Performance Thermal Insulation
IEA/ECBCS Annex 39

Vacuum Insulation **Panel Properties and Building Applications**

Summary

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Title

Vacuum Insulation - Panel Properties and Building Applications

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Abstract

Vacuum insulation panels (VIP) were already developed some time ago for use in appliances such as refrigerators and deep-freezers. Their insulation performance is a factor of five to ten times better than that of conventional insulation. Used in buildings they enable thin, highly insulating constructions to be realized for walls, roofs and floors.

The motivation for examining the applicability of high performance thermal insulation in buildings (i.e. evacuated insulation in the form of vacuum insulation panels) came from the difficulties involved in renovation – namely severe space limitations and therefore technical constraints, as well as from aesthetic considerations.

Vacuum Insulation Panels

The thermal resistance of evacuated insulation is a factor of five to ten better than conventional insulation of the same thickness. Vacuum insulation panels (VIP) in general are flat elements consisting of an open porous (and therefore evacuation-capable) core material which has to withstand the external load caused by atmospheric pressure, as well as a sufficiently gas-tight envelope to maintain the required quality of the vacuum.

Nano-structured materials have been found to require the least quality of vacuum, which has to be achieved and to be maintained. In panels basically made of pressed fumed silica, the contribution of the gas to the total heat transfer is virtually eliminated even at an internal gas pressure of a few hundred Pascals. The requirements on the gas-tightness of the envelope are also relatively moderate for these extremely fine-structured core materials – the largest pores are in the order of 100 nanometres. Thin laminated metal foils and special high-barrier metallized laminates consisting mainly of polymers are therefore used for the envelope. This report focuses especially on this type of VIP, which combines relatively simple and flexible production methods (and is therefore currently the least expensive alternative) with an service life of 30 to 50 years, limited by air permeation into the panels. Even if the vacuum failed completely, the thermal resistivity of this filler material is twice as efficient as that of any standard insulation material.

Investigations have been performed individually on the core materials and laminates designed for the envelope as well as manufactured VIP.

Building Applications

The introduction of such a novel insulation system in the building trade, however, is hampered by many open questions and risks. The work illustrates a wide selection of reports from practice, shows how the building trade deals with this new insulation system today, the experience gained and the conclusions drawn there from. As well as presenting recommendations for the practical use of VIP, the report is also able to answer questions regarding the effective insulation values to be expected with today's VIP.



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1 Introduction

The motivation for examining the applicability of high performance thermal insulation in buildings (i.e. evacuated insulation in the form of vacuum insulation panels) came from the difficulties involved in renovation – namely severe space limitations and therefore technical constraints, as well as from aesthetic considerations.

The following numbers give an impression on potential impact vacuum insulation could have on energy consumption:

In 1997, about 25% of the energy consumption in the EU came from room heating.

In 1995, there were roughly 150 million dwellings in the EU-15, 32% of this stock was built prior to 1945, 40% between 1945 and 1975 and 28% between 1975 and 1995.

Table 1: Energy consumption of buildings in Europe. (Source: Directive of the European Parliament And The Council on the energy performance of buildings.)

Residential Sector	[%]	Commercial	[%]
Space Heating	57	Space Heating	52
Water Heating	25	Water Heating	9
Electric Appliances	11	Lighting	14
Cooking	7	Office Equipment	16
		Cooking	5
		Cooling	4



2 IEA/ECBCS Annex 39

Germany and Switzerland were the first two countries supporting R&D activities with the aim of introducing VIP-technology to the building industry. In 2000 Switzerland decided to launch the topic on an international level. This happened in the frame of the IEA (International Energy Agency) Implementing Agreement called ECBCS (Energy Conservation in Buildings and Community Systems). Implementing Agreements are a kind of international networks of national representatives with the aim of coordinating applied research in the field of energy.

Annex 39 was the 39th research program of ECBCS. It was officially adopted by the Executive Committee of ECBCS in November 2000 and started with an international conference in January 2001.

Since the topic was new to the research community, it was quite difficult to set up a work plan with the participating institutes. One problem for instance was the lack of standard methods to study VIP. But finally a work plan with two main fields of activity (subtasks) was developed:

Subtask A: Panels

Existing products, mainly VIP, were analysed and their properties optimised in the way, that they meet the requirements of the systems in which they are applied.

Measurement standards concerning product declaration and quality monitoring procedures were developed.

Subtask B: Applications

Part 1: Application and system development

Companies developing VIP-systems for the building envelope and HVAC components were supported. The support consisted in informing potential companies about VIP, forming suitable groups for each development project, providing theoretical and practical information (simulation and testing of systems).

Part 2: Demonstration and information dissemination

Demonstration projects were realized together with architects and building owners.

Lessons learned from the demonstration projects were collected and used for further improvement of the materials and systems.

Information material was distributed to increase the interest of construction companies and clients.



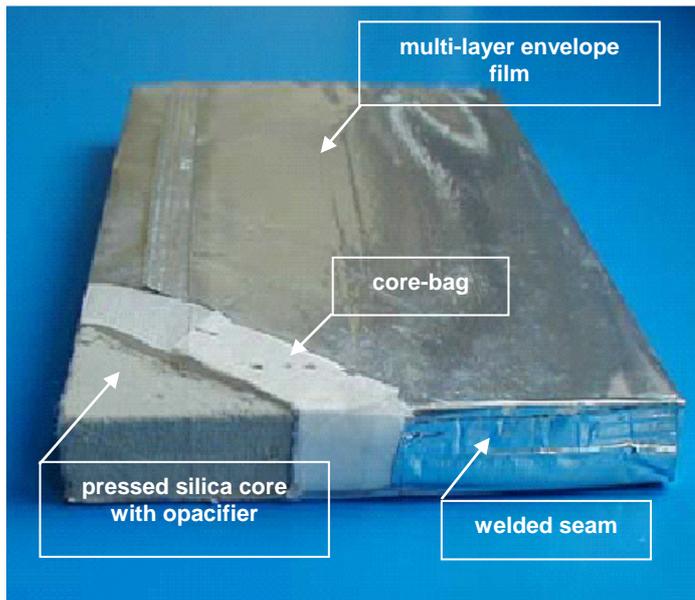
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3 Vacuum Insulation Panels

Vacuum insulation panels (VIP) in general are flat elements consisting of an open porous (and therefore evacuation-capable) core material which has to withstand the external load caused by atmospheric pressure, as well as a sufficiently gas-tight envelope to maintain the required quality of the vacuum.



*Figure 1: Components of a VIP. The core-bag provides mechanical stability for handling and protects the welding area from being polluted by core-powder.
(foto: va-Q-tec).*

3.1 Core

Nano-structured materials have been found to require the least quality of vacuum, which has to be achieved and to be maintained. In panels basically made of pressed fumed silica, the contribution of the gas to the total heat transfer is virtually eliminated even at an internal gas pressure of a few hundred Pascal.

