International Energy Agency
Energy Conservation in Buildings and Community Systems Programme

Project Summary Report

Vacuum Insulation Panel Properties & Building Applications

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ECBCS Annex 39

Vacuum Insulation Panel Properties and Building Applications

ECBCS Annex 39 Project Summary Report

Edited by Markus Erb and Will Symons

Based on the reports:
'VIP - Study on VIP-components and Panels for Service Life Prediction of VIP in Building Applications, Subtask A report' and
'Vacuum Insulation in the Building Sector – Systems and Applications, Subtask B report.'

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Preface

International Energy Agency

The International Energy Agency (IEA) was established in 1974 within the framework of the Organisation for Economic Co-operation and Development (OECD) to implement an international energy programme. A basic aim of the IEA is to foster co-operation among the twenty-eight IEA participating countries and to increase energy security through energy conservation, development of alternative energy sources and energy research, development and demonstration (RD&D).

Energy Conservation in Buildings and Community Systems

The IEA co-ordinates research and development in a number of areas related to energy. The mission of one of those areas, the ECBCS - Energy Conservation for Building and Community Systems Programme, is to develop and facilitate the integration of technologies and processes for energy efficiency and conservation into healthy, low emission, and sustainable buildings and communities, through innovation and research.

The research and development strategies of the ECBCS Programme are derived from research drivers, national programmes within IEA countries, and the IEA Future Building Forum Think Tank Workshop, held in March 2007. The R&D strategies represent a collective input of the Executive Committee members to exploit technological opportunities to save energy in the buildings sector, and to remove technical obstacles to market penetration of new energy conservation technologies. The R&D strategies apply to residential, commercial, office buildings and community systems, and will impact the building industry in three focus areas of R&D activities:

- Dissemination
- Decision-making
- Building products and systems

The Executive Committee

Overall control of the program is maintained by an Executive Committee, which not only monitors existing projects but also identifies new areas where collaborative effort may be beneficial. To date the following projects have been initiated by the executive committee on Energy Conservation in Buildings and Community Systems (completed projects are identified by (*)):

Annex 1: Load Energy Determination of Buildings (*)
Annex 2: Ekistics and Advanced Community Energy Systems (*)
Annex 3: Energy Conservation in Residential Buildings (*)
Annex 4: Glasgow Commercial Building Monitoring (*)
Annex 5: Air Infiltration and Ventilation Centre
Annex 6: Energy Systems and Design of Communities (*)
Annex 7: Local Government Energy Planning (*)
Annex 8: Inhabitants Behaviour with Regard to Ventilation (*)
Annex 9: Minimum Ventilation Rates (*)
Annex 10: Building HVAC System Simulation (*)
Annex 11: Energy Auditing (*)
Annex 12: Windows and Fenestration (*)
Annex 13: Energy Management in Hospitals (*)
Annex 14: Condensation and Energy (*)
Annex 15: Energy Efficiency in Schools (*)
Annex 16: BEMS 1- User Interfaces and System Integration (*)
Annex 17: BEMS 2- Evaluation and Emulation Techniques (*)
Annex 18: Demand Controlled Ventilation Systems (*)

Annex 19: Low Slope Roof Systems (*)
Annex 20: Air Flow Patterns within Buildings (*)
Annex 21: Thermal Modelling (*)
Annex 22: Energy Efficient Communities (*)
Annex 23: Multi Zone Air Flow Modelling (COMIS) (*)
Annex 24: Heat, Air and Moisture Transfer in Envelopes (*)
Annex 25: Real time HEVAC Simulation (*)
Annex 26: Energy Efficient Ventilation of Large Enclosures (*)
Annex 27: Evaluation and Demonstration of Domestic Ventilation Systems (*)
Annex 28: Low Energy Cooling Systems (*)
Annex 29: Daylight in Buildings (*)
Annex 30: Bringing Simulation to Application (*)
Annex 31: Energy-Related Environmental Impact of Buildings (*)
Annex 32: Integral Building Envelope Performance Assessment (*)
Annex 33: Advanced Local Energy Planning (*)
Annex 34: Computer-Aided Evaluation of HVAC System Performance (*)
Annex 35: Design of Energy Efficient Hybrid Ventilation (HYBVENT) (*)
Annex 36: Retrofitting of Educational Buildings (*)
Annex 37: Low Exergy Systems for Heating and Cooling of Buildings (LowEx) (*)
Annex 38: Solar Sustainable Housing (*)
Annex 39: High Performance Insulation Systems (*)
Annex 40: Building Commissioning to Improve Energy Performance (*)
Annex 41: Whole Building Heat, Air and Moisture Response (MOIST-ENG) (*)
Annex 42: The Simulation of Building-Integrated Fuel Cell and Other Cogeneration Systems (FC+COGEN-SIM) (*)
Annex 43: Testing and Validation of Building Energy Simulation Tools (*)
Annex 44: Integrating Environmentally Responsive Elements in Buildings
Annex 45: Energy Efficient Electric Lighting for Buildings
Annex 46: Holistic Assessment Tool-kit on Energy Efficient Retrofit Measures for Government Buildings (EnERGo)
Annex 47: Cost-Effective Commissioning for Existing and Low Energy Buildings
Annex 48: Heat Pumping and Reversible Air Conditioning
Annex 49: Low Exergy Systems for High Performance Buildings and Communities
Annex 50: Prefabricated Systems for Low Energy Renovation of Residential Buildings
Annex 51: Energy Efficient Communities
Annex 52: Towards Net Zero Energy Solar Buildings
Annex 53: Total Energy Use in Buildings: Analysis & Evaluation Methods
Annex 54: Analysis of Micro-Generation & Related Energy Technologies in Buildings
Annex 55: Reliability of Energy Efficient Building Retrofitting - Probability Assessment of Performance & Cost (RAP-RETRO)

Working Group - Energy Efficiency in Educational Buildings (*)
Working Group - Indicators of Energy Efficiency in Cold Climate Buildings (*)
Working Group - Annex 36 Extension: The Energy Concept Adviser (*)
Working Group - Energy Efficient Communities

(*) – Completed

Executive Summary

Vacuum insulation panels (VIP) were 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 metallised 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 a service life of 30 years 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.

Contents

1. Introduction

1.1. Insulation Standards

Most conventional thermal insulation materials were developed before 1950, with its extensive use starting only after the oil crisis in 1973. Thermal insulation of buildings is the key method used to prevent heat losses and to improve the energy efficiency of buildings. For a long time, 10 cm of standard insulation (such as Styrofoam, foamed PU, fibreglass, etc.), was considered best practice. However, energy specialists have calculated that the economically optimised thickness is around 30 cm and goes up to 50 cm, depending upon climatic conditions. Currently, most existing building regulations and standards demand U-values for roofs and walls of around 0.2 W/(m·K), which requires insulation layers of about 12 cm to 20 cm. Many architects find such regulations problematic as they want to create functional, aesthetically appealing spaces, not insulated bunkers. The use of thick layers of insulation is especially problematic in the case of renovated buildings, where there are often severe limitations on space and also many other technical constraints.

These constraints provided a driver for the development of alternative, efficient methods of insulating buildings whilst reducing the space requirements of such insulation. Evacuated insulation, in the form of Vacuum Insulation Panels (VIP) have this potential.

1.2. Energy in Buildings

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. In 1997, approximately 25% of the energy used in the EU was consumed through space heating in these dwellings, in addition to commercial premises (see Table 1 for a full breakdown of energy consumption in buildings).

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

By virtue of its higher U value, VIP have the potential to reduce the energy consumed in buildings through space heating. A significant adoption of VIP in buildings would result in a substantial reduction in energy use in the EU.

The ratio of new house builds vs. existing housing stocks varies between 1% and 2% in the EU. Therefore the possible reduction in energy use (and therefore CO_2 emissions) by using VIP technology depends largely on how well the new technology is adopted in retrofitting old building stock, which to a large extent (around 50%) is not insulated at all. This success depends not only on the technical solutions but also on regulations and energy prices. However, it can be assumed that the energy consumption of the dominating old buildings could be reduced by a factor of three. As outlined above, VIP are considered especially promising for application in retrofitting projects, due to their thin profile.

A roll-out of VIP on this scale would reduce EU CO_2 emissions by about 8%, which is equal to the reduction that the EU agreed to as part of its Kyoto Protocol commitment. Additionally, VIP based systems are less resource intensive than conventional solutions as they are thinner and recycling is economically attractive. A wide take-up of VIP in Europe would also lead indirectly to a reduction in the negative impacts of transporting fuel to and within Europe and a reduction in the rate of depletion of global energy reservoirs. Taking into account that use of the VIP technology will not be limited to Europe only, actual energy use reductions could be more substantial.

2. Vacuum Insulation Panels

Vacuum insulation panels (VIP) 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.

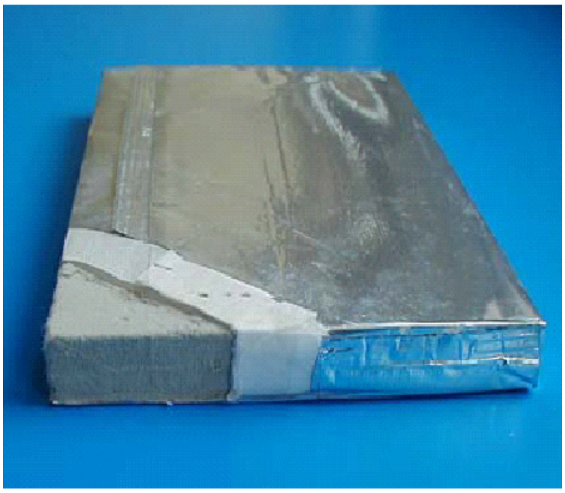

Figure 1: Components of a VIP. The core-bag provides mechanical stability for handling and protects the welding area from being polluted by core-powder. (photo: va-Q-tec).

2.1. Core

Nano-structured materials require the least quality of vacuum to be achieved and maintained. In panels 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. The following elements outline the key requirements of material selection for VIPs:

- To reduce the gas conductivity in normal insulation materials the pressure has to be very low, which is difficult to maintain by an envelope mainly made of organic materials. This explains why for VIP a combination of a nano-structured core material and pressure reduction is used.
- To enable evacuation, the core material has to be 100% open-celled, so that air can be quickly removed out of the material.
- The internal pressure of a VIP is only few mbar. Consequently the pressure load on the panel is close to 1 bar or 10 tons/m^2. The core material therefore has to be stable enough so that the pores do not collapse when evacuated.
- Radiation has also to be reduced to reach very low conductivity values. This is done by adding opacifiers to the core material.

A variety of different organic and inorganic insulation materials fulfil these requirements. Fumed silica is considered the best material currently available as it exhibits low conductivity up to a pressure of more than 50 mbar and a conductivity at ambient pressure of half that of a conventional insulation material.

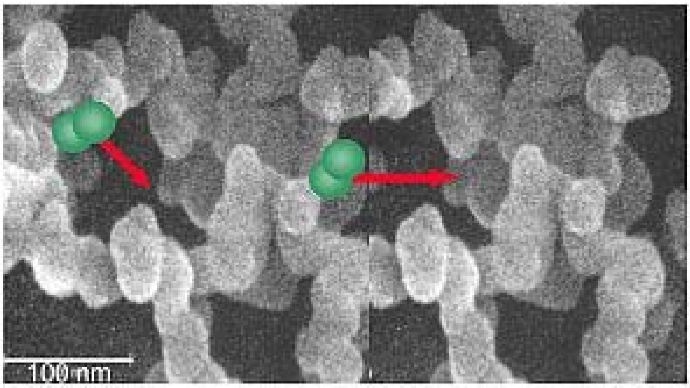

Figure 2: SEM image - Pore size distribution, showing fumed silica's fine porosity and the net like structure of the grains. (Source: Wacker / ZAE-Bayern)

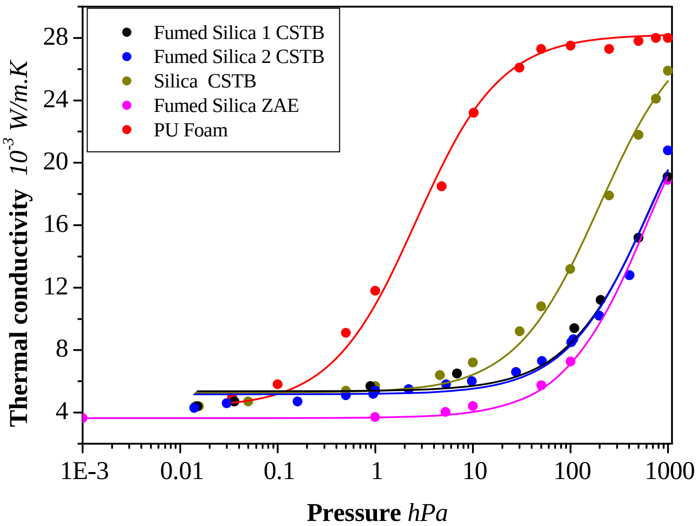

Figure 3: Thermal Conductivity versus pressure of a PU Foam sample, three fumed silica samples and one precipitated silica sample.

The density of fumed silica is in the range of 160 kg/m³ to 190 kg/m³, nearly an order of magnitude higher than traditional insulating materials. Fumed silica's porosity is higher than 90% and its specific surface area is higher than 200 m²/g. A high sorption capability results from this large specific surface area. Thus fumed silica may act as a desiccant.

For low humidity (relative humidity (RH) < 60%) the amount of adsorbed water is low and the sorption isotherm can be approximated by a linear relationship. For high humidity, from 60% up to 95%, there is an exponential increase in sorption mainly due to 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.

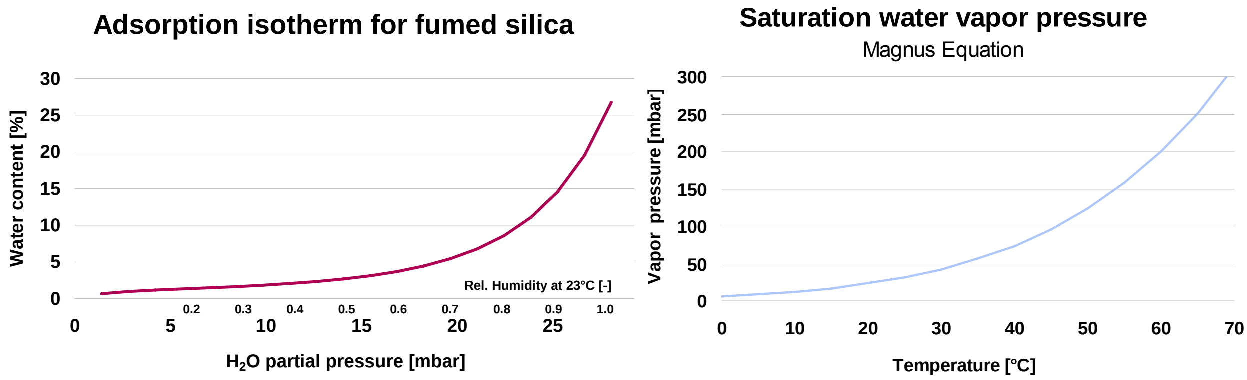

Figure 4: Left: Adsorption isotherm of fumed silica (fitted curve, based on data of three laboratories). Right: Partial water vapour pressure of saturated air.

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

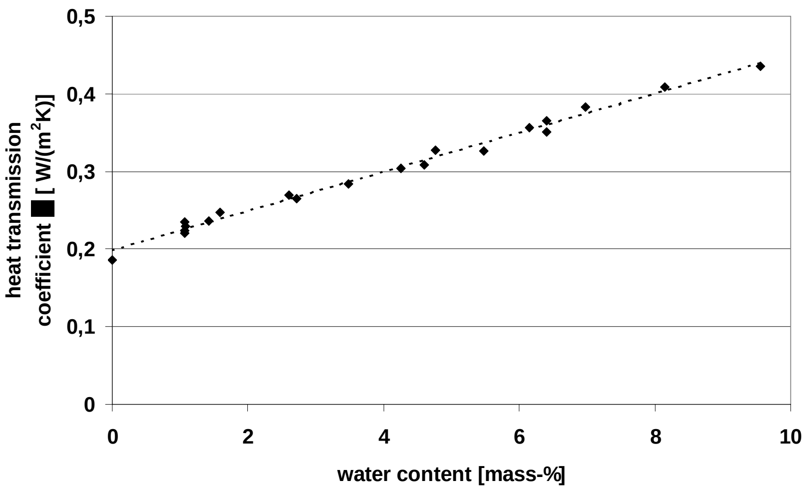

Figure 5: Measured heat transfer coefficient versus the water content for a 20 mm thick VIP. Mean temperature was 10°C.

A significant increase in VIP's heat transfer with increasing internal water content is observed. 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.

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

Starting with an approximate initial thermal conductivity of about 4 x10^{-3} W/(m K) for the dry core, with moisture equilibrium at 50% RH, thermal conductivity rises to between 5x10^{-3} W/(m K) and 6x10^{-3} W/(m K).

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

$$\frac{\partial \lambda}{\partial p} \approx 0.035 \, \frac{mW}{m\,K\,mbar} \quad \textit{in the range up to 100 mbar} \tag{2}$$

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 $1x10^{-3}$ W/(m·K).

The fire behaviour of core materials is dependent on the type of fibres used for structural binding in the fumed silica core. The use of non-organic fibres results in a calorific value of around -206 kJ/kg (due to an endothermic reaction and the absence of combustible materials in this type of fumed silica). The use of organic fibres give a calorific value of around 1200 kJ/kg. This compares with around 1000 kJ/kg for rock wool and 1500 kJ/kg for glass wool.

Building materials in Europe are generally separated into 5 acceptable classes (A1 or A2 (not inflammable), B, C, D, and E (acceptable reaction to fire)). Fumed silica core VIP are in class A, but the polymer barrier material is combustible. This is less of a problem for floor or (flat) roof application, but there are more serious restrictions for façade application. Classification questions and testing requirements are currently under discussion on a national level in several countries, including Germany and Switzerland.

2.2. Envelope

The most critical component of a VIP is the envelope, which is responsible for the maintenance of the vacuum inside the panel. The most common material used for VIP envelopes are polymer laminates, which contain metallised polymers or aluminium foils as barrier layer.

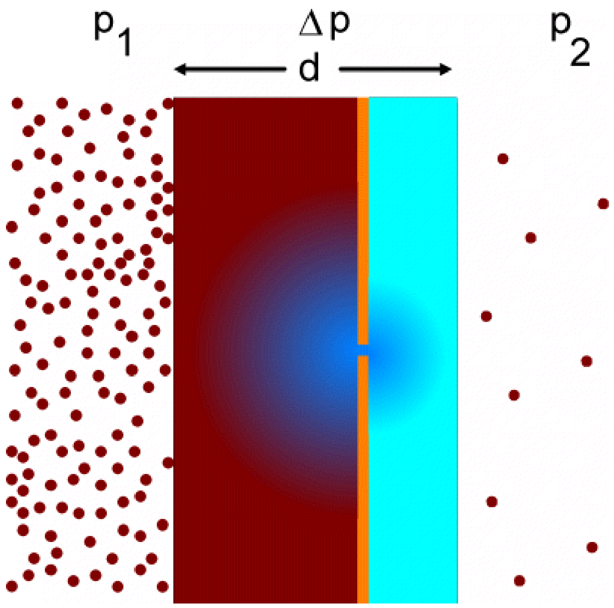

Figure 6: Permeation mechanism (schematic) through a three layer stack containing an inorganic barrier layer.

As with all polymeric films, the water vapour transmission rate (WVTR) for these laminates was found to be several orders of magnitude greater than the oxygen transmission rate (OTR) or the transmission rate of nitrogen: The unit used for WVTR is g/(m^2·d) and for OTR cm^3(STP)/(m^2·d). At present products do have WVTR and OTR in the same range but 1g H_2O equals 1244 cm^3.

Table 1: Laminate transmission rates according to manufacturer's specifications for the tested laminates. AF = Aluminium (Al) Foil; MF = Metallised Film; PET = PolyEthylenTerephtalate, PE = PolyEthylen, PP = PolyPropylen, LD = Low Density, met = Al-layer 30 to 80nm thick.

Name	**Laminate composition**	**OTR** *[cm³(STP)/(m²·d)]*	**WVTR** *[g/(m²·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)

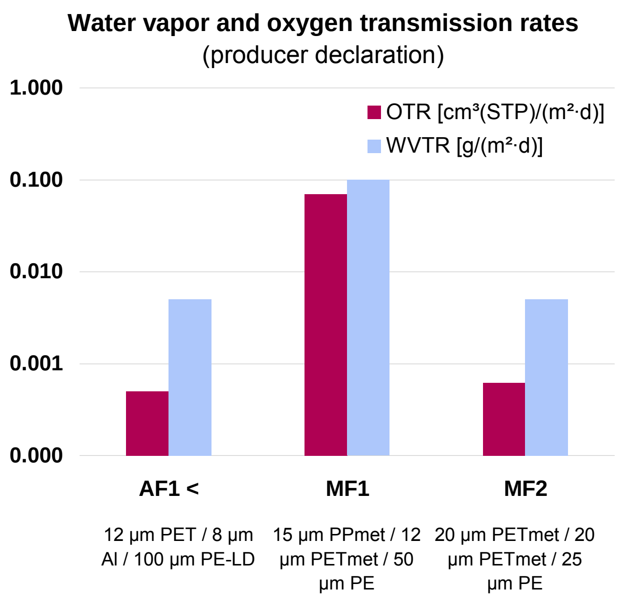

Figure 7: Transmission rates (manufacturers' measurements) of an aluminium foil based film (AF) and two polymer based metallised films (MF).

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.

2.3. VIP Service Life

The service life of VIP is dependent on two key factors; aging and durability.

Aging is a continuous process of performance degradation due to the 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. This process occurs because the low pressure internal environment of a VIP (0.004 W/(m·K) after production) is not in equilibrium with the environment, creating pressure gradients that act as driving forces for the intrusion of atmospheric gases (essentially N_2, O_2 and H_2O). Through this process, the thermal performance of VIP is impaired over time by:

- increasing internal gas pressure; and
- increasing internal water content.

In contrast, durability is the ability of a VIP to withstand chemical or mechanical impacts that could cause failure of the barrier envelope, thus changing the internal low-pressure state by severe damage or rupture of the barrier. 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 and by storing the panels during a specified time under defined conditions and checking them before they are shipped. The number of damaged or defective panels leaving production plants was substantially reduced during this annex, to below one percent. Envelope failure risks are most prominent before or during installation; without protection the envelope is highly sensitive to mechanical impact, especially to point loads (sand grains, bricks or stone fragments, or other sharp objects including tools and corners of other panels). Once installed, failure risks are observed to be low.

2.3.1. Measurement Methods

Building on results from the testing of different envelope materials, measurements were made of air and water vapour permeation of assembled panels. Measurements on panels stored in different climatic conditions gave detailed information on these permeation rates as a function of temperature and humidity, including all the effects of edges, corners and processing.

A depressurisation based method was applied to measure the internal pressure of panels. According to this method, the pressure around a VIP specimen is continuously reduced in a vacuum chamber and when the pressure in the chamber diminishes to below the VIP pressure, the VIP envelope lifts off the core surface, providing an accurate measure of the panel's internal pressure. This can be recorded visually or by using photo electric sensors.

2.3.2. Results

Overview

The laminate with one metallised layer did not to fulfil acceptable permeation rate requirements. Acceptable pressure increases of about 1 mbar per year can be expected for VIP with an Al foil and for laminates with three metallised layers.

Table 2: Area (subscript A) and perimeter (subscript L) related transmission characteristics of VIP with metallised polymer laminates (MF) for 23°C, 50% RH and 1 bar. For the MF1 and MF2 samples, a WVTRL 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

Air-Transmission - Edge-Effects

It was found that there was a significant contribution of air permeation through the edge-area of the VIP (see Figure 8). Due to this effect, it is recommended that panel sizes are as large as practicable for the application, and certainly larger than 0.5 m x 0.5 m. Additionally, it is recommended that panels are as square as possible, reducing the surface area to edge area ratio.

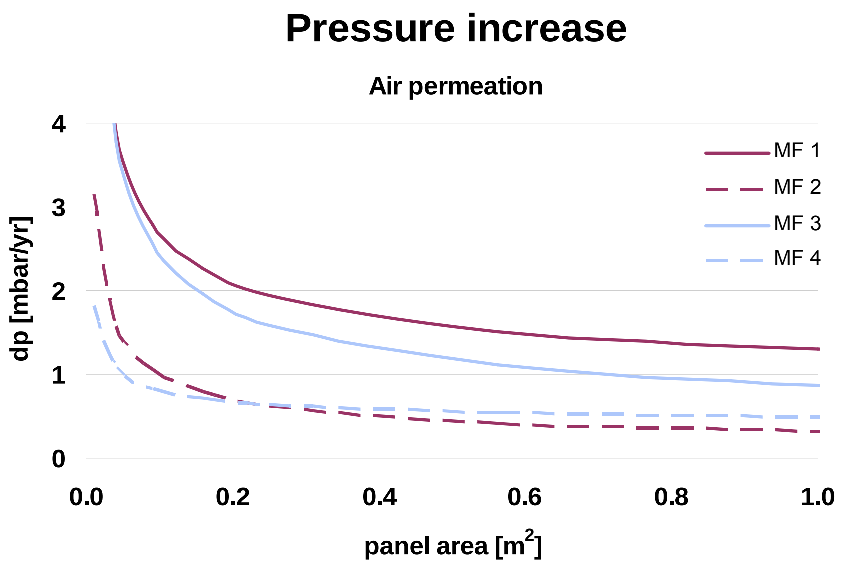

Figure 8: Edge effect on internal pressure increase by air permeation through four different metallised films (rectangular panel).

Water Vapour Transmission

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

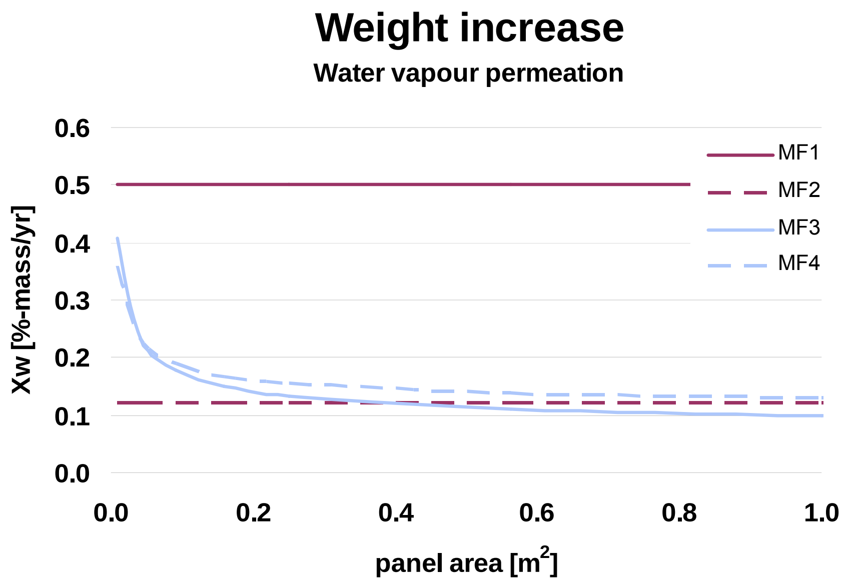

Figure 9: Edge effect on weight increase by water vapour permeation through four different metallised films. For the MF1 and MF2 samples, an edge effect could not be determined since the panels were too small (rectangular panel).

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 kJ/mol to 40 kJ/mol.

Water vapour transmission rates are proportional to the differences in the partial pressures inside and outside, and the permeation rates of gases increase exponentially with temperature. It should be noted that the rate of permeation of Al envelopes increases with pH values above 8.5, which should be considered particularly if concrete or other alkaline substances are in the immediate vicinity of installed panels.

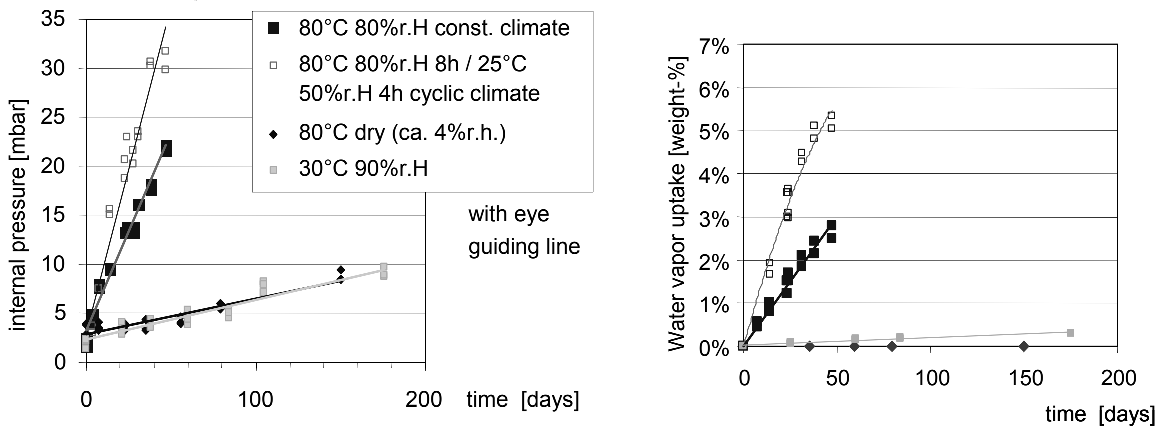

Figure 10: Increase of internal pressure (left) and moisture content (right) for a 'small' VIP size (i.e. 25 cm x 25 cm x 2 cm) at elevated temperature/humidity. The measurements were done at room temperature after cooling down the samples for some hours.

Service Life Prediction

Service life is the time between production and failure. There is no standardised definition of failure, which can be understood as the VIP reaching a certain defined performance indicator.

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

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

The following values apply to VIP with fumed silica kernels of density ρVIP ≈ 170 kg/m³, λ_{evac} = 4.10^{-3} W/(m·K), $p_{1/2}$,air ≈ $p_{1/2,N2}$= 600 mbar, λ_{air} = 25·10^{-3} W/(m·K) at 10°C and b = 0.5·10^{-3} W/(m·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_{air}(t) and X_W(t) can be obtained and λ(t) calculated, as shown for MF2 in the figure below.

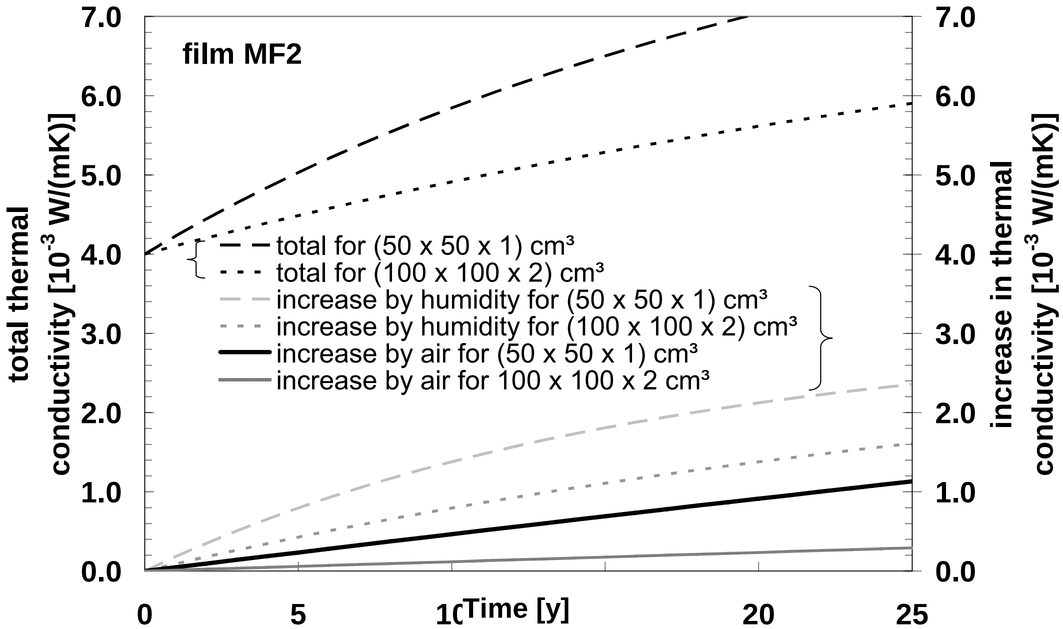

Figure 11: Total thermal conductivity as a function of time (upper part, left ordinate) and increases in air related and humidity related thermal conductivity (lower part, right ordinate) of VIP with film MF2 for different panel sizes.

2.3.3. Conclusions

Temperature and humidity dependent aging was investigated in detail for a wide range of environmental conditions and different products. It was found that the aging speed depends on a number of parameters such as barrier material, panel dimensions and temperature, humidity and pH conditions. A weak-point of polymer based high quality barriers is their water vapour permeability that takes place throughout the whole envelope surface. Dry gas permeation is much slower and mainly related to the panel perimeter.

If a time span of 25 years and typical environmental conditions (23°C 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 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 approximate values for yearly permeation rates of air and moisture for VIP with multi-layer metallised polymer laminate barriers 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 also provided. 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 (23°C to 25°C).

Barrier materials should be carefully protected against moisture and temperatures above the approved maximum service temperatures (60°C to 80°C). Occasional condensation can be accepted if drying is ensured. If these measures are taken into consideration, the service life of VIPs should not be limited by envelope material degradation. Polymer barriers become more brittle below the glass-rubber transition temperature. However, as aluminium becomes more ductile with decreasing temperature, the combined effect of low temperature on VIP barrier materials is not likely to decrease service life (as the lower limit of service temperature is outside the range of application in buildings). Additionally, water vapour and gas permeation rates through the high barrier envelope decreases exponentially with decreasing temperature, further decreasing the effect of low temperature of VIP service life.

Table 3: Aging characteristics for SiO_2 core VIP with polymer based three times metallised 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

2.3.4. Design Values

From the results of the aging studies, design values of the thermal conductivity for the centre-of-panel (λcop) can be derived.

Table 4: Swiss design values (safe values) of Centre-of-panel thermal conductivities (λcop) for aluminium and polymer based three times metallised barrier envelopes.

Swiss centre-of-panel conductivity values		λ_{cop}
AF: aluminium foil films	[W/(m·K)]	0.006
MF: metallised 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 a metallised polymer barrier. Part of this safety increment is due to 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). The remainder of the safety increment (0.002 W/(m·K)) results from an anticipated dry air pressure increase of 50 mbar. Half of this safety increment is applied to VIP with metal foil based barrier. These increments 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 a better envelope technology is developed and proper initial conditions (low pressure, low moisture content) are guaranteed by the manufacturer, lower design values may be considered by the Swiss thermal insulation standardisation committee.

2.3.5. Quality Assurance

Quality assurance and proper declaration of proven product performance data is very important to all parties involved in VIP. Requirements for factory production control, test methods and declaration of properties are standardised for conventional thermal insulation products, but are not currently for VIP. Following an EN standard for PU foam insulation, suggestions have been made on factory production control of VIP and barrier material as well as on product declaration. The discussion of suitable thermal design values is still at the beginning. Possible or preliminary rules are currently under evaluation in Germany and Switzerland.

3. Building Applications

The core part of the Subtask B report consists of practice reports, showing actual examples where VIP have been used, and discussing special issues and open questions. A wide range of built examples are provided, all using VIP, such as floor and ceiling constructions, terrace insulation, non-load bearing sandwich elements, parapet insulation and prefabricated façade elements. These examples 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 effects of the panel envelopes, life cycle impacts of VIP and recommended constructions with VIP.

3.1. Thermal Bridging

Thermal bridges are areas or spots in building constructions that have high local heat flows through the construction relative to the surrounding construction, or have a local low inside surface temperature, again relative to the surrounding construction. Thermal bridges result in increased heat loss through the building envelope or increased the risk of condensation at the inner surface of the building envelope. Due to the structure of VIPs, it is impossible to entirely exclude thermal bridging. However, it is important to minimise this effect.

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; and
- thermal bridging due to constructional irregularities.

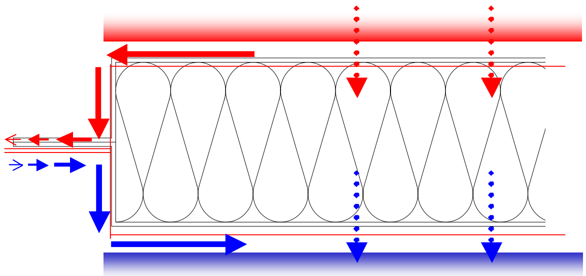

Figure 12: Schematic representation of a cold bridge caused by the VIP envelope.

Due to thermal bridging the effective or overall thermal conductivity, λ_{eff}, of VIP 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 of 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. 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 VIP has been determined.

This effective thermal conductivity can be calculated as:

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

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)]

The linear thermal transmittance, Ψ_{VIP}, in the above equation depends on panel thickness, d, centre-of-panel thermal conductivity, λ_{cop}, barrier film thickness t_f, and film thermal conductivity, λ_f. This results in different linear thermal transmittance values for different laminates and the thermal properties material layers immediately surrounding the VIP.

3.1.1. Envelope materials

Effective thermal conductivities for different envelope materials have been measured and modelled. Assuming a panel size of 1.00 x 0.50 x 0.02 m^3 results:

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

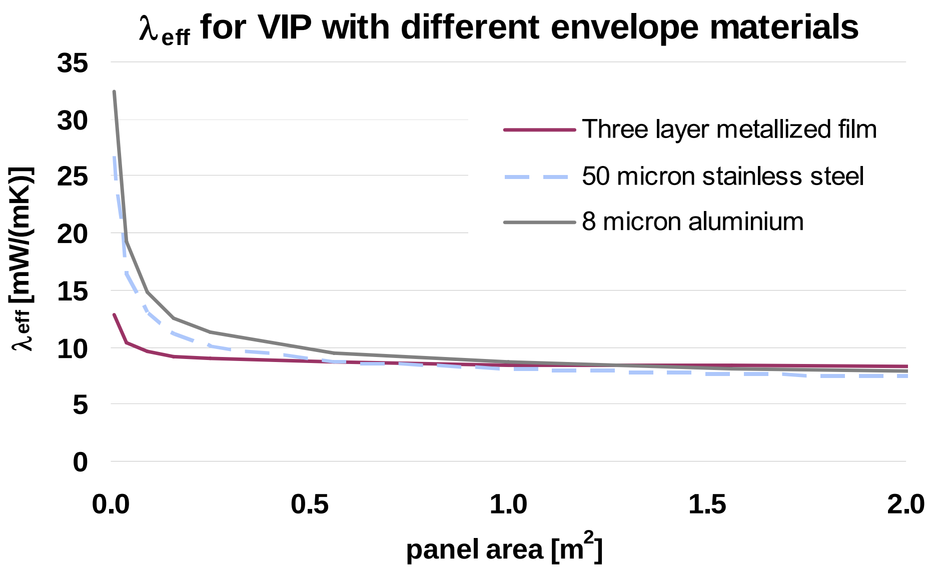

Figure 13: Thermal bridge effect of different envelope materials on overall conductivity (λ_{eff}) of a rectangular panel with center-of-panel conductivity (λ_{cop}) of 8 10^{-3} W/(m·K) for the metallised film and $6 \cdot 10^{-3}$ W/(m·K) for the aluminium foil and the stainless steel envelope.

3.1.2. 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. Investigations into the influence of various surrounding materials, including metal, glass, wood and insulation, were conducted for a VIP (20 mm) with metallised enveloping laminate, in each case with no air gap between the VIP and with a 5 mm air gap between the panels. Here the design value of λ_{cop} for metallised films of 8×10^{-3} W/(m·K) was used.

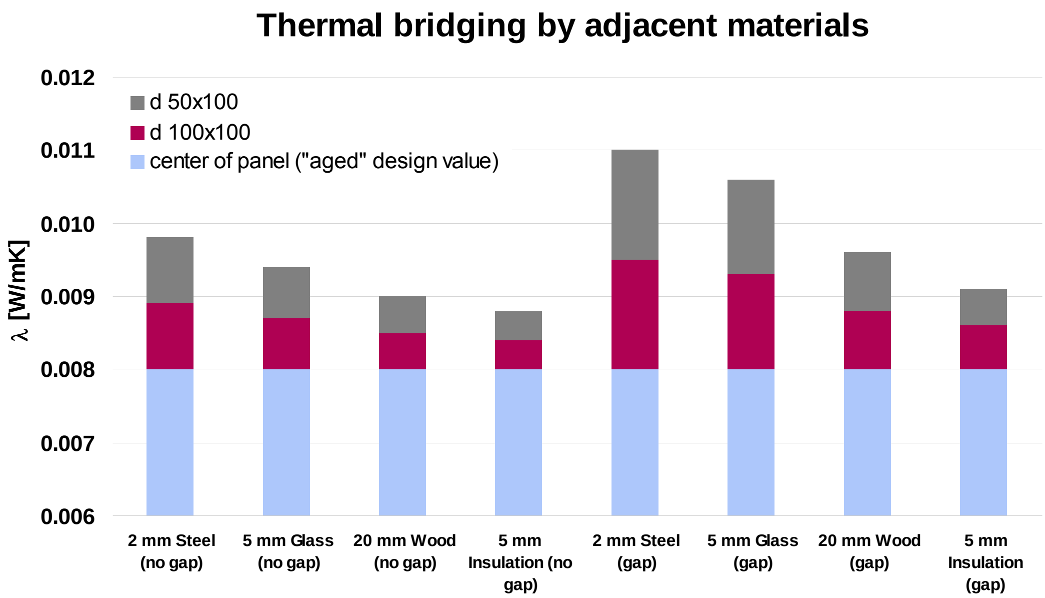

Figure 14: Thermal bridge edge effect of different adjacent materials on overall conductivity (λ_{eff}) of a panel with an MF-envelope and a centre-of-panel conductivity of 8x10^{-3} W/(m•K). "d 100x100" is the increase for a panel of 100x100 cm^2 compared to λ_{cop} and "d 50x100" is the increase for a panel of 50x100 cm^2 compared to the lager format.

Material layers adjacent to VIP with a high thermal conductivity lead to a deterioration of the λ_{VIP} values. As far as possible, therefore, insulating materials, wood or other substances should be used as they have a low thermal conductivity.

3.1.3. Façade Panel Constructions

Within the design process of façade panels, the influence of the edge spacer construction on the thermal properties of the façade panel should be considered. Two façade panel constructions have potential for VIP integrated façade components: sandwich construction and edge spacer construction. The difference between these two types of construction lies in the load transmitting system of the components.

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. This sandwich construction, unlike the edge spacer construction, does not require a section at the panel sides, though it might be wise for protection of the VIP against damage. As a consequence, thermal bridge effects due to the spacer are especially significant for edge spacer constructions.

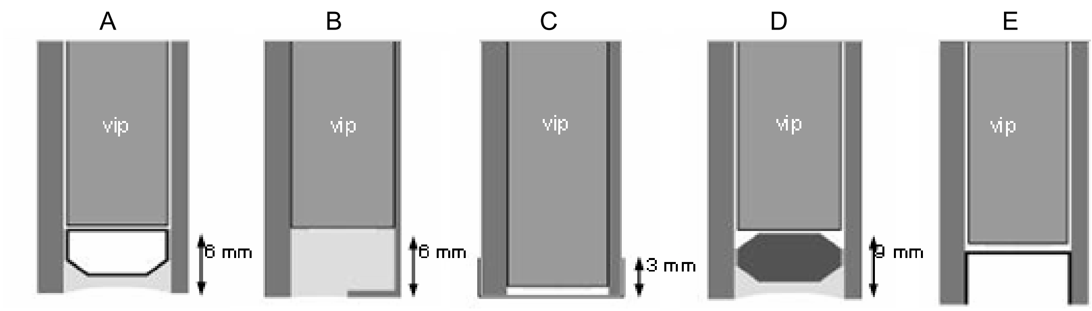

Figure 15: Different edge spacers, from left to right; spacer A: aluminium spacer double-glazing ; spacer B: butyl sealant spacer; spacer C: reinforced non-metallic tape (0.15 mm); spacer D: optimised thermoplastic spacer (Henkel Tereson Thermoplastic Spacer); spacer E: polymer U-section.

For the calculations the following edge spacer materials were used, assuming a 1 m^2 x 1 m^2 20 mm thick fumed silica based VIP (λ_{cop} = 0.008 W/(m·K)). Calculations were not conducted for spacer e.

- Spacer a: standard double-glazing aluminium edge spacer (λ = 225 W/(m·K)) polysulfide sealant (λ = 0.40 W/(m·K)) and silicon sealant (λ = 0.35 W/(m·K))
- Spacer b: butyl sealant (λ = 0.24 W/(m·K))
- Spacer c: reinforced non-metallic tape (λ ≈ 0.33 W/(m·K)); thickness ≈ 0.15 mm
- Spacer d: optimised thermoplastic spacer (λ = 0.25 W/(m·K)) polysulfide (λ = 0.40 W/(m·K))

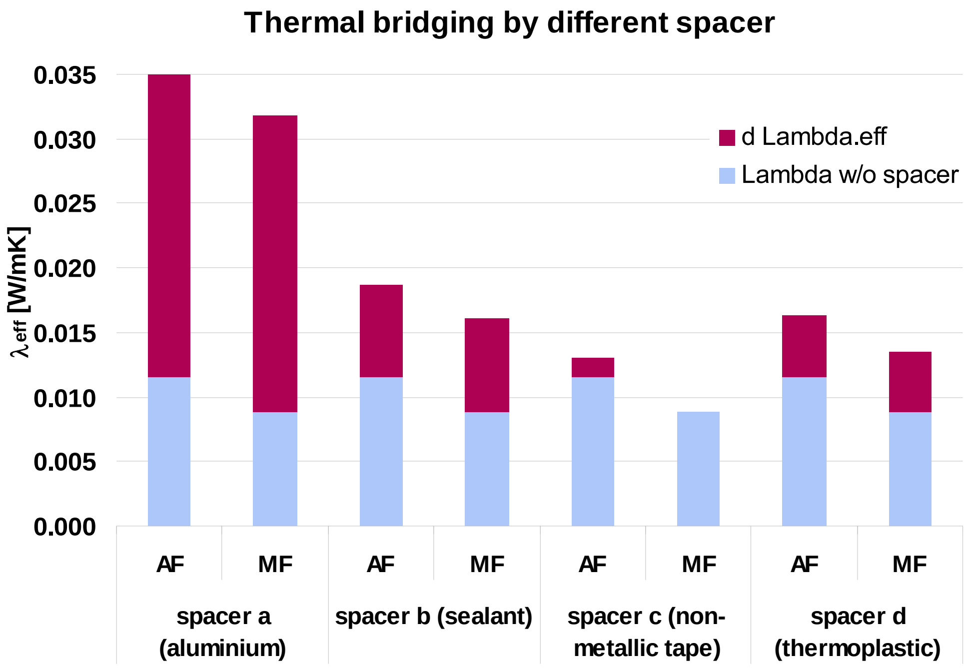

Figure 16: Thermal bridge edge effect of different spacers in façade panel constructions. VIPs with two difference envelopes were used; metallised (MF) and aluminium foil (AF). The centre-of-panel conductivity for both is 8 10^{-3} W/(mK). The outside facing is 6 mm glass and the inside facing is 1.5 mm aluminium. "d Lambda.eff" is the increase for a panel of 100 x 100 x 2 cm^3 compared to λ_{cop}.

As can be seen, 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 the effective U-value from approximately 0.31 (MF) and 0.39 (AF) to 1.23 and 1.33 W/(m^2·K). Spacers b and d performed better, while spacer c performed the best (for λ_{cop} = 0.008 W/(mK) the U-value U_{eff} = 0.65 W/(m^2·K) for AF envelopes and U_{eff} = 0.44 W/(m^2·K) for MF envelopes. However, reinforced non-metallic tape might not adequately transmit forces, especially if wind suction is the main load to be transmitted. For sandwich panels edge spacers do not have to transmit loads and so non-metallic tape can thus be used for safety and protection against damage.

3.1.4. Mechanical Properties

Three-point and four-point bending tests were conducted on 20 mm thick fumed silica core based VIP and on sandwich panels made of the same 20 mm VIP and 4 mm thick medium density fibreboard (mdf) or glass facings.

Table 5 summarises the measured flexural mechanical properties for single VIP (both intact and damaged). VIPs have a Young's modulus higher than the single fumed silica core material itself, because the core is restricted in its movement by a low gas pressure, and a high barrier envelope. However, the value for the Young's modulus is rather low compared to steel, aluminium, glass or the high barrier envelope, which have moduli of 210000 MPa, 70000 MPa, 70000 MPa and approximately 2000 MPa respectively. VIP are therefore preferably applied in situations in which no large flexural loads act upon the panels.

Table 5: Flexural properties of vacuum insulation panels

	Flexion Modulus VIP *MPa*	**Ultimate Flexural Strength VIP** *kPa*	**Deformation at Yielding VIP** *%*	**Deformation at Fracture VIP** *%*
VIP, intact	63.8 ± 8.6*	639.8 ± 109.9*	1.34 ± 0.38*	-
VIP, no vacuum	38.6 ± 10.7*	611.6 ± 45.3*	0.80 ± 0.16*	-

* uncertainty for a 95% confidence interval

Table 5 also shows that damaged VIP are less stiff than undamaged panels, whereas the ultimate flexural strength of both panels is more-or-less equal. For practical purposes in the case of a perpendicular to surface loaded panel, a loss of vacuum will increase the deflection of the panel by a factor of 2, but will not cause the panel to fail directly so additional safety precautions are not required.

For the application of VIP as part of façade elements, it is important to know the mechanical flexural behaviour of such sandwich panels. The results of tests of this construction type with a VIP core for different facings are presented in Table 6. As can be seen from comparing the data in Table 5 and Table 6, the values for the Young's modulus of the VIP obtained from in-panel measurements are more-or-less equal to the values obtained from single panel measurements, although the modulus of elasticity for undamaged panels obtained from in panel measurements (Table 6) are slightly higher. Although the VIP themselves seem to be rather flexible, the entire flexural stiffness of a sandwich panel is dominated by the Young's modulus and the area moment of inertia of the facings. A sandwich panel is therefore stiffer than a single VIP. This effect is responsible for the differences in deformation at fracture between sandwich panels with mdf and glass facings. So, despite their low value for the modulus of elasticity, VIP can be applied in sandwich panels, as long as the distance between both facings is enough to give structural stiffness.

Table 6: Flexural properties of sandwich panels with VIP as core material and different facings. The ultimate fracture strength is the normal stress at which the facing fails

	Flexion Modulus VIP *MPa*	**Shear Modulus** *MPa*	**Ultimate Flexural Strength Panel** *MPa*	**Deformation at Fracture Panel** *%*
Mdf facing VIP, intact	83.1	27.3	4.3 ± 0.6*	12.2 ± 4.5*
Mdf facing VIP, no vacuum	34.0	12.9	3.9 ± 0.5*	12.3 ± 0.6*
Glass facing VIP, intact	86.2	62.9	4.1 ± 1.6*	1.2 ± 0.3*
Glass facing VIP, no vacuum	36.9	31.3	4.1 ± 0.5*	1.5 ± 0.3*

The measured data are representative for panel dimensions of 0.35 m x 0.15 m. It is uncertain if the data can be used for structural calculations on panels of different dimensions, because the influence of the high barrier envelope and the vacuum on the mechanical behaviour at a microscopic level has not yet been fully investigated.

3.1.5. Life Cycle Impacts

Given the market potential of VIP, it is important to understand if the use of VIP is problematic from an energetic and ecological standpoint: whether in the final analysis, more energy is absorbed in the manufacture of VIP than is actually saved, and whether more ecological damage is caused during production than benefits accrue at the end.

Whole of life environmental effects of VIP were investigated using three different methods of life cycle analysis (LCA). For these analyses, VIP was compared with glass wool and polystyrene EPS. The energy and material flows required for the production of the VIP were calculated.

For a comparative LCA study of thermal insulation materials, a number of assumptions must be made, boundary conditions specified and use made of today's sometimes very short-lived facts, some of which have a considerable effect on the result. These assumptions are outlined in detail in ECBCS (2005b).

The effectiveness of conventional insulating materials is based on enclosing as much air in as little material as possible in cells that are as small as possible. Insulating materials are thus light materials, containing little material compared with brick, concrete, glass or wood. The LCAs of insulating materials hence show in general that upon use in building skins, the benefits by far outweigh the ecological disadvantages, even with very good insulation. Thermal insulation plays a minor role in the assessment of environment effects for an entire building. The main result of the present LCA study is that this essentially also applies for vacuum insulation. Whether VIP performs better or worse than glass wool or polystyrene does not change this basic fact. Moreover, the VIP upon which this study is based is a pre-commercial product, not yet optimized in respect of environmental effects, but which has a great potential for improvement. All known and presently used alternatives to fumed silica for the core material feature less production energy consumption (but do not exhibit the same favourable properties for VIP).

The LCA of VIP is primarily dominated by the high energy consumption of production. The material flow aspects thus become secondary. For instance, the aluminium coated foil or the type of foil selected play a completely subordinate role. In this sense it is unimportant from the standpoint of an LCA of the material whether VIP is installed in one or two layers.

The results of LCAs of all insulating materials studies are generally favourable, with little difference in overall environmental impacts found between the different insulating materials investigated. As such, although VIP was rated either 2nd or 3rd out of the 3 products investigated (depending upon the evaluation method) little actual difference was found. Utilisation of less energy intensive core materials (e.g. Silicon Carbide) and the replacement of the currently used precursor (Silicon Tetrachloride) would reduce VIP’s environmental impacts (as measured through the LCAs conducted) by around 45%.

3.2. VIP in Practical Use

VIP are today mainly installed directly in the construction on site. The following table presents and characterises the 20 examples which have been analysed and documented in ECBC (2005b).

	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	
	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	Landschlach t SWI	x		x				x	

	Project	City / Country	Building		Application				Place	
			New.	Renov.	Façade	Ceiling	Roof	Other	exterior	interior
	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	
	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

	Project	**City / Country**	**Building**		**Application**				**Place**	
			New.	**Renov.**	**Façade**	**Ceiling**	**Roof**	**Other**	**exterior**	**interior**
	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	
	Façade insulation Passive house	Bersenbrueck 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	Kempten GER		x		x			x	x

	Project	City / Country	Building		Application				Place	
			New.	Renov.	Façade	Ceiling	Roof	Other	exterior	interior
	Floor insulation Renovation of the historic court house	Schaffhausen GER		x		x				x
	Floor insulation Renovation with insulation under underfloor heating	Gemuenden GER		x		x				x

4. Recommendations

4.1. Information and Consulting

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. Good examples of this include VIP being integrated into stainless steel building panels and doors. 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 advised on its unique properties as early as possible and are supported by a specialist during the entire planning and installation process (preferably by the VIP supplier). No matter how VIP are used, during the planning and building process, no one should handle VIP without having sufficient knowledge of its properties. Wherever they are not absolutely safe from damage, tenants, owners and renovation workers should also be warned with a label indicating the sensitive contents of building components containing VIP. We thus recommend VIP manufacturers and suppliers to develop a warning label.

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

A series of general and use specific recommendations have been developed, for both the use of VIP directly on construction sites, and for the use of VIP in prefabricated components.

4.2. VIP on the Construction Site

Included in this section are a series of general recommendations, in addition to recommendations for the use of VIP in specific on site building applications.

4.2.1. General Recommendations

Provided below is a list of general recommendations for the ordering, handling and assembly of VIP on construction sites:

- VIP cannot be cut to size on site so exact parts lists and laying plans must be drawn up at an early stage, in consultation with the VIP supplier;
- Consideration should be given to using the maximum size VIP panel possible to reduce edge effects and increase overall insulation performance (minimum size of 0.5 m^2 x 0.5 m^2);

- Suitable conventional insulation material must be specified and made ready for taking up tolerances or adapting to edge joints. The use of such materials should be minimised as their overuse will result in lower overall U values. Given current production tolerances of 3 mm to 6 mm, such materials are essential;
- To reduce the use of such filling materials, production tolerances need to be further reduced, to between 1 mm and 3 mm.
- The delivery mode (package, weight, protection, accessibility) must be clarified to:
    - Ensure permanent protection of the VIP; and
    - Mitigate against handling risks due to the high bulk density of VIP.
- The installation area must be thoroughly cleaned and sharp-edge irregularities and projections removed from the work surface;
- Protective mats must be placed on both faces of the VIP. Mats on the upper facing surface will reduce the risk of damage due to the VIP being walked on or having objects dropped on its surface. Felt shoes should be provided to installers;
- Ideally, installation should occur in dry conditions as even small amounts of moisture, when trapped in the building structure next to VIP, can be detrimental to its insulation properties and service life;
- Wherever possible, consideration should be given to designing VIP applications to enable their easy inspection and/or replacement, should they be damaged or otherwise fail.

4.2.2. Outer Walls with Interior Insulation

The retrofitting of VIP into existing buildings is considered an especially promising application, given its advantages in space constrained situations. The following recommendations should be considered for this application:

- If insulation is to be installed internally, consideration should be given to protecting VIP from damage due to user interventions (ie. screws, nails, electrical installations etc);
- The possibility of condensation from room humidity must be considered, including:
    - Surface condensation on joints between walls and ceilings (this risk tends to be increased by VIP);
    - Condensation from rear ventilation;
    - Condensation from vapour diffusion; and
    - Air leak condensation.

4.2.3. Terrace Insulation

The use of VIP for terrace insulation is its most frequent current application in Switzerland, as it allows a lower installed height difference between inside and outside areas when compared with conventional insulation, offering accessibility and aesthetic advantages.

It is possible to achieve high vapour tightness of terrace constructions. As such, special consideration should be given in this application to reducing the presence of moisture during the installation of VIP as it will be effectively sealed into the structure once sealed. As discussed in this document, the presence of moisture adjacent to VIP, especially in the presence of alkaline substances such as concrete can reduce VIP insulation properties and service life.

4.3. VIP in Prefabricated Components

Included in this section are a series of general recommendations, in addition to recommendations for the use of VIP in specific prefabricated building applications.

4.3.1. General Recommendations

Provided below is a list of general recommendations for the design and assembly of VIP in prefabricated components:

- The service life of the VIP is likely to be less than the service life of other elements of the assembly, if designed properly. As such, the anticipated service life of the VIP element should be specified, in addition to the assumptions used in service life calculations;

- Consideration should be given to the thermal requirements of the panel, to minimise both thermal losses and avoid surface condensation due to high inside surface temperature. In both cases, centre of panel thermal transmittance and linear specific thermal transmittance of the panel edge should be considered;
- The structural abilities of VIP should be considered if used in sandwich components. 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);
- Local requirements regarding fire prevention, fire spread, smoke reduction and acoustical, hygiene, health and environmental requirements should be carefully considered during design;
- Interrelationships between the above mentioned considerations should be considered, especially between thermal performance and the structural system design, and thermal performance and service life requirements;
- In addition to general edge spacer requirement, applicable to all façade panels, the following specific VIP related issues should be considered:
    - Protection of the VIP against damage;
    - Reducing thermal bridging at VIP edges by using materials with low thermal conductivity and reducing the width of the edge zone;
    - Air tightness of the edge;
    - The mechanical connection of the outer to the inner facing in a case of damage to the VIP; and
    - Accommodation of the seam, if one is present near the VIP edges.
- Consideration should be given to designing prefabricated components to enable the easy inspection and/or replacement of VIP, should they be damaged or otherwise fail.

4.3.2. Prefabricated Wood Construction

Façade elements prefabricated in wood are a highly promising application area for VIP. Vapour tight execution of the joints between wood beam ceilings and the outer wall and at the butt joint between individual wood construction elements should be given special consideration to avoid condensation. Additionally, when using VIP in façade elements, temperature peaks should be smoothed out by installing a barrier layer with high thermal inertia, to avoid temperatures above 50°C to 60°C (depending upon the envelope type used), as these temperatures can effect envelope durability.

4.3.3. Dormer Windows

VIP can allow thin constructions of dormer windows and as such are increasingly popular in prefabricated dormer windows. The following recommendations should be considered for this application:

- When installed sun shading and guide rails, the adjacent VIP must not be damaged by fixing screws;
- Consideration should be given to ensuring that the temperature at the VIP surface does not increase beyond design tolerances on summer days. The use of a soft wood fibre board is recommended to significantly lower surface temperatures at this point;
- Vapour barriers should be installed in front of the condensation plane present at dilation gaps to reduce condensation risk by blocking warm moist indoor air from reaching the VIP panel at this point.

4.3.4. Door Panels

VIP are increasing being used in door constructions as they offer significantly lower thermal conductivity than conventional materials (mostly polyurethane). However, overall U values are reduced (by between 20% and 30%) in this application by the presence of stabilising steel elements which cause a large cold bridge. New designs are needed which fulfil stiffness requirements whilst improving the structure's overall U value. Until such a time as this occurs, the thermal performance benefits gained by using VIP are effectively cancelled out by the cold bridge.

4.3.5. Low Temperature Floor and Wall Heating Systems

An interesting application of VIP would be using them as the basis for thin low temperature wall or floor heating systems, as long as the requirement for a dry system is fulfilled to enable VIP replacement on failure. Besides improved thermal performance, the use of VIP in this application is attractive as a reduced floor height is possible.

The following recommendations should be considered for this application:

- The structural layer should be as flat as possible and a protective layer (ideally 3mm thick Ethafoam) installed, to reduce the risk of panel damage;
- Seams between individual VIP should be sealed with aluminium tape to prevent convective heat losses and water vapour diffusion;
- A watertight layer should be placed between the VIP and the heating system to reduce the risk of VIP service life being reduced by heating system water leaks;
- As VIP cannot be cut to size on site, exact laying plans must be drawn up at an early stage, in consultation with the VIP supplier and conventional insulation materials should be used at VIP edges and to take up floor edge discontinuities;
- To prevent high point loads that could damage the VIP, the top layer should be able to diffuse loads;
- The temperature of the water flowing through the heating system should be as low as possible, to improve the thermal aging behaviour of the VIP. The maximum allowable temperature will depend upon the VIP type chosen and its required service life. In general, a maximum water temperature of 40°C is recommended;
- Little information is currently available regarding the acoustic performance of VIP. However, it is anticipated that the use of VIP might reduce the overall acoustic performance of floors and walls. As such, if acoustical requirements are in place, field measurements after construction are recommended.

5. Outlook

During this research programme vacuum insulation has developed rapidly. At the beginning VIP was hardly known in the building industry and only a few pilot applications were realized. Only little was known concerning key questions such as durability, gas tightness of envelope materials and behaviour under humid and hot conditions. VIP properties are now well known and some important weaknesses have been eliminated. We now have well documented experience from construction sites which have been implemented by the building industry for their new VIP developments. VIP production has been professionalised and they have been better adapted to the needs of building applications.

Today we see a very broad interest in the VIP technology from the building industry and a large number of buildings in which VIP have been applied. A broader expansion in the use of VIP is still hindered by mainly two factors:

- high price; and
- low confidence in VIP technology and their use in building applications.

5.1. Present 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 ~0.004 W/(m·K), but 0.006 to 0.008 W/(m·K). Hereby the already high material cost rises to a level which hinders strongly its mass use. Even when gains by space savings and constructional simplifications are considered, the resulting costs are hardly acceptable for standard insulation applications. As such, little use is being made of these low U value building parts with new slim designs. VIP is mainly used in special applications where further advantages are obtained. In renovations the use of VIP can reduce other additional expenses, such as the lengthening of the roof when insulating the façade. Often VIP is used as a problem solver: for terrace insulation VIP is the only solution to prevent a step between the heated room and the terrace.

High VIP prices are probably the reason why the large volume direct use of unprotected panels on construction sites has not occurred. Only very innovative producers of prefabricated insulated building parts (sandwich panels, doors, façade systems etc.) have invested in the new technology. Many others hesitate because they assess VIP as being too expensive to be used in their products.

5.2. Cost Reduction Potentials

To achieve a distinctly 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. For envelope materials, it can be assumed that it is mainly 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 also required for construction applications in more humid and 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 production steps which are automated has increased in recent years. This development should 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 insulation materials are also being improved.

5.3. Quality Assurance and Official Certification

Annex 39 has contributed to increased confidence in VIP. For instance a VIP service life of 50 years and more is expected in most construction applications.

Further action is 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. Measurement technology currently available 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. Another obstacle are missing product approvals for VIP and VIP based systems for buildings.

6. References

ECBCS 2005(a) ECBCS Annex 39 (2005), VIP - Study on VIP-components and Panels forService Life Prediction of VIP in Building Applications, Subtask A report. Download: www.ecbcs.org/annexes/annex39.htm).

ECBCS 2005(b) ECBCS Annex 39 (2005), Vacuum Insulation in the Building Sector – Systems and Applications, Subtask B report. Download: www.ecbcs.org/annexes/annex39.htm).

Appendix: Participating Institutes

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KTH Stockholm Sweden	Gudni Johannesson Thomas Thorsell	gudni@bim.kth.se thomas.thorsell@byv.kth.se	Edge effect (stainless steel)

International Energy Agency (IEA)
Energy Conservation in Buildings & Community Systems Programme (ECBCS)

The International Energy Agency (IEA) was established as an autonomous body within the Organisation for Economic Co-operation and Development (OECD) in 1974, with the purpose of strengthening co-operation in the vital area of energy policy. As one element of this programme, member countries take part in various energy research, development and demonstration activities. The Energy Conservation in Buildings and Community Systems Programme has co-ordinated various research projects associated with energy prediction, monitoring and energy efficiency measures in both new and existing buildings. The results have provided much valuable information about the state of the art of building analysis and have led to further IEA co-ordinated research.

www.ecbcs.org

International Energy Agency
Energy Conservation in Buildings and Community Systems Programme