CHALMERS

Vacuum Insulation Panels in Buildings

Literature review

Report in Building Physics

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Division of Building Technology
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Cover:
Vacuum insulation panels (VIP) used in the roof of a retrofitted single family house in Thun, Switzerland. Photo: Neofas AG.

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ABSTRACT

The European Union has decided to decrease the energy use for heating of buildings with 50% in 2050. To reach the target, the amount of insulation in the building envelope has to increase. With conventional insulation materials, such as mineral wool and expanded polystyrene (EPS), the required additional thickness of the building envelope leads to a larger share of the building volume dedicated for structural elements. A novel thermal insulation components introduced to the building market during the last decade is the vacuum insulation panel (VIP). It can give the same thermal resistance using a thinner construction. This report presents the properties of VIP and the factors which have to be considered when using VIP in buildings.

A number of examples of different constructions are presented where VIP is used in both new buildings and in retrofitting of old buildings. VIP cannot be adapted on the construction site and is very prone to damages. In case a VIP is punctured, the thermal conductivity increases fivefold. The metalized multi-layered polymer film around the VIP creates a thermal bridge which has to be considered. A construction with VIP has to be designed in a way to protect the VIP during the entire service life without risk of damaging the surrounding materials.

Despite the obstacles which have to be overcome to use VIP in building applications, it is an interesting component that may play an important role on the path to reduce the energy use for heating of buildings. In the literature it is recommended to integrate the VIP in a way that they are easy to exchange after their service life has expired. By doing so and by educating the builder and designer in the special considerations when working with VIP the energy use for heating in the existing building stock could be reduced.

Key words: vacuum insulation panel, retrofit, building, floor, wall, roof, terrace

Contents

Preface

This report was produced at the Division of Building Technology, Building Physics Research group, at Chalmers University of Technology in Gothenburg, Sweden. The study was financed by FORMAS, the Swedish Research Council for Environment, Agricultural Sciences and Spatial Planning through the projects "Retrofit applications on old buildings using highly efficient novel thermal insulation materials".

The study is based on research papers, conference papers and reports which have been gathered to give an introduction to the use of vacuum insulation panels (VIP) in various parts of the building envelope.

Gothenburg, March 2012

Pär Johansson

1 Introduction

The energy use in the European Union should decrease with 20% in 2020 and with 50% in 2050 compared to the energy use in 1990 (European Commission, 2008). A large part of the energy use is related to heating of buildings and production of domestic hot water. In Sweden this part is just below 30% of the total end energy use which corresponds to around 10% of the Swedish greenhouse gas emissions. The data on energy use is uncertain, but according to the Swedish National Board of Housing, Building and Planning (Boverket), which is responsible for the Swedish energy use targets in buildings, the energy use for heating and domestic hot water has been reduced by 8%[1] between 1995 and 2008. To reach the Swedish energy use targets of a 20% reduction in 2020 and a 50% reduction in 2050 compared to 1995, further decisive actions are needed (Boverket, 2010).

The Swedish building regulations, enforced in January 2012, equalized the demands on energy efficiency of retrofitted buildings with the demands on new buildings. For residential buildings the demands were reduced with 20%. For example the maximum energy use is 90 kWh/m^2 and year for heating and domestic hot water in the south of Sweden. Also, the maximum average thermal transmittance, U (W/m^{2}K), of the building envelope was lowered from 0.5 to 0.4 W/m^{2}K. The regulations are the same, unless they are unreasonable with regard to the magnitude of the retrofitting measure or the prerequisites of the building. Also, the architectural, historical, environmental and artistic features of the building have to be considered since they should be preserved after the retrofit. If the demand on the maximum average thermal transmittance of 0.4 W/m^{2}K cannot be reached, the energy use should at least not increase after a retrofitting, unless under very special circumstances. These very special circumstances could be that another demand, e.g. on indoor air quality, cannot be met without increasing the energy demand (Boverket, 2011).

The use of conventional insulation materials, such as mineral wool, would demand thick insulation in the construction, around 20-30 cm. Vacuum insulation panels (VIP) is a novel thermal insulation component which can be used in buildings. With five times higher thermal resistance than e.g. mineral wool, a substantial improvement in energy performance could be reached using VIP. Meanwhile, the features and aesthetics of the building could be preserved.

This study gathers and summarizes the experiences gained during the last decade from using VIP in buildings. The study is based on reports of experiences and solutions which have been described in the literature. Research papers, conference papers and reports have been gathered to give a comprehensive basis for the conclusions.

The report is limited to building constructions with VIP. Different constructions, both new constructions and retrofitting applications, have been described. The report is not a complete library of buildings with VIP, merely a list of example constructions to show the possibilities and drawbacks when using VIP in buildings. The additional costs associated with the use of VIP in buildings compared to traditional insulation materials have only been treated briefly in the report.

[1] Temperature corrected; the reduction is 15% in absolute figures.

2 Vacuum Insulation Panels (VIP)

Vacuum insulation panels (VIP) were developed to be used in refrigerators, freezers and cold shipping boxes where the space for insulation is limited. The product was introduced in the mid 1980s following the search for materials that could replace insulation materials which contained CFCs, harmful to the ozone layer. The potential of using VIP in buildings is large but VIP cannot be integrated in buildings without considering the ageing of the material. The technical life time of a refrigerator is around 10-20 years, which is much shorter than what can be expected from a building. Buildings should typically last for 80-100 years without too much maintenance while VIP available today typically has a service life of around 25-40 years.

2.1 History of VIP

The first VIP originates from 1930 when a German patent on a rubber enclosed porous body was filed. Around 20 years later a patent on a glass wool core welded to a steel foil was filed in the US. In 1963, the first patent of a panel with a core of a nanostructured material was filed. The development of VIP continued with experiments of different core material and envelope techniques. The increasing demands from food, pharmaceutical and electronic industries boosted the development of thin films with low permeability. Nanostructured materials that could be used in the core were available already in the 1930s following Kistlers experiments with aerogels. However, the commercial production of aerogels was suspended in the 1970s which lead to development of alternative core materials (Fricke et al., 2008).

Figure 2.1 shows a VIP of the type that is common today (February 2012) which was first introduced in the early 1990s. The core material was at that time precipitated silica which was enclosed by a plastic envelope with a 12 µm tick aluminum film. Another product that was introduced at the same time was a VIP with a fiber core and an envelope of 75 µm thin welded sheet steel. The product was intended for the refrigerator industry and the thermal conductivity of the products ranged around 2-7 mW/(m·K). VIP with a diatomite filling and a 100 µm sheet steel casing were also tested for application in district heating pipes (Fricke et al., 2008).

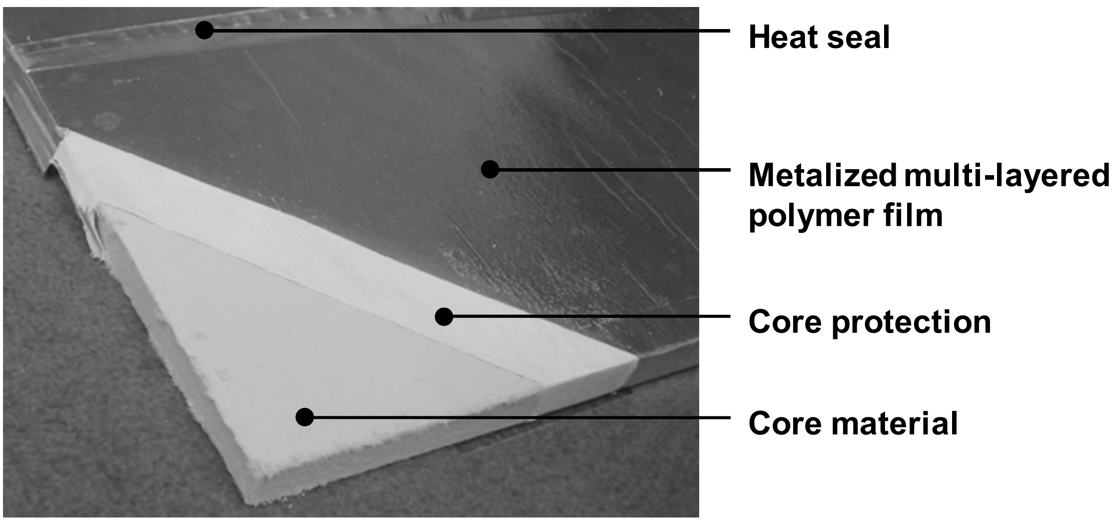

Figure 2.1 VIP is a composite material with a fine powder core wrapped in a heat sealed metalized multi-layered polymer film (Photo: va-Q-tec AG).

2.2 VIP properties

The core material of VIP is a fine powder or fiber from which the air has been removed to a gas pressure of 0.2-3 mbar. The core has to be able to resist the atmospheric pressure on the envelope, i.e. 1 000 mbar. The most common core material in Europe is fumed silica while also glass fiber and open cell polyurethane are common in Asia. Figure 2.2 shows the relation between the gas pressure and the thermal conductivity of a number of different materials common in the VIP core.

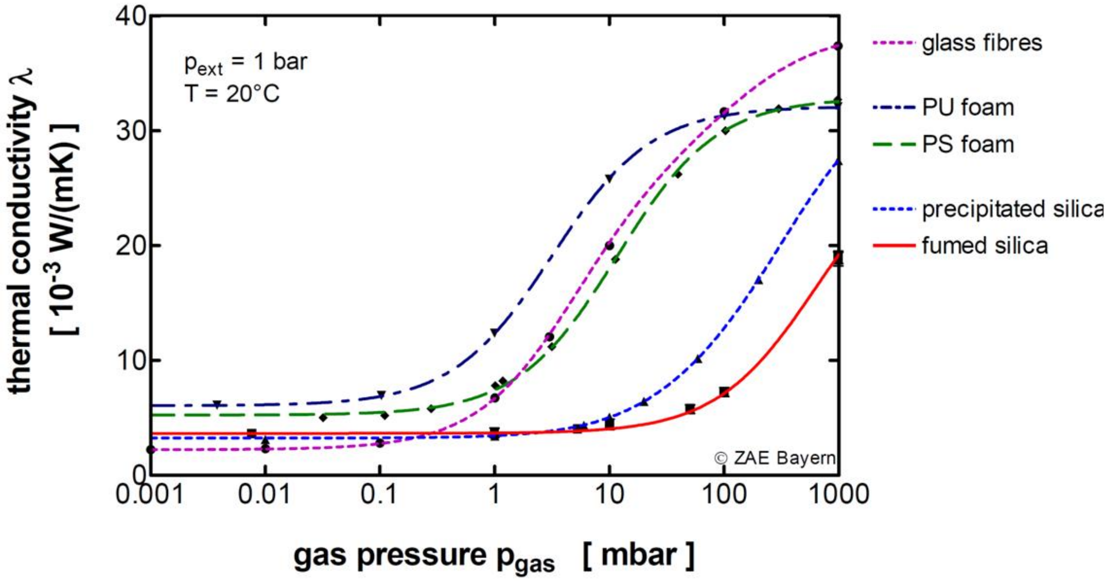

Figure 2.2 Thermal conductivity of different materials which are used in the core of VIP as a function of the ambient pressure. Normal atmospheric pressure is 1 000 mbar (Simmler et al., 2005).

Three distinct areas are visible in Figure 2.2 which are governed by the three modes of heat transfer through the material. The glass wool is a porous material with large cavities where the heat transfer by convection and gas conduction are dominant at atmospheric pressure. Polystyrene, polyurethane and precipitated silica have smaller pores compared to glass wool which means the gas conduction and convection are smaller in these materials.

The pore size of fumed silica is around 10-100 nm which is the same order of magnitude as the mean free path of air molecules, around 70 nm, in normal temperature and atmospheric pressure. When the pressure decreases towards vacuum, the heat transfer by gas conduction and convection decreases and heat transfer by radiation and conduction through the solid are left. They are constant as long as the temperature and density of the material are left unchanged.

Fumed silica is used in semiconductor industry and in the production of photovoltaic cells. It is produced by pyrolysis of silicon tetrachloride, $SiCl_4$, which is vaporized and reacts with oxygen to form silicon dioxide, SiO_2. To reduce the heat transfer by radiation silicon carbide, SiC, is added to the silica and a fiber material is used to increase the stability of the mixture. Around the core material, a metalized multi-layered polymer films with thin aluminum layers, 30-100 nm, are typically used as envelope. The film is not perfectly gas tight which makes it possible for gas molecules to diffuse through the envelope. An irreversible pressure increase take place which increases the thermal conductivity of the VIP, see Figure 2.3.

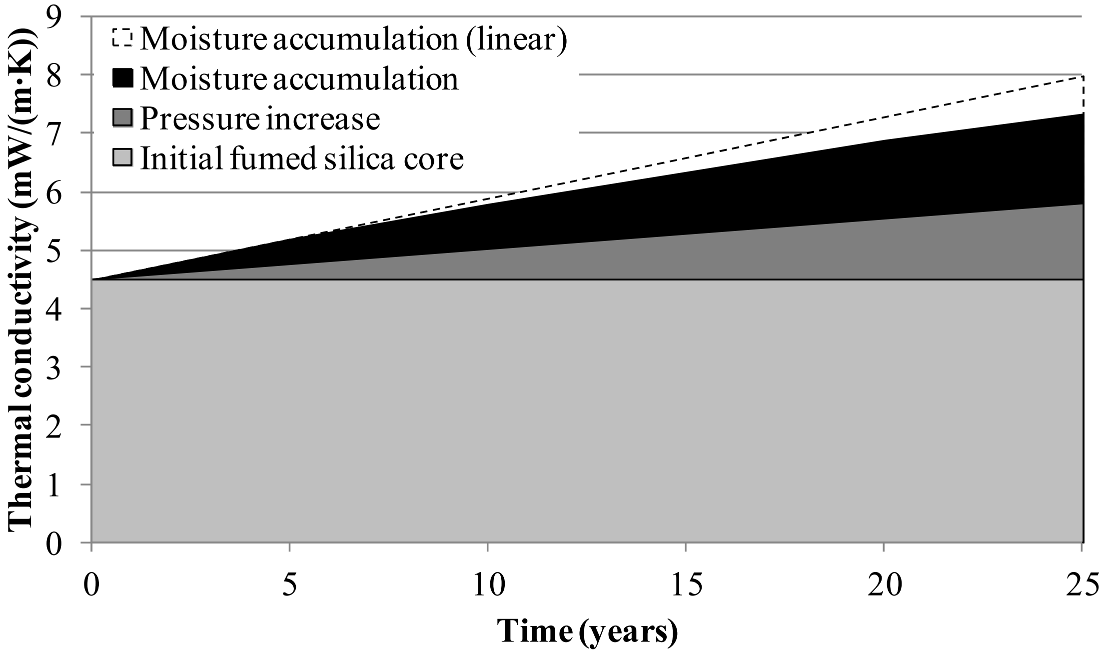

Figure 2.3 *Effect of thermal conductivity by pressure increase and moisture accumulation in the VIP during 25 years based on accelerated ageing experiments. The dashed line indicates the moisture accumulation omitting the moisture saturation. Approximation for panels of 1 000x600 mm with 20 mm thickness (From Brunner and Simmler, 2008).*

The centre-of-panel thermal conductivity of a new VIP is around 4.5 mW/(m·K) which can be expected to increase with 2.9 mW(m·K) after 25 years. Thus, the recommended design value of the thermal conductivity of a VIP with fumed silica is 7-8 mW/(m·K) depending on the moisture conditions in the construction. If the panel is punctured, the thermal conductivity increases to 20 mW/(m·K) which is still lower than e.g. mineral wool which has a thermal conductivity around 40 mW/(m·K) (Brunner and Simmler, 2008).

The metalized multi-layered polymer film around the VIP creates a thermal bridge as shown in Figure 2.4. A thermal bridge is defined as the linear thermal transmittance, ψ (W/(m·K)), which is multiplied with the length of the thermal bridge, i.e. the perimeter of the VIP. The magnitude of the thermal bridge is dependent on the center-of-panel thermal conductivity and the equivalent thermal conductivity of the film. Also the thickness of the panel and film influences the thermal bridge together with the thermal conductivity of the surrounding materials (Binz et al., 2005).

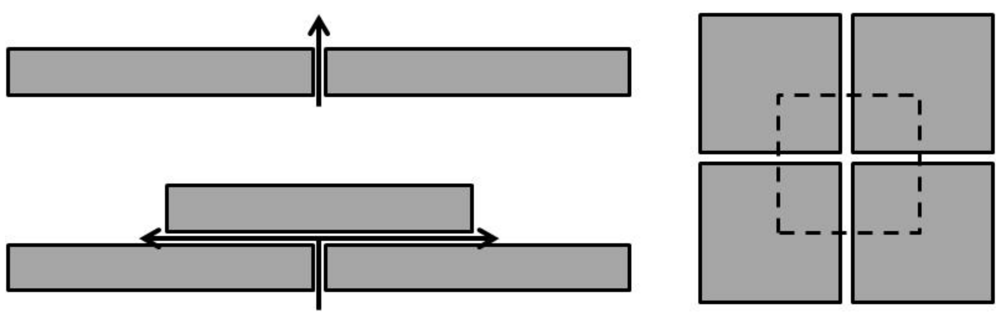

Figure 2.4 *Thermal bridge around the perimeter of the VIP. The thermal bridge can be reduced by adding a second layer of VIP.*

Studies of the thermal bridges created by the VIP envelope have been performed by a number of researchers. Schwab et al. (2005) used a numerical method to calculate the influence by air gaps between the VIP and also investigated the influence by encapsulating the VIP in polystyrene. The simulations showed that the effective U-value increased with up to 360% for the laminated aluminum film with a 5 mm air gap, while the effective U-value for the VIP with metalized multi-layered polymer film only increased with 44%.

Ghazi Wakili et al. (2004) compared numerical simulations with measurements of the thermal bridge effect of the film on 20 mm thick VIP of sizes 500x500 and 500x250 mm. Two different films were tested, one film with a total aluminum thickness of 90 nm and another film with 300 nm. The linear thermal transmittance was 7 mW/(m·K) for the 90 nm aluminum and 9 mW/(m·K) for the 300 nm aluminum. The increased heat flow through the film leads to a higher effective thermal conductivity of the VIP; 14% higher for the film with 90 nm aluminum and 19% higher for the film with 300 nm aluminum compared to the centre-of-panel thermal conductivity.

In a follow-up study by Ghazi Wakili et al. (2011), the effect of the film in constructions with double layered VIP was investigated. Different arrangements of 15-40 mm thick, 500x500 and 500x250 mm panels were measured in guarded hot plate apparatus. The panels were encapsulated in a multi-layered polymer film with a total aluminum thickness of 300 nm. The panels had an average centre-of-panel thermal conductivity of 4.1 mW/(m·K). Adding the effect of the thermal bridge created between the two small panels on top of an unbroken layer of VIP, the average effective thermal conductivity increased by around 2.5 mW/(m·K).

The VIP is prone to damages and has to be handled with great care during the construction process. To increase the durability of VIP, different approaches have been suggested and tested. A more robust version of the panels is the vacuum insulated sandwiches (VIS) which are covered by a stainless steel casing. The sandwich can be part of the load-bearing system and take loads without any additional protection (Tenpierik et al., 2007). Gudmundsson (2009) calculated the thermal bridges created by the robust protective casing around the VIS and found that the thermal bridge could be reduced by using insulation materials adjacent to the VIS. Also, the length of the edge could be elongated to decrease the influence of the casing. Thorsell (2006a) investigated a serpentine edge of the casing which showed that the thermal bridges decreased with this design. With 11 slots of 20 mm depth the influence could be minimized to a linear thermal transmittance of 11 mW/(m·K) which is comparable to the metalized multi-layered polymer film. The linear thermal transmittance of the casing was 28 mW/(m·K) without any slots.

2.3 Environmental impact

Three Swiss life cycle analysis (LCA) methods were used by Schonhardt et al. (2003) to study the environmental impact by VIP with fumed silica wrapped in a metalized polymer multi-layered film. The VIP was compared to the equivalent amount of glass wool and expanded polystyrene (EPS) used in 1 m^2 wall with a U-value of 0.15 W/(m^2K). The first method measured the embodied energy (MJ/m^2) which is a summation of how much energy that has been used in the production and processing of the material. The calculation was done for a service life of 40 years. The second method is the UBP97 method which makes it possible to compare materials in regard of resource use, production of radioactive waste, need of landfill and emissions to air, water and ground. The third method is called Eco-indicator 99 (Eco99) and is used to calculate the impact by production on the human health, effects on the eco system and resource depletion. The method uses a weighting system where the impact on different time scales, e.g. impact on future generations, is taken into account. Also the environmental impact on local and global scale is included in the model. Table 2.1 presents the results of the three methods with the absolute values and as percentage of the results for VIP. A comparison between aerogel and VIP could be interesting but since no LCA of the aerogel materials could be found it was not possible here.

Table 2.1 Results from three different Swiss LCA methods for 1 m² material with a U-value of 0.15 W/(m²K) where the equivalent amount of glass wool and EPS are compared to VIP (Schonhardt et al., 2003).

Method	Glass wool		EPS		VIP	
	Abs.	% of VIP	Abs.	% of VIP	Abs.	% of VIP
Embodied energy (MJ/m^2)	455	46	890	89	999	100
UBP97 (UBP97/m^2)	21 646	50	35 767	83	43 245	100
Eco99 (milli-points/m^2)	1 254	52	3 402	142	2 393	100

The LCA calculations showed that the VIP is worse than glass wool and EPS in regard of embodied energy and UBP97 methods. Eco99 showed that VIP had a lower environmental impact than EPS which was 42% higher than VIP, while mineral wool was only half compared to VIP. The high figure for EPS was caused by the use of fossil based goods. The analysis showed that 90% of the energy used in VIP production derived from the core material while only 4% was used for the film production. With an alternative core material or a more energy efficient process, calculations show that the environmental impact of VIP could be lowered by 45% (Schonhardt et al., 2003).

2.4 Considerations when using VIP in buildings

Since the film around the VIP is vapor tight, the vapor permeability of the panels is virtually zero. This may cause problems around the panels if the connection between them is insufficiently sealed and allows for air and vapor transport through the layer. In some cases sealing tape has been used to increase the air tightness of the connections. Another option is to use an additional layer of vapor retarder to ensure a vapor tight layer. It might also be worth to investigate if a dynamic vapor barrier could be used, i.e. a material that let the vapor through when it is in moist environment and stop the vapor when it is dry. Especially this solution could be worthwhile if there is a risk of condensation in the construction.

The moisture and heat flow through the construction where the VIP is integrated will change substantially. The risk of damages to the construction in case of a punctured VIP has to be investigated with hygrothermal simulations. In Johansson (2012), a theoretical study of a wall retrofitted with VIP is presented. The study showed that the risk for moisture damages was decreased when VIP was added to the exterior of an old exterior wall. If the VIP was punctured, only a small change in the moisture performance of the wall could be found.

If a VIP is damaged in the construction, the heat flow through the construction will increase. In the design process this have to be treated and if it has an unacceptable consequence for the energy use for heating of the building, the construction should be prepared for easy exchange of the damaged panel. In that case the construction has to be flexible and designed in a way that the VIP is easily accessible and possible to remove. It should also be possible to detect the damaged VIP with e.g. infrared thermography, which means that the VIP should not be covered on both sides with high conductive materials or be placed behind a ventilated air space (Binz et al., 2005).

A way to avoid unnecessary risks on the construction site is to integrate the VIP in prefabricated constructions. Industrial treatment of the VIP means they will be in a controlled environment where the staff involved in the handling of the panels can gain experience and be trained to treat the VIP with care. Also the surroundings of the site of assembly can be equipped with the right protective equipment such as protective mats and felt shoes (Binz et al., 2005).

All attachments and joint details need to be carefully designed since brackets, window attachments and such components may harm the envelope of the VIP. A good design can ensure this which means the designers and builders have to be aware of the special requirements of the VIP early in the design process. If the design and construction are performed following the recommendations from producers VIP can be feasible and an important mean for building energy efficient buildings (Binz et al., 2005).

Fumed silica is nonflammable and is therefore classified A1 according to DIN ISO EN 13501-1 (Porextherm, 2010). On the other hand, the silica is encapsulated by a multi-layered polymer film which is highly flammable. The multi-layered polymer will start decomposing at around 150°C causing production of carbon monoxide, formaldehyde and possibly other aldehydes. The film auto ignites at around 350°C (Microtherm, 2009) with a fast fire development, see Figure 2.5. Newly developed VIP has a 6 µm thick flame-retardant brominated acrylic copolymer coating on the outside of the film.

Figure 2.5 Melting and burning of a metalized multi-layered polymer film (Photo: Bijan Adl-Zarrabi).

3 Application and feasibility studies of VIP

An investigation in 1999-2002 commenced by the US Department of Housing and Urban Development evaluated the market potentials for VIP in residential buildings in the US. 27 different constructions were evaluated during a brainstorming process based on a number of evaluation criteria (NAHB Research Center, 2002):

- Cost of manufacturing
- Significance of impact of VIP on performance of home
- Performance of home
- Required life span of material
- Risk of damage on jobsite
- Risk of damage after construction
- Construction
- Additional installation costs

The brainstorming process and evaluation resulted in ten alternatives of which five alternatives were chosen as most promising based on their respective annual market potentials (NAHB Research Center, 2002):

- Manufactured housing floor panels (45.4 km^2)
- Exterior doors (9.3 km^2)
- Garage doors (3.1 km^2)
- Manufactured housing ceiling panels (45.4 km^2)
- Attic access panels/stairway insulation (approx. 1 million access panels)

The five other applications were (NAHB Research Center, 2002):

- Precast concrete panels, foundation/wall (0.1 km^2, could expand)
- Insulated metal roofing panels (0.4 km^2)
- Rectangular duct insulation (3.7 km^2)
- Retrofit exterior insulation (6 km^2, could expand)
- Acoustical ceiling panels (potentially large commercial building market)

The recommendation from the first part of the study was to investigate insulated attic hatches and insulated attic stairs further. Together with the two VIP producers, designs were evaluated and contacts taken with attic hatch and stair producers. The study was based on American building traditions for detached single family houses which means that the conclusions cannot be directly applied on the European building market where other applications might be more interesting. After the report was produced, the development in the durability and thermal resistance of the VIP has continued and the number of possible applications increased.

During 2002-2005, an international research team investigated the possibilities to use VIP in buildings. Researchers from Switzerland, Germany, France, the Netherlands, Sweden and Canada worked in the IEA/ECBCS Annex 39 High Performance Thermal Insulation (HiPTI). The research was divided in two subtasks where the first part was regarding the VIP properties and durability while the second part concerned the use of VIP in building applications. In total 20 constructions were built or retrofitted and the consequences on energy use, thermal bridges and moisture performance were analyzed. The research team concluded that VIP has become a feasible and important mean for designing energy efficient buildings. There are obstacles to overcome, mainly cost and issues with durability and quality assurance of VIP in buildings, before VIP can be introduced on a wide scale (Binz et al., 2005).

Willems and Schild (2005) discussed different construction where VIP could be used. Examples of how loggias and roof terraces, curtain walls, flat roofs, pitched roofs, floors and external walls could be designed with VIP integrated in the construction are presented. Examples of how the more load resistant VIS, covered by a stainless steel casing, can be a part of the load-bearing system were also presented.

A Norwegian investigation by Grynning et al. (2009) concluded that the building traditions in the Nordic countries are different from the traditions in central Europe. Many of the constructions with VIP are located in Switzerland and Germany where the use of timber constructions is less common. Norwegian single family houses are almost exclusively built using timber frame constructions with a ventilated roof. This means that the conclusions from the Swiss and German studies cannot be applied directly to the Nordic buildings without more evaluations. A number of constructions where it could be possible to use VIP in the Nordic countries were identified:

- Prefabricated sandwich elements
- Continuous insulation layer in non-load bearing walls
- Thin timber frame walls
- Floors and compact roofs
- Retrofitting of buildings with limited available space
- New buildings in areas with high ground costs
- Doors and windows
- Insulation of terrace floors where even connections are important

The use of VIP in these constructions is limited by the higher cost in relation to the commonly used insulation materials. Grynning et al. (2009) presented a simplified economical calculation where a 6 cm thick VIP was used in an exterior wall. At a market value of 17 500 NOK/m^2 (approx. EUR 2 300 per m^2) there was no additional costs for the VIP compared to using mineral wool. In this example, the thermal resistance of the VIP was five times higher than for the mineral wool and the cost of the 6 cm thick VIP was 1 600 NOK/m^2 (approx. EUR 200 per m^2). The costs for increased design and construction times were not included in the study.

A study of the economical consequences of using VIP in Swedish multi-family buildings was performed by Pramsten and Hedlund (2009). A wall with VIP was compared to a wall with the same thermal transmittance using EPS. With the assumptions in the study, VIP is not an economical alternative compared to EPS. Either the price of the VIP has to decrease or the energy price has to increase to make VIP an economical alternative for buildings. For a market value of 22 450 SEK/m^2 (approx. EUR 2 500 per m^2) the price of EPS and VIP are equal. The prize of the 20 mm thick VIP was 1 800 SEK/m^2 (approx. EUR 200 per m^2).

Alam et al. (2011) calculated the payback period (PBP) using VIP in four different retrofitting scenarios where the thickness of the VIP was varied. The PBP using VIP was compared to a wall with the same thermal resistance using EPS. The scenarios were based on commercial buildings in the UK where the available space for the construction is limited. The results are presented in Table 3.1.

Table 3.1 Insulation scenarios and payback period for VIP compared to EPS (Alam et al., 2011).

U-value ($W/(m^2K)$)	EPS (mm)	PBP (years)	VIP (mm)	PBP (years)	PBP with space savings (years)
0.40	48.3	0.5	10	15.3	3.3
0.31	113	0.7	25	9.6	1.7
0.27	180	0.8	40	8.0	1.1
0.24	256	0.9	60	7.1	0.8

The cost of the VIP was £70/m^2 (EUR 84 per m^2) for the 10 mm thick VIP and £80/m^2 (EUR 96 per m^2) for the other thicknesses (Alam et al., 2011). The difference between the cost in EUR of the VIP used in this study and the Nordic studies is mainly caused by the currency exchange rates which have changed considerably between 2009 and 2011.

The PBP was 15.3 years for the case with 10 mm VIP and decreased to 9.6 years with 25 mm VIP. For the wall with an U-value of 0.27 $W/(m^2K)$, the PBP was 10 times higher for the VIP compared to the EPS. In the fourth scenario the PBP was 6 years longer using VIP compared to EPS. However, the EPS required 256 mm insulation thickness compared to only 60 mm VIP for the same thermal resistance. The PBP was reduced significantly when the additional income from the rentable space gained by using VIP was taken into consideration. The value of the gained space was £40/ft^2 which is approximately EUR 500 per m^2, corresponding to the average yearly rent of commercial buildings in London, UK. With this increased income the payback period was less using VIP compared to EPS, 0.8 compared to 0.9 years, for the wall with an U-value of 0.24 W/m^2K (Alam et al., 2011).

4 Constructions with VIP

There are a number of buildings where VIP has been used both in new constructions and in retrofitting applications. A detailed technical drawing of where each VIP should be installed in the construction is needed before construction can start since the panels cannot be adjusted on the construction site. This chapter is based on case studies and suggested designs that have been described in the literature and should not be seen as a complete library of buildings with VIP, merely a list of example constructions. The focus is on practical considerations and experiences from construction.

VIP is interesting to use in floors where the requirements on the thermal resistance are high, alternatively where the construction thickness is limited. In floors where floor heating is used, VIP could be used to increase the efficiency of the floor heating system. VIP could also be used in doors to increase the thermal performance with up to 50%. In dormer windows, the VIP could be used to make the construction thinner.

One of the major possible constructions where VIP could be used is in exterior walls. Glazed façades can be thinner while maintaining the thermal resistance. VIP could be used in new buildings, both in light-weight timber frame walls and in heavy concrete walls. In old buildings, VIP could be used on the exterior or interior of the existing wall. So far, the most common wall application with VIP is on the exterior of the existing wall. It is also possible to integrate the VIP in a structural sandwich panel, e.g. made of concrete, to increase the protection of the VIP.

The use of VIP in prefabricated attic access panels and stairways has been proposed in the US. For flat roofs and terraces, VIP could be used to increase the thermal resistance of the construction. Accelerated ageing experiments have shown that VIP in roof constructions could be expected to have a service life of at least 25 years. A special application where VIP could be used is in saunas where the large temperature difference presents an interesting challenge for the durability of the panels.

4.1 Floor insulation

In rooms with extreme temperature demands, such as cold storage or freezer rooms, it is be possible to use VIP in the floor. The VIP has to be covered with a layer which can distribute the loads from the goods stored in the room (Willems and Schild, 2005). Figure 4.1 presents a floor design where VIP is used to increase the efficiency of a floor heating system (Schwab et al., 2004).

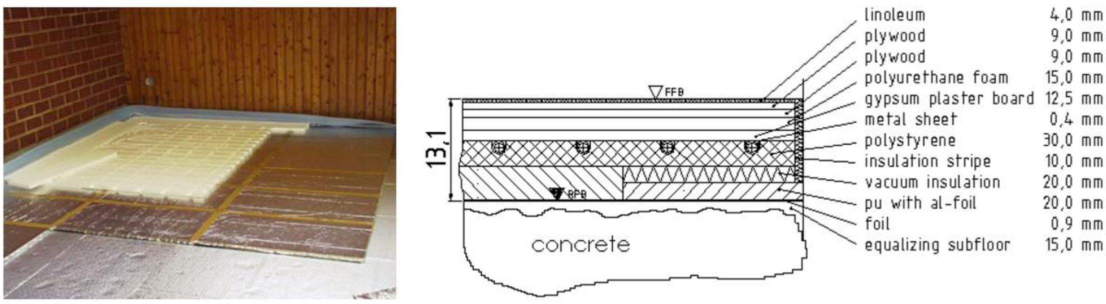

Figure 4.1 The floor of a gym was retrofitted with 20 mm VIP which decreased the U-value of the floor from 0.43 to 0.15 W/m^{2}K (Photo: ZAE Bayern).

In older multi-family buildings in Sweden, it is common with archways from the street to enter the common backyard where the entrance of the building is located.

Above the archway there is usually an apartment which in some cases suffers from a cold floor due to insufficient insulation between the apartment and the archway (Jasim, 2010). VIP can be used to increase the thermal comfort in apartments by raising the temperature on the interior floor surface.

4.2 Door insulation

Doors are thin constructions with a limited amount of available space for insulation. With VIP integrated in the door, the thermal resistance could be substantially improved. Nussbaumer et al. (2005) investigated the thermal performance of a wooden door with two integrated VIP. The results from the investigation showed that the energy efficiency of the door system including the frame could be improved by 25% using VIP instead of common insulation materials. If the influence of the frame was neglected, calculations showed that the thermal transmittance could be reduced by 50%, from 1.08 W/(m^{2}K) for the conventional door to 0.58 W/(m^{2}K) for the door with integrated VIP. If one of the two integrated VIP was punctured, measurements showed that the heat flow through the door including frame increased with 8.5% and with both panels punctured the heat flow increased with 14%.

4.3 Dormer windows

Another construction where the space is limited for additional thermal insulation is in dormer and bay windows. In these constructions there is little space for conventional insulation materials. Care has to be taken to ensure that the temperature shifts around the VIP are not too large since the panels can be damaged by fast changes in the surrounding temperature.

Two buildings in Zürich, Switzerland were retrofitted with 30 mm VIP integrated in a prefabricated dormer window construction, see Figure 4.2. The VIP was protected by wooden boards and a layer of wooden laths in the roof transferred the load to the window frame. The U-value did not rise above 0.27 W/(m^{2}K) if the VIP was punctured, due to the additional insulation layers (Binz et al., 2005).

Figure 4.2 Dormer window insulated with 30 mm VIP (Photo: Viridén + Partner AG).

4.4 Glazed façades

It is possible to protect the VIP from mechanical damages, compared to a normal wall assembly, by placing the VIP between two panes of glass. Since the VIP is opaque, it is only at the opaque parts of the façade where the use of VIP is possible.

Traditionally the producers of glazed façades have used foam insulation with a higher thermal conductivity which requires a thicker construction than what is the case of the ordinary transparent windows (Thorsell, 2006b). By using VIP between two glass panes, placed in a modified timber window frame, the thickness of the construction could be reduced while maintaining a high thermal resistance. This approach was tested in an office building in Munich, shown in Figure 4.5 (Pool, 2005).

4.5 Façade insulation in new buildings

When designing new buildings, there are high requirements on the energy performance of the entire system. Walls with high thermal resistance can decrease the heating demand for the building throughout its service life. Exterior light-weight walls are traditionally insulated with mineral wool or expanded polystyrene (EPS) which are attached between wooden battens. VIP can replace some of the conventional insulation materials to decrease the required thickness of the wall assembly.

Light-weight timber frame walls with VIP in the frame were evaluated by Haavi et al. (2010). The thermal resistance of three different stud designs (36 mm studs, I-studs and U-studs) was tested in a hot box apparatus. The walls had a total thickness of 182 mm which was divided in 6 mm MDF board, 65 mm mineral wool, 40 mm VIP, 65 mm mineral wool and 6 mm MDF board, see Figure 4.3.

Figure 4.3 Three walls with VIP and different stud designs were investigated in hot box apparatus (Photo: Thomas Haavi).

The heat flow through the walls was measured with thermocouples attached on the surface of the MDF boards. The measured thermal transmittance was between 0.09 and 0.11 W/(m^{2}K) for the complete wall, which gave an average thermal conductivity of 0.017 and 0.020 W/(m·K) respectively. The 36 mm stud wall had the lowest thermal transmittance and the I-stud wall had the highest. The difference between the walls was lower when the thermal transmittance at the centre-of-panel was compared for the three walls, on average 0.083 W/(m^{2}K) which gave an average thermal conductivity of 0.015 W/(m·K). The measurements were also compared to numerically calculated heat flows which were deviating with 1.5-11.6% from the measured flows. The study did not consider how moisture in the wall should be treated, neither the workmanship.

It is possible to place the VIP in the frame of the load-bearing wooden laths in the wall or as an additional insulation layer on the exterior of the load-bearing structure.

Willems and Schild (2005) concluded that special attention has to be paid to reduce the thermal bridges which are caused by the higher thermal conductivity of the wooden laths compared to the VIP. Schwab et al. (2005) investigated the effect of the wooden laths on a new building in Munich, Germany, see Figure 4.4.

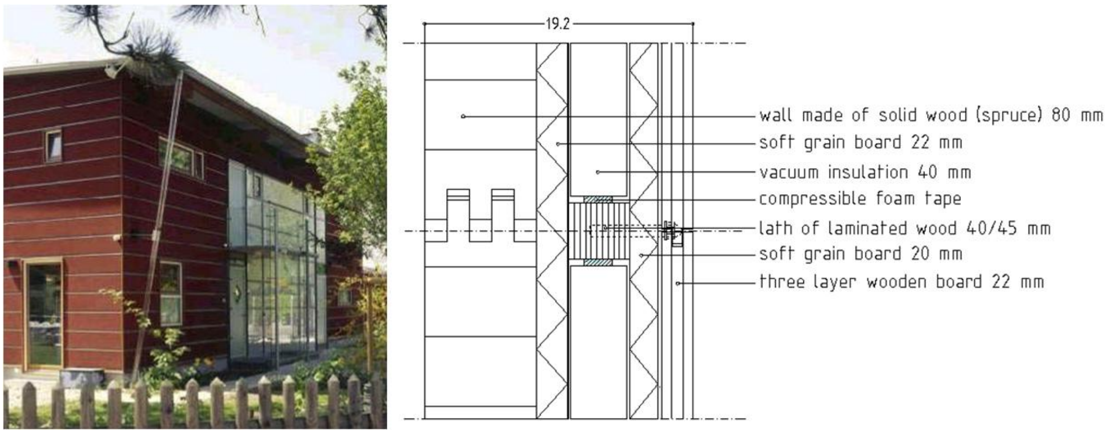

Figure 4.4 Building where the VIP is separated by a system of laminated wooden laths (Photo: Lichtblau architects).

The U-value of the wall without consideration to the wooden laths was 0.10 W/(m^{2}K) and with the wooden laths it was increased to 0.14 W/(m^{2}K). This can clearly be seen on infrared thermography where the temperature difference was 2.5°C with an interior temperature of 20°C and an exterior temperature 0°C (Schwab et al., 2005). With punctured VIP, the U-value increased from 0.14 to 0.29 W/(m^{2}K). The punctured VIP can be replaced by removing the wooden boards on the façade, a big advantage with the design. Compared to using conventional insulation materials in the wall, the internal area of the house was increased with 15 m^2 using VIP (Binz et al., 2005).

An office building in Munich, Germany was insulated on the exterior with VIP. The structure of the building was concrete where compressed recycled PUR battens were casted with 500 mm distance. A vapour barrier was placed on the concrete and PUR battens were attached on the exterior. 20 mm thick VIP was placed between the battens and covered with a layer of 80 mm PUR and plaster as shown in Figure 4.5 (Pool, 2005).

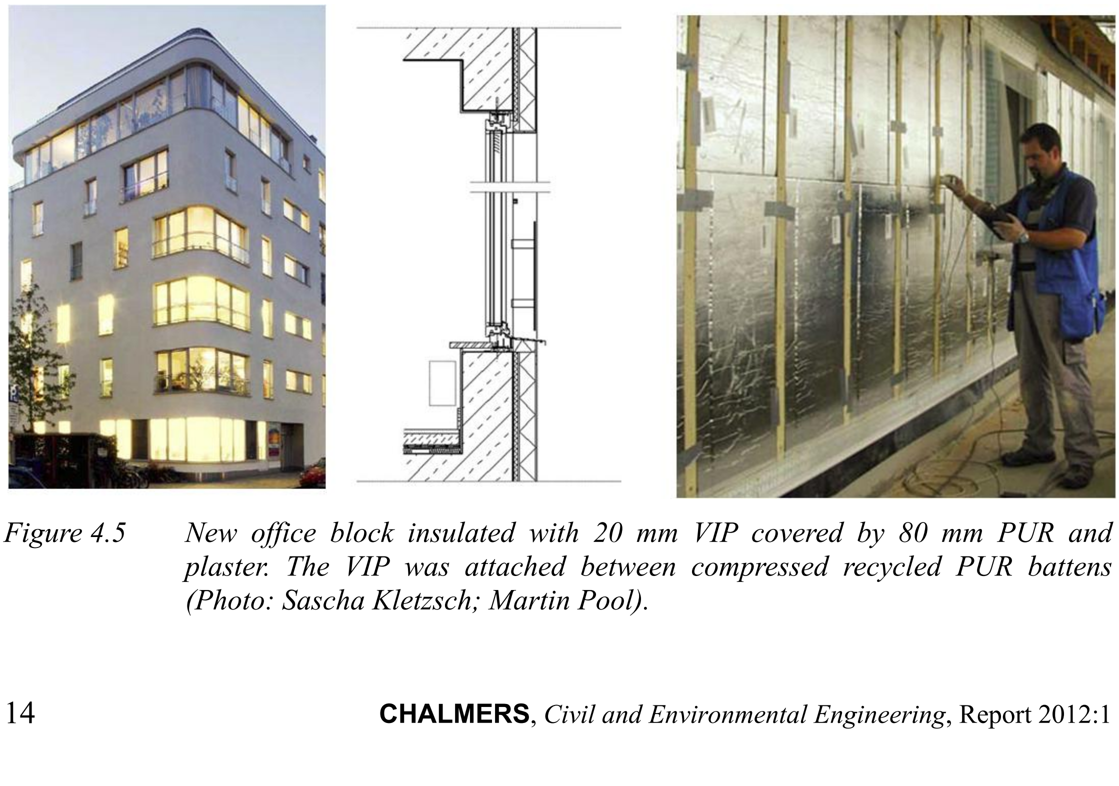

Figure 4.5 New office block insulated with 20 mm VIP covered by 80 mm PUR and plaster. The VIP was attached between compressed recycled PUR battens (Photo: Sascha Kletzsch; Martin Pool).

To protect the fragile VIP from damages they can be integrated in a protective layer of e.g. EPS. This kind of VIP was installed in a façade in Bersenbrück, Germany. The 20 mm VIP was encapsulated on all sides in 20 mm EPS, see Figure 4.6. The average U-value 0.15 W/(m^{2}K) was reached by adding an additional layer of 80 mm EPS on the exterior of the encapsulated VIP. The additional insulation layer made the total thickness of the insulation in the wall to be 14 cm which is about half what is needed with conventional insulation materials to reach the same thermal transmittance. The largest disadvantage with encapsulation of the VIP in polystyrene is the thermal bridges that are created at the connections of the panels (Zwerger and Klein, 2005).

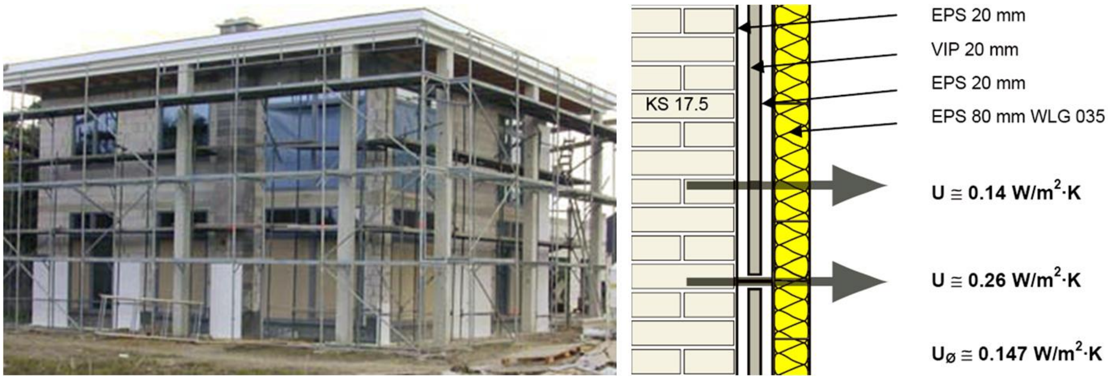

Figure 4.6 House insulated with 20 mm VIP encapsulated in 20 mm polystyrene which were attached by a rail system (Photo: Zwerger and Klein, 2005).

Another solution tested was to only have the EPS on the largest sides of the VIP. In Petrisburg/Trier, 12 terraced houses were equipped with the system of 20 mm VIP laminated on both sides with 20 mm EPS, see Figure 4.7 (Zwerger and Klein, 2005).

Figure 4.7 Terraced house insulated with 20 mm VIP laminated on the largest sides with 20 mm EPS (Photo: Zwerger and Klein, 2005; Sto AG).

4.6 Façade insulation exterior retrofit

In new constructions it is quite easy to integrate the VIP in the construction since the design team is in control of all measurements and requirements of the construction. When all materials are added on site and assembled by skilled workers, the probability of a successful construction with VIP is high. However, the largest possible application of VIP is in existing constructions and especially in existing façades. The control of how the old construction will react when insulated with VIP has to be carefully investigated to maximize the benefits of the VIP and not to cause damages to the old construction.

The exterior wall of a traditional Austrian building in Vienna was simulated in WUFI and COND by Korjenic and Dreyer (2003). VIP were investigated on the interior or the exterior of a 50 cm brick wall covered with 2 cm plaster on the exterior and 1.5 cm plaster board on the interior. The walls were simulated during 10 years with the climate of Vienna and Holzkirchen in southern Germany. In the case with exterior insulation of the façade, the total moisture content in the wall decreased. The plaster and brick was much wetter, especially during the first three years, if the VIP was put on the interior of the interior plaster board. The water content of the wall was reduced when a more water resistant exterior plaster was used. The risk of mold growth was also investigated at the thermal bridge created by the attachment between the wooden ceiling and the brick wall and at a wooden window attachment. The simulations showed that there was little risk of mold growth with interior VIP at those details. On the other hand, gaps between the VIP could lead to an increased risk of moisture damages (Korjenic and Dreyer, 2003).

A gable wall of an old building in Nuremberg was retrofitted using VIP in 2000. The system for attaching the VIP to the façade was based on a plastic rail system, see Figure 4.8 (Binz et al., 2005).

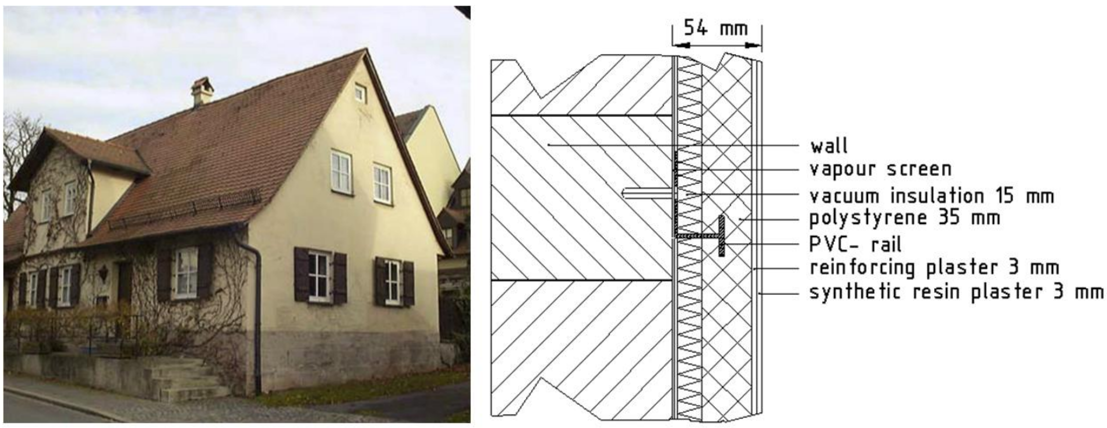

Figure 4.8 A building retrofitted on the exterior with 15 mm VIP using a special plastic rail system (Photo: ZAE Bayern).

The 15 mm thick VIP was secured between 35 mm thick horizontal plastic rails that were fastened in an exterior 35 mm thick layer of EPS. The VIP was attached to the EPS with an adhesive and a vapor barrier was attached between the VIP and existing wall. Infrared thermography showed a temperature difference of 0.7°C between the centre of panel and the edge. The U-value of the wall was improved from 0.7 to 0.19 W/(m^{2}K) which would increase to 0.32 W/(m^{2}K) if the panels were punctured. An investigation with infrared thermography in 2008 showed that one more panel had been punctured after the façade was investigated in 2001 and 2003 (Heinemann and Kastner, 2010).

In Freiburg in 2004, the Frauenhofer ISE building was retrofitted using VIP that had been coated by an organically bound leveler. The leveler worked both as adhesive of the VIP to the old façade and for plaster carrier. Several damaged VIP had to be removed and replaced in 2004 and in the same year the façade was reinforced using plaster with mesh inlay. In the spring of 2005 even more VIP had been punctured, clearly visible on infrared thermography as shown in Figure 4.9. This solution with adhesive