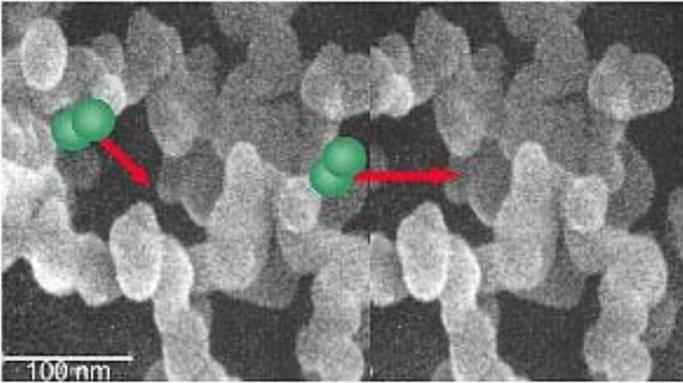


Figure 2: SEM image - Pore Size Distribution.
(Source: Wacker / ZAE-Bayern)

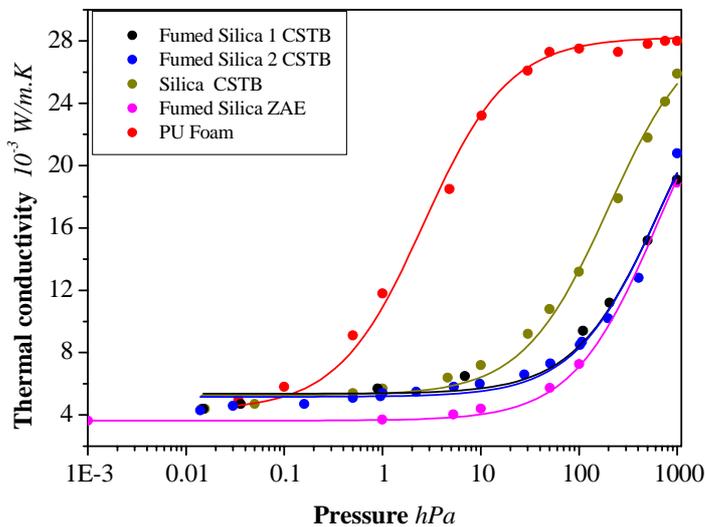


Figure 3: Thermal Conductivity versus pressure of a PU, three fumed silica and one precipitated silica sample.

The densities are in the range of 160 kg/m³ to 190 kg/m³. The porosity is higher than 90%, the specific surface area is higher than 200 m²/g. High sorption capability results from the huge specific surface area. Thus fumed silica may act as a desiccant.

For high humidity, from 60 up to 95%, there is an exponential increase mainly due to the capillary condensation in the small pores. Indeed, according to the Kelvin-Laplace law, at 95%, all the pores with a size smaller than 20 nm are filled with water.

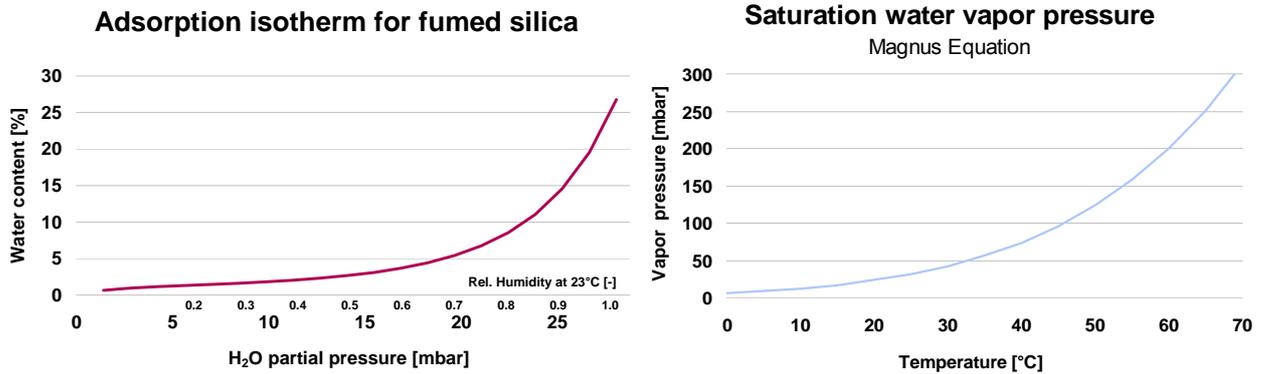


Figure 4: Left: Adsorption isotherm of fumed silica (fitted curve, based on data of three laboratories). Right: Partial water vapor pressure of saturated air.

At a low gas pressure (1 mbar) and at room temperature the total thermal conductivity of the core material is about 0.004 W/(m·K) - 0.001 W/(m·K) from infrared radiative heat transfer and 0.003 W/(m·K) due to heat conduction via the solid skeleton. The thermal conductivity increases with the internal gas pressure to about 0.020 W/(m·K) at ambient pressure.

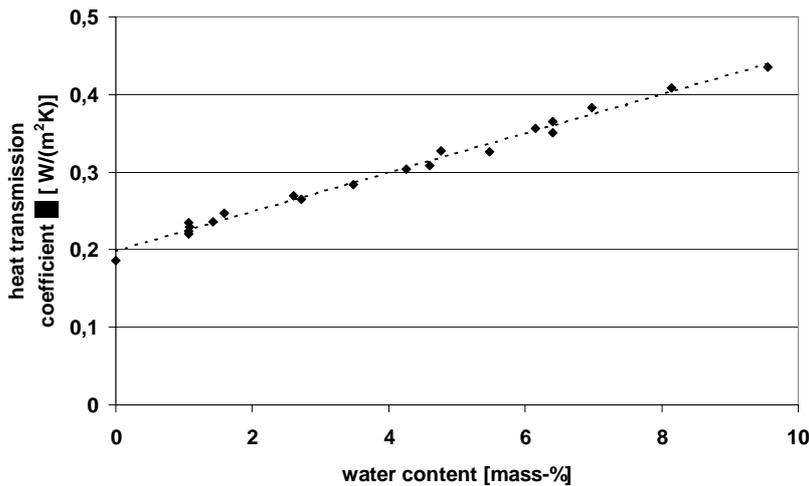


Figure 5: Measured heat transfer coefficient versus the water content for a 20 mm thick VIP. Mean temperature was 10°C.

At 10°C the impact of water content on the thermal conductivity was found to be linear with an increase of about 0.0005 W/(m·K) per mass-% of adsorbed water.

$$\frac{\partial \lambda}{\partial X_w} \approx 0.5 \frac{mW}{mK \% - mass} \quad (1)$$

Starting with an approximate initial thermal conductivity of about $4 \cdot 10^{-3}$ W/(m·K) for the dry core, a value of about $6 \cdot 10^{-3}$ W/(m·K) results for moisture equilibrium at 50% RH.

The influence of other atmospheric gases on the thermal conductivity may be estimated by the following linear relation between gas pressure and thermal conductivity:



$$\frac{\partial \lambda}{\partial p} \approx 0.035 \frac{mW}{mK mbar} \text{ in the range up to 100 mbar} \quad (2)$$

λ : thermal conductivity, W/(m·K)

p : “dry gas” pressure in the pores, mbar

Thus a dry gas pressure increment of 30 mbar corresponds to a thermal conductivity increase of about $1 \cdot 10^{-3}$ W/(m·K).

3.2 Envelope

The most critical component of a Vacuum Insulation Panel (VIP) is the envelope, which is responsible for the maintenance of the vacuum inside the panel. Normally polymer laminates are used which contain metallized polymers or aluminium foils as barrier layer.

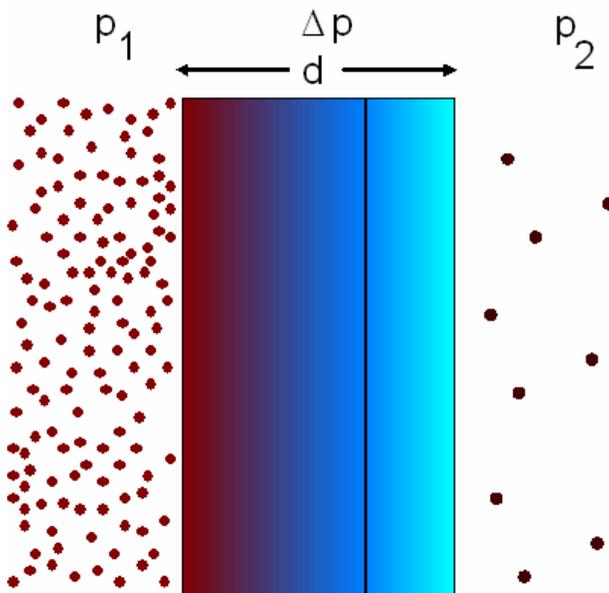


Figure 6: Permeation mechanism (schematic) through a laminate containing two homogenous polymers.

As with all polymeric films, the transmission rate for water vapour (WVTR) for these laminates was found to be several orders of magnitude greater than those for oxygen (OTR) or nitrogen: The units used for WVTR is g/(m²·d) and for OTR cm³(STP)/(m²·d) and today products do have WVTR and OTR in the same range but 1 g H₂O equals 1'244 cm³.



Table 1: Laminate transmission rates according to manufacturer's specifications for the tested laminates. PET=PolyEthylenTerephthalate, PE=PolyEthylen, PP=PolyPropylen, LD=LowDensity, met=Al-layer 30 to 80 nm thick.

Name	Laminate composition	OTR [cm ³ (STP)/(m ² ·d)]	WVTR [g/(m ² ·d)]
AF	12 µm PET / 8 µm Al / 100 µm PE-LD	< 0.0005 (25°C / 50% RH)	< 0.005 (20°C / 50% RH)
MF1	15 µm PPmet / 12 µm PETmet / 50 µm PE	0.07 (23°C / 50% RH)	0.1 (38°C / 90% RH)
MF2	20 µm PETmet / 20 µm PETmet / 25 µm PE	0.00062 (23°C / 75% RH)	0.005 (23°C / 75% RH)

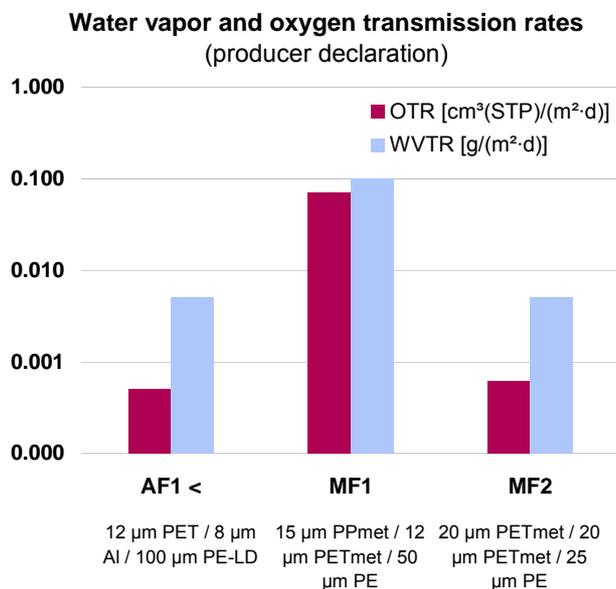


Figure 7: Transmission rates (producer declaration) of an aluminium foil based film (AF) and two polymer based metallized films (MF).

Measuring extremely low permeation rates is challenging and very time-consuming. A fast measurement tool was developed to derive water vapour transmission rates from helium transmission measurements. The effects of corners and edges on water vapour and on oxygen transmission rates were also determined.



3.3 Aging

The thermal conductivity λ_{cop} of a well evacuated dry VIP with a fumed silica core is typically about 0.004 W/(m·K) after production. As the low internal pressure is not in equilibrium with the environment, pressure gradients are present that act as driving forces for the intrusion of atmospheric gas (essentially N₂, O₂ and H₂O) and by this the thermal performance of VIP is impaired in two ways:

- increasing internal gas pressure and
- increase in the internal water content.

3.3.1 Aging vs. durability

In this context one might distinguish between aging and durability in the following sense: aging is a continuous process of performance degradation due to (normally) slow permeation of atmospheric gas molecules through the imperfect barrier, resulting in a non-reversible pressure increase and moisture accumulation in the hygroscopic VIP core. In contrast, durability is the ability of a VIP to withstand chemical or mechanical impacts that would cause failure of the barrier envelope, thus changing the internal low-pressure state within a short time by severe damage or rupture of the barrier. Regarding durability the risks for VIP in suitable building applications occur mainly before or during installation. A certain failure rate is present at the production plant, caused by material imperfections or processing errors. This type of failure can be largely avoided by quality control as well as by storing the panels during a specified time under defined conditions and checking them before they are shipped. It can be stated that the number of damaged or defective panels leaving the production plant was substantially reduced in the last few years. The figure is roughly assumed to be less than one percent. More frequent failures occur during transportation and handling of the panels until they are safely installed. Without protection the envelope is highly sensitive to mechanical impact, especially to point loads e.g. by sand grains, bricks or stone fragments, or other sharp objects including tools and corners of other panels. Once installed workmanlike, failure risks are observed to be low.

3.3.2 Measurement methods

Measurements on panels stored in different climatic conditions gave detailed information on permeation rates for air and water vapour as a function of temperature and humidity including all the effects of edges, corners and processing.

As a very accurate method to measure the internal pressure of panels a depressurization based method has been successfully applied by ZAE-Bayern, EMPA and NRC: the pressure around a VIP specimen is continuously reduced in a vacuum chamber. If the pressure in the chamber diminishes to below the VIP pressure, the VIP envelope lifts off the core surface. This can be recorded visually or by using photo electric sensors.



3.3.3 Results

3.3.3.1 Overview

The laminate with only one metallized layer was clearly proved not to fulfil the requirements. Acceptable pressure increases of about 1 mbar per year can be expected for VIP with an Al-foil and for laminates with three metallized layers.

Table 2: Area (subscript A) and perimeter (subscript L) related transmission characteristics of VIP with metallized polymer laminates (MF) for 23°C, 50% RH and 1 bar. For the MF1 and MF2 samples, an $WVTR_L$ value (edge effect) could not be determined since the panels were too small.

Barrier type	$WVTR_A$, g/(m ² d)	$WVTR_L$, g/(m d)	ATR_A , cm ³ /(m ² d)	ATR_L , cm ³ /(m d)
MF1	0.0233	-	0.0160	0.0080
MF2	0.0057	-	-	0.0039
MF3	0.0030	0.0008	0.0034	0.0091
MF4	0.0048	0.0006	0.0088	0.0018

3.3.3.2 Air-transmission - edge-effect

The significant contribution of air permeation through the edge-area of the VIP postulates that panels may not be too small in size, (i.e. larger than 50 cm x 50 cm).

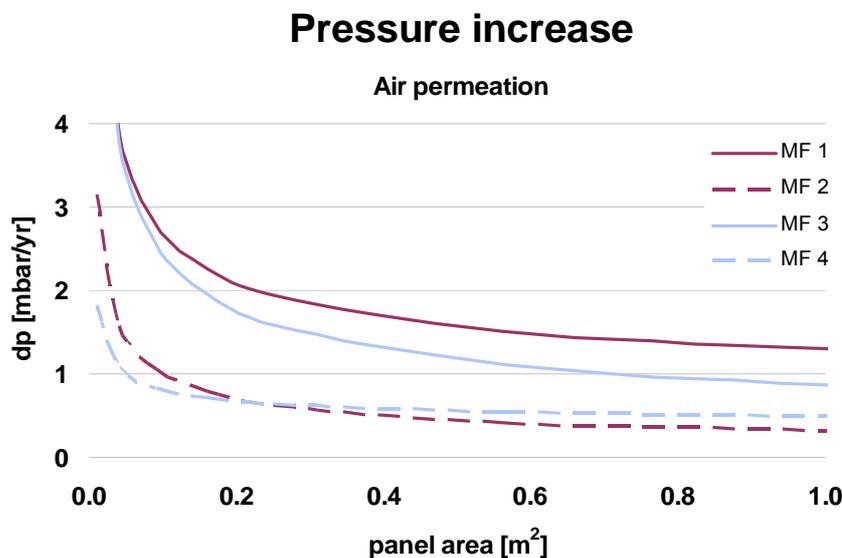


Figure 8: Edge effect on internal pressure increase by air permeation through four different metallized films (rectangular panel).

3.3.3.3 Water vapour transmission

Water vapour uptake in the threefold metallized film was found to be mainly dependent on the size of the panel surface - much smaller edge effect than for air permeation, whereas the panels with Al-film absorbed water vapour at a much lower rate, and this occurred mostly through the edges and seams.



Weight increase

Water vapour permeation

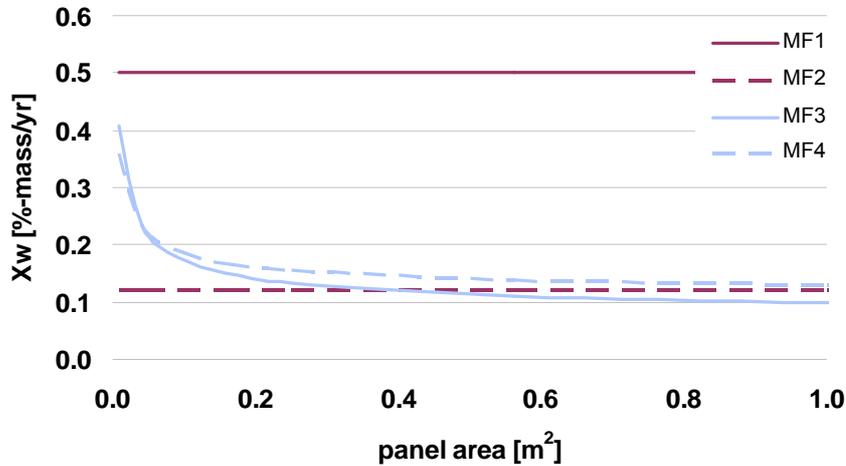


Figure 9: Edge effect on weight increase by water vapour permeation through four different metalized films. For the MF1 and MF2 samples, an edge effect could not be determined since the panels were too small (rectangular panel).

3.3.3.4 Climatic dependencies of transmission rates

The dependence of air transmission rates on temperature can be described by the Arrhenius law with activation energies that are in the range of 25 to 40 kJ/mol.

Water vapour transmission rates are proportional to the differences in the partial pressures inside and outside, a significant explicit dependence on temperature could not be observed.

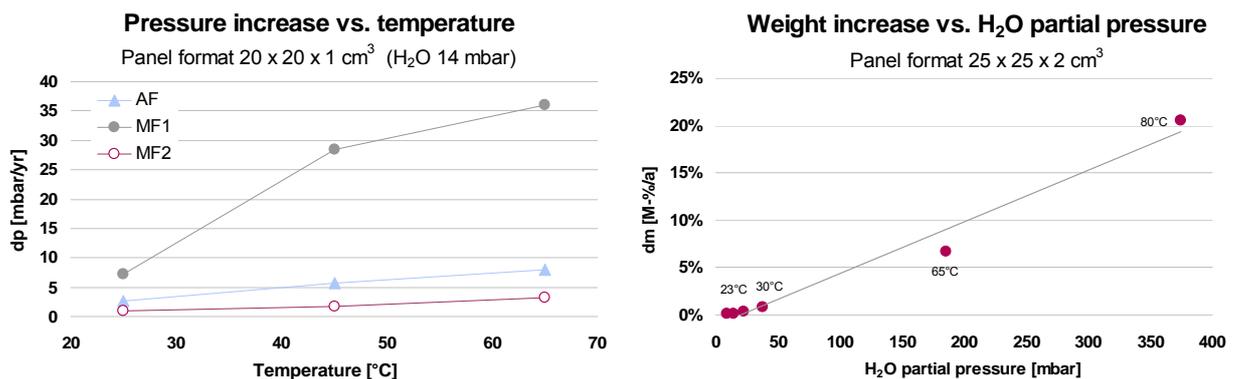


Figure 10: Internal pressure increase caused by dry air (left) and water vapour (right) permeation. The measurements were done at room temperature after cooling down the samples for some hours.



3.3.3.5 VIP service life prediction

With the following equation the increase in the thermal conductivity of the VIP as a function of time can be calculated:

$$\lambda(t) = \lambda_{\text{evac}} + \frac{\lambda_{\text{free,air}}}{1 + \frac{p_{1/2,\text{air}}}{p_{\text{air}}(t)}} + b \cdot X_w(t) \quad (3)$$

The following values apply to VIP with fumed silica kernels of density $\rho_{\text{VIP}} \approx 170 \text{ kg/m}^3$, $\lambda_{\text{evac}} = 4 \cdot 10^{-3} \text{ W/(m}\cdot\text{K)}$, $p_{1/2,\text{air}} \approx p_{1/2,\text{N}_2} = 600 \text{ mbar}$, $\lambda_{\text{air}} = 25 \cdot 10^{-3} \text{ W/(m}\cdot\text{K)}$ at 10°C and $b = 0.5 \cdot 10^{-3} \text{ W/(m}\cdot\text{K)}/\%$ -mass at a mean temperature of 10°C . From the sorption isotherm $k = 0.08\%$ -mass per percent of relative humidity follows.

With the transmission characteristics of a certain laminate, $p_{\text{air}}(t)$ and $X_w(t)$ can be obtained and $\lambda(t)$ calculated, as shown for MF2 in the figure below.

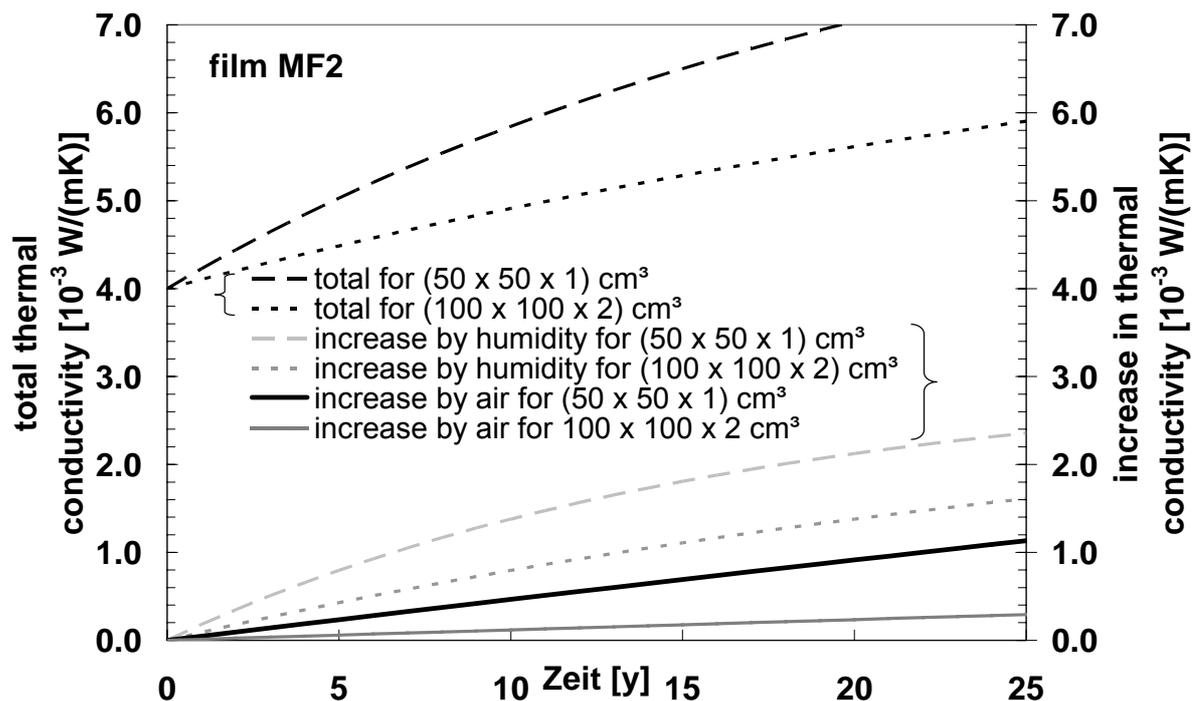


Figure 11: Total thermal conductivity as a function of time (upper part, left ordinate) and increases in air-related and humidity-related thermal conductivity (lower part, right ordinate) of VIP with film MF2 for different panel sizes.

3.3.4 Conclusions

If a time span of 25 years and typical environmental conditions (23 to 25°C and ambient vapour pressure) are taken as a basis for the long-term performance it can be concluded that the pressure increase will be rather linear over the whole period, whereas the moisture



content could approach the saturation range (about 4%-mass) within this time period. Moisture equilibrium under normal conditions is basically acceptable, but must be accounted for by a respective increment on the initial thermal conductivity.

Maximum values (approximate) for VIP with actual multi-layer metallized polymer laminate barriers, measured or calculated from laboratory based aging experiments, are given in the table below. Applying known relations for the pressure and moisture impact on the thermal conductivity, maximum values for the thermal conductivity after 25 years are given in the table as well. These values are thought to be on the safe side in applications with VIP surface temperatures and vapour pressures in the range of ambient or indoor air.

Table 3: Aging characteristics for SiO₂-VIP with polymer based multiple metallized barrier (safe values).

		50 x 50 x 2 cm ³	100 x 100 x 2 cm ³
Pressure increase	[mbar/yr]	< 2.0	< 1.0
Moisture accumulation (initial)	[%-mass/yr]	< 0.2	< 0.2
Thermal conductivity λ_{cop} (25 yr)	[W/(m·K)]	< 0.008	< 0.007

3.3.5 Design values

From the results of the aging studies, design values of the thermal conductivity for the center-of-panel (λ_{cop}) can be derived.

Table 4: Swiss design values (safe values) of Center-of-panel thermal conductivities (λ_{cop}) for aluminium and polymer based multiple metallized barrier envelopes.

Swiss center-of-panel conductivity values		λ_{cop}
AF: aluminium foil films	[W/(m·K)]	0.006
MF: metallized polymer films	[W/(m·K)]	0.008

In Switzerland a safety increment of 0.004 W/(m·K) is put on the “ideal” initial thermal conductivity value of 0.004 W/(m·K) for VIP with metallized polymer barrier. One part is due to the non-negligible moisture accumulation, which may be around 4%-mass in the long term, corresponding to a thermal conductivity increment of about 0.002 W/(m·K). In addition, a dry air pressure increase of 50 mbar is accounted for, roughly corresponding to another 0.002 W/(m·K) increment. Half increments are taken for VIP with metal foil based barrier. These figures are thought to be on the safe side with respect to both pressure increase and moisture accumulation over a time span of 25 years. It should be noted that this is a preliminary approach. If clearly better barrier quality is proven and proper initial conditions (low pressure, low moisture content) are guaranteed by the manufacturer, lower (individual) design values may be considered by the Swiss thermal insulation standardisation committee.



4 Building Applications

The core part of the Subtask B report consists of practice reports, showing actual examples where vacuum insulation panels (VIP) have been used, and discussing special issues and open questions. A wide range of built examples, all using VIP, such as floor and ceiling constructions, terrace insulation, non-loadbearing sandwich elements, parapet insulation, prefabricated façade elements etc. form a rich basis of experience for interested planners and experts as well as manufacturers in search of new products with integrated VIP. Furthermore, the report states the actual knowledge on reliability, thermal bridge effect of the panel envelopes, i.e. the resulting thermal resistance of VIP, and recommended constructions with VIP.

4.1 Thermal bridging

Three different basic levels of thermal bridging can be distinguished:

- thermal bridging due to the thin film high barrier enveloping the core material
- thermal bridging due to the small air gap between two adjacent panels
- thermal bridging due to constructional irregularities

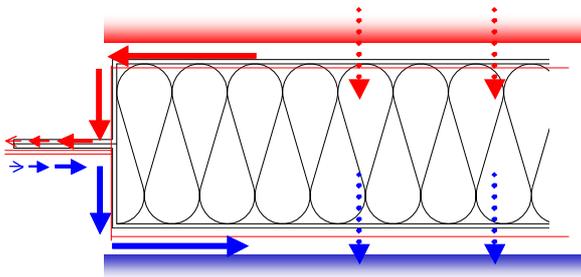


Figure 12: Schematic representation of a cold bridge caused by the VIP envelope.

Due to thermal bridging the effective or overall thermal conductivity, λ_{eff} , of the vacuum insulation panel is higher than the ideal centre-of-panel thermal conductivity λ_{cop} . The amount of this thermal bridge effect is also affected by the thermal properties material layers immediately surrounding the VIP. The effective thermal conductivity of a VIP takes all non-homogeneities, originating from the product itself as well as from the joint between adjacent VIP into account. With other words, the effective thermal conductivity of a VIP represents the conductivity of a homogeneous material with equivalent thermal behaviour. By means of measurements carried out in a guarded hot plate apparatus on VIP samples of three different thicknesses and two different sizes, the effective thermal conductivity, i.e. the linear thermal transmittance Ψ_{VIP} of the VIP themselves has been determined.



This effective thermal conductivity can be calculated as

$$\lambda_{\text{eff}} = \lambda_{\text{cop}} + \Psi_{\text{VIP}} \cdot d \cdot p / A \quad (4)$$

λ_{cop}	centre-of-panel thermal conductivity	[W/(m·K)]
d	thickness of the VIP (in the heat flux direction)	[m]
A	surface of the VIP (perpendicular to the heat flux direction)	[m ²]
p	perimeter of the surface A	[m]
Ψ_{VIP}	linear thermal transmittance	[W/(m·K)]

4.1.1.1 Envelope materials

Effective thermal conductivities for different envelope materials have been measured and modeled. Assuming a panel size of 1.00 x 0.50 x 0.02 m³ results:

- 8 μm aluminium foil: $\lambda_{\text{cop}} 6 \cdot 10^{-3}$ W/(m·K), $\Psi 0.033$ W/(m·K)
→ $\lambda_{\text{eff}} 10.0 \cdot 10^{-3}$ W/(m·K)
- 50 μm stainless steel foil: $\lambda_{\text{cop}} 6 \cdot 10^{-3}$ W/(m·K), $\Psi 0.026$ W/(m·K)
→ $\lambda_{\text{eff}} 9.1 \cdot 10^{-3}$ W/(m·K)
- three layer metallized film: $\lambda_{\text{cop}} 8 \cdot 10^{-3}$ W/(m·K), $\Psi 0.006$ W/(m·K)
→ $\lambda_{\text{eff}} 8.7 \cdot 10^{-3}$ W/(m·K)

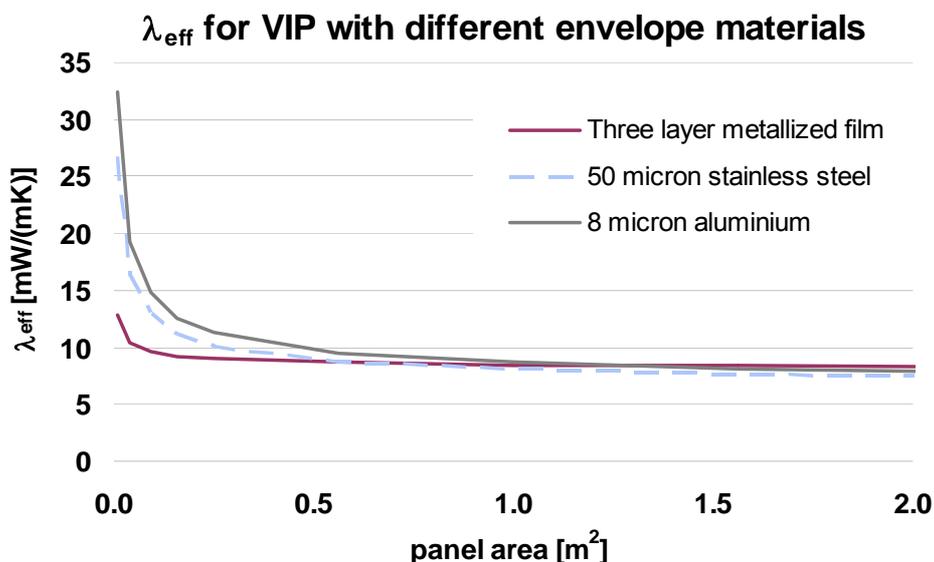


Figure 13: Thermal bridge effect of different envelope materials on overall conductivity (λ_{eff}) of a rectangular panel with center-of-panel conductivity (λ_{cop}) of $8 \cdot 10^{-3}$ W/(m·K) for the metallized film and $6 \cdot 10^{-3}$ W/(m·K) for the aluminium foil and the stainless steel envelope.



4.1.1.2 Adjacent materials

As well as the properties of the core material and the envelope, the Ψ_{VIP} value is influenced by the material layers immediately surrounding the VIP. At the EMPA the influence of various surrounding materials has been investigated. The calculations were performed for a VIP (20 mm) with metallized enveloping laminate for the adjacent materials metal, glass, wood and insulation, in each case without an air gap between the VIP and with a 5 mm air gap between the panels. Here the design value of λ_{cop} for metallized films of $8 \cdot 10^{-3}$ W/(m·K) was used.

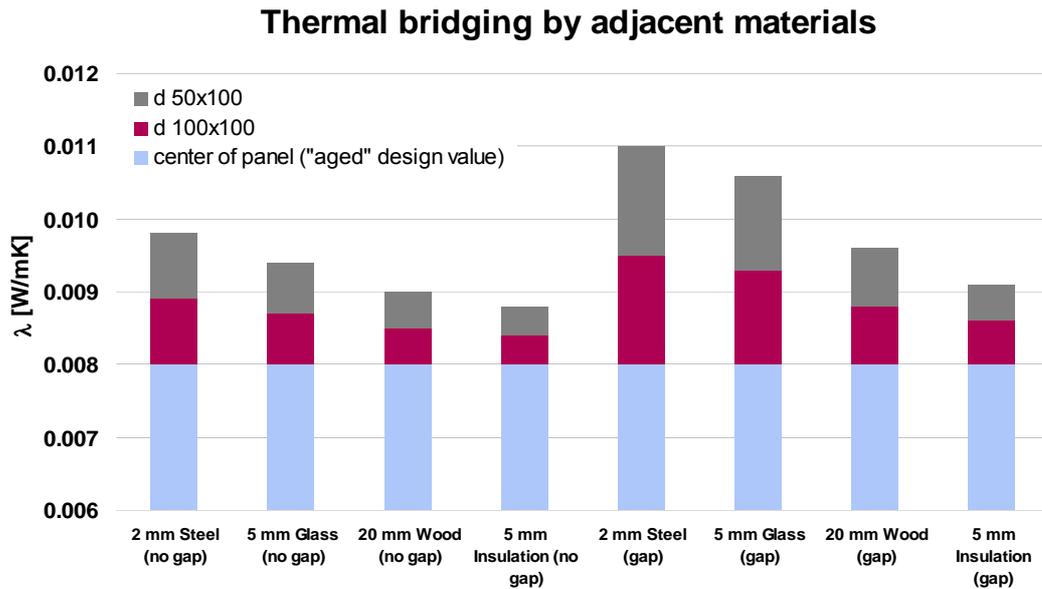


Figure 14: Thermal bridge edge effect of different adjacent materials on overall conductivity (λ_{eff}) of a panel with MF-envelope and a center-of-panel conductivity of $8 \cdot 10^{-3}$ W/(m·K). “d 100x100” is the increase for a panel of 100×100 cm² compared to λ_{cop} and “d 50x100” is the increase for a panel of 50×100 cm² compared to the larger format.

4.1.1.3 Façade panel constructions

With edge spacer constructions both component facings are mechanically jointed by means of a load transmitting edge spacer, while with the sandwich construction the component facings are adhered to a core material to form a structurally active sandwich.

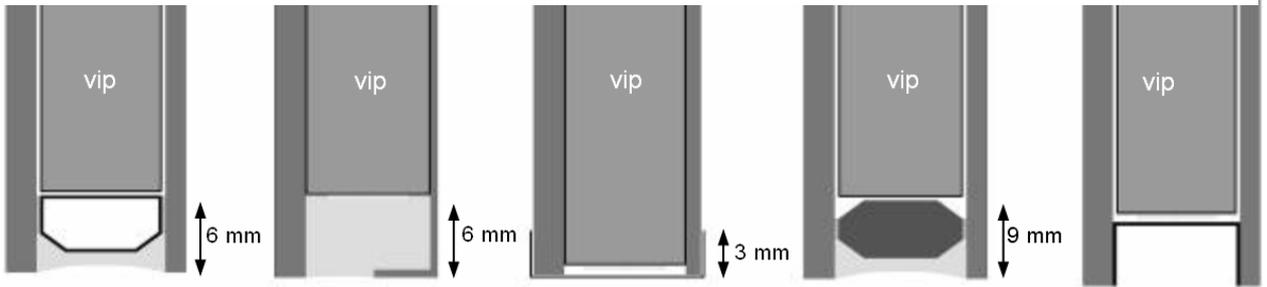


Figure 15: Different edge spacers. a.) aluminium spacer double-glazing; b.) sealant spacer; c.) reinforced non-metallic tape (0.15 mm); d.) optimised thermoplastic spacer (Henkel Tereson Thermoplastic Spacer); e.) polymer U-section.

For the calculations the following edge spacer materials were used:

Fumed silica based VIP ($\lambda_{cop} = 0.008 \text{ W/(m}\cdot\text{K)}$)

- Edge spacer a: standard double-glazing aluminium edge spacer ($\lambda = 225 \text{ W/(m}\cdot\text{K)}$) polysulfide sealant ($\lambda = 0.40 \text{ W/(m}\cdot\text{K)}$) and silicon sealant ($\lambda = 0.35 \text{ W/(m}\cdot\text{K)}$)
- Edge spacer b: butyl sealant ($\lambda = 0.24 \text{ W/(m}\cdot\text{K)}$)
- Edge spacer c: non-metallic tape ($\lambda \approx 0.33 \text{ W/(m}\cdot\text{K)}$); thickness $\approx 0.15 \text{ mm}$
- Edge spacer d: thermoplastic spacer ($\lambda = 0.25 \text{ W/(m}\cdot\text{K)}$) polysulfide ($\lambda = 0.40 \text{ W/(m}\cdot\text{K)}$)

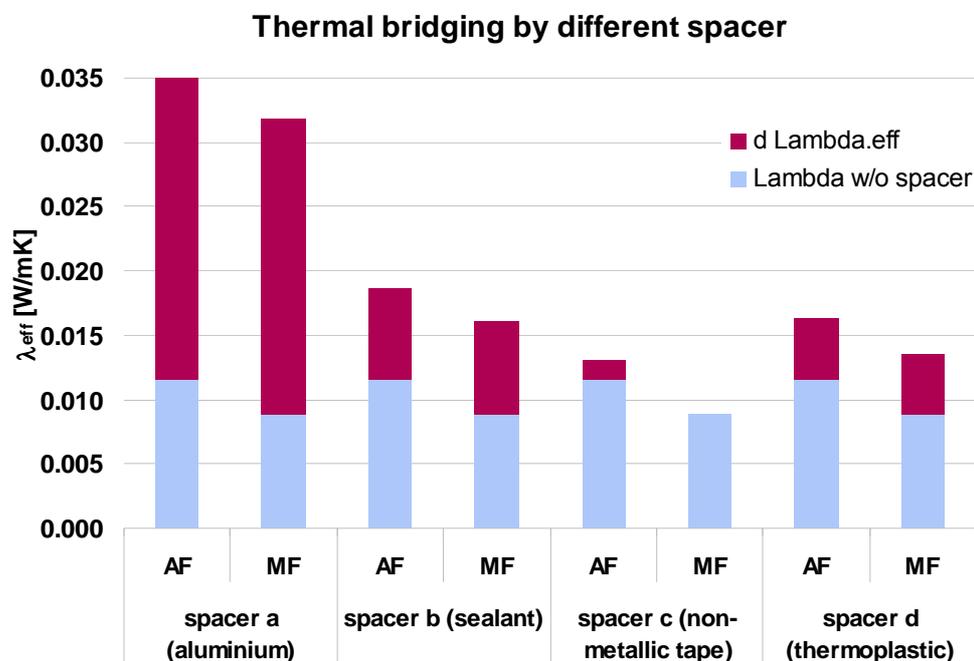


Figure 16: Thermal bridge edge effect of different spacers in façade panel constructions. The usedVIP have metallized- (MF) or aluminium foil (AF) envelopes. The center-of-panel conductivity is $8 \cdot 10^{-3} \text{ W/(m}\cdot\text{K)}$. The outside facing is 6 mm glass and the inside facing is 1.5 mm aluminium. "d Lambda.eff" is the increase for a panel of $100 \times 100 \times 2 \text{ cm}^3$ compared to λ_{cop} .



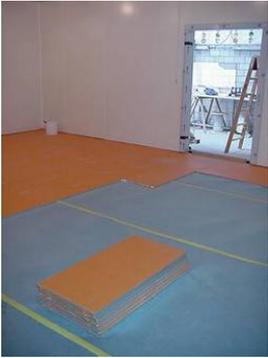
As can be seen as well, aluminium spacers (spacer a) are not suitable for façade panels with incorporated vacuum insulated panels, because a linear thermal transmittance, Ψ , of approximately 0.30 (MF) to 0.34 (AF) leads to an increase in effective U -value for a panel of $1 \times 1 \text{ m}^2$ with 20 mm vacuum insulation panel from approximately 0.31 (MF) and 0.39 (AF) to 1.23 and 1.33 $\text{W}/(\text{m}^2\cdot\text{K})$. Better performances can be expected from the spacers b and d, while the best performance is calculated for the reinforced non-metallic tape (for $\lambda_{\text{cop}} = 0.008 \text{ W}/(\text{m}\cdot\text{K})$ the U -value $U_{\text{eff}} = 0.65 \text{ W}/(\text{m}^2\cdot\text{K})$ for a 20 mm vacuum insulation panel construction with an aluminium foil and $U_{\text{eff}} = 0.44 \text{ W}/(\text{m}^2\cdot\text{K})$ for a 20 mm vacuum insulation panel construction with a metallized polymer film. This reinforced tape, however, might not adequately transmit forces, especially if wind suction is the main load to be transmitted. For sandwich panels, however, this edge spacer does not have to transmit loads and can thus be used for safety and protection against damage.

4.2 VIP in practical use

VIP are today mainly installed directly in the construction on site. By far the commonest use is the insulation of flat roof terraces with VIP. In the following table the 20 examples, which have been analysed and documented in [IEA 2005b] of VIP applications are shortly characterized.

	Project	City / Country	Building		Application				Place	
			New.	Renov.	Façade	Ceiling	Roof	Other	exterior	interior
	Floor and ceiling insulation Attachment to a single-family house	Zug SWI	x			x				x
	Interior and dormer window insulation Refurbishment of property	Zürich SWI		x	x		x	x	x	x
	Terrace insulation Multifamily houses	Kerzers SWI	x			x	x		x	



	Project	City / Country	Building		Application				Place	
			New.	Renov.	Façade	Ceiling	Roof	Other	exterior	interior
	Floor insulation in a cold and deep-freeze room Conversion of a shop	Winterthur SWI		X		X				X
	Non-load bearing wall sandwich elements Single-family house	Land-schlacht SWI	X		X				X	
	Parapet insulation in window element Apartment conversion in a multifamily house	Basel SWI		X	X				X	
	Façade insulation with prefabricated panels Terraced houses	Binningen SWI	X		X				X	
	Façade insulation Renovation of a semi-detached house	Nuernberg GER		X	X				X	



	Project	City / Country	Building		Application				Place	
			New.	Renov.	Façade	Ceiling	Roof	Other	exterior	interior
	Insulation of outside walls, roof and door A new semi-detached wooden house	Munich GER	x		x		x	x	x	
	Insulation of the building envelope Complete renewal of a terraced house	Munich GER		x	x	x	x		x	
	Insulation of a wall heating system Renovation of a former church	Wernfeld GER		x	x			x		x
	Jamb-crossbar construction Extension of the Hospital	Erlenbach GER	x		x				x	
	Integrated façade element with radiator Test façade ZAE Bayern	Wuerzburg GER	x		x			x	x	
	Insulated prefabricated concrete elements Office building with an apartment	Ravensburg GER	x		x				x	



	Project	City / Country	Building		Application				Place	
			New.	Renov.	Façade	Ceiling	Roof	Other	exterior	interior
	Façade insulation Passive house	Ber- senbruec k GER	X		X				X	
	Façade insulation with polystyrene- lined VIP Terraced house	Trier GER	X		X				X	
	Façade insulation Refurbishment of an apartment and office block	Munich GER		X	X				X	
	Floor insulation Allgäu Energy and Environment Centre	Kempton GER		X		X			X	X
	Floor insulation Renovation of the historic court house	Schaff- hausen GER		X		X				X
	Floor insulation Renovation with insulation under underfloor heating	Ge- muenden GER		X		X				X



4.3 Use of VIP – Recommendations

Although the processing of VIP under controlled conditions by specially trained personnel in a factory would be highly desirable, only a few prefabricated products and systems are available for the building sector. However, ongoing activities point out that more and more component and system manufacturers are becoming involved in the development of such products. It can therefore be expected that in the near future, a wide range of products such as floor heating systems, outside doors and façade elements with VIP will be available.

VIP is more than a new material – it must rather be regarded as a system, one of considerable complexity and sensitivity. It is therefore important that all concerned are informed, advised as early as possible and are supported by a specialist during the entire planning and installation process (preferably by the VIP supplier). In whatever way VIP are used in the construction branch, those responsible should make sure that during the planning and building process, no one handles VIP without having sufficient knowledge of its properties. Postal parcels with sensitive contents are marked with a „Handle with care“ label because they pass through many hands. VIP should, as a rule, fulfil their function in buildings over decades. Wherever they are not installed absolutely safe from damage, tenants, owners and renovation workers should also be warned with a label of the sensitive contents of building components. We thus recommend VIP manufacturers and suppliers to develop a warning label.

VIP must be handled with care and suitable protective measures and tools should be used (protective mats, felt shoes, etc.). The most important recommendations for handling VIP both in the factory on fabrication of components and systems, and also for direct installation on site are:

In order to minimize the edge effects of the VIP

Select panels that are as square and large as possible (min. 0.5 x 0.5 m²)

If the envelope of the panel is made of aluminium foil (only rarely nowadays), lay the panels in a double layer, overlapping by at least 5 cm (which, however, is expensive).



Figure 17: Draft sketch for an adhesive warning label to mark VIP panels and building components containing VIP.

VIP must be well protected from mechanical damage. This applies equally to functional loading (e.g. from the floor), inadvertent loading (e.g. dilatation) and subsequent manipulations (e.g. nailing).

VIP are vapour-tight insulation systems, which has to be taken into account in planning the order and thickness of the layers. Furthermore, special attention must be given to the joints between the panels. The joints and edges are usually sealed with a special adhesive aluminium tape, which assures tightness but is relatively brittle.



Tolerances are of major concern, when designing and detailing building components. Special attention, must be given to the differences in production dimensions of vacuum insulation panels. The production tolerances of VIP are currently of the order of 3 to 6 mm in length and width. The resulting air gap, although small, does conduce to a higher thermal conductivity value for the construction as a whole. It is therefore important that production tolerances for vacuum insulation panels go down to 2 to 3 mm.

The possibility of individual panels or entire areas failing should - at least to date - be included as a risk in the planning and execution. A strategy would be desirable that would aim at being able to replace the VIP in case of failure. This implies two things that in our experience to date are not usually paid attention to:

The VIP should be embedded in the construction such that they can be replaced without undue effort in preparation or as a result (e.g. mechanically fixed covers).

Installation of the VIP in such a way that inspection of their correct functioning can be made, particularly with infrared thermograph. As a rule this is impossible if on both sides, either well conducting, massive covers (e.g. concrete) or back-ventilated constructions are employed (provided that the latter cannot be removed relatively simply for checking the VIP).

As a rule, one has limited oneself up to now to mitigating the effects of failure, so that a deterioration in the U-value can be accepted and it is assured that on loss of vacuum, there is no risk of loss of comfort or of condensation.



5 Outlook

During this research program vacuum insulation has developed rapidly. At the beginning VIP was hardly known in the building branch and only a few pilot applications were realized. Only little was known concerning key questions as durability, gas tightness of envelope materials, behaviour under humid and hot conditions. Today it can be stated that VIP properties are well known and some important weaknesses have already been eliminated. We now have well documented experiences from the building site which have been implemented by the building industry for their VIP developments. The VIP production has been professionalized and the VIP have been better adapted to the needs of building applications.

Today we see a very broad interest in the VIP technology from the building branch and a large number of buildings in which VIP have been applied. But the quantitative wide use of vacuum insulation is still hindered by mainly two factors:

- high price
- lacking confidence in VIP technology and their use in building applications

Today cost

The work under the annex has shown that for the design of vacuum insulated constructions one may not use the thermal conductivity of VIP just after production of $\sim 0.004 \text{ W}/(\text{m}\cdot\text{K})$ but 0.006 to $0.008 \text{ W}/(\text{m}\cdot\text{K})$. Hereby the already high material cost rise to a level which hinders strongly the mass use. Even when gains by space savings and constructional simplifications are considered, the resulting costs are hardly acceptable for standard insulation applications. Unfortunately today just little advantage is taken of the regained liberty to develop low U-value building parts with new slim designs. VIP is mainly used in special applications where further advantages are obtained. In renovations by the use of VIP, additional expenses can be avoided, as for instance the lengthening of the roof when insulating the façade. Often VIP is used as a problem solver, e.g. for terrace insulation, VIP is here the only possibility to prevent a step between the heated room and the terrace.

That today the rather crucial direct use of unprotected panels has become the common practice on building sites, has its reason probably also in the high VIP prices. Only very innovative producers of prefabricated insulated building parts (sandwich panels, doors, façade systems etc.) do invest in the new technology. Many others hesitate because they assess VIP as too expensive to be used in their products.

Cost reduction potentials

To achieve a distinct higher market share it is absolutely necessary that VIP prices come down. To estimate how and to what extent price reductions are possible, it would be interesting to know the main cost factors for VIP production. Unfortunately we only have limited information on that topic. For example, it is known that the materials (core and envelope materials) represent quite a high portion of the total cost. With the envelope materials, it can be assumed that it is mainly the production quantity which defines the price. However, fumed silica is already a mass product. Physically it seems to be possible to reduce the portion of fumed silica in the board or to replace it with a cheaper material (e.g. organic foam). In particular the latter requires tighter films to maintain a lower pressure in the panel. Such high barrier films are not only needed for VIP with other core materials but also for (building) applications in more humid / hotter environments. This kind of extreme high barrier film is



also developed for other applications (e.g. OLED) which have similar demands. It is therefore quite probable that they will be available soon.

Furthermore the production of VIP is still dominated by expensive manual work. But the portion of the automated production steps has increased in the last years. This development must lead to a price reduction in the near future.

For the next five to ten years, it can be assumed that VIP solutions will remain more expensive than conventional constructions with the same U-value. This is also caused by the fact that conventional insulations are being improved.

Quality assurance

Annex 39 has also contributed to increased confidence in VIP. For instance it was shown that the environment in the main building applications allow a VIP service life of 50 years and more.

Actions are needed in the field of quality assurance. It has to be made sure that the VIP applied in a building do not get damaged during handling and installation processes. Through systematic measurements of the internal pressure of the panels, defective specimens can be tracked down and crucial processes identified. The today available measurement technology is only partially suitable for quality control of the whole process chain. Ongoing developments lead to the conclusion that in the near future a cheaper and more easily applicable measurement device will be available.

Official certification

Another obstacle are missing product approvals for VIP and VIP based systems for buildings.



References

- 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. Download: www.vip-bau.ch).
- IEA 2005b IEA/ECBCS Annex 39 (2005), *Vacuum Insulation in the Building Sector - Systems and Applications*, Subtask B report. Download: www.vip-bau.ch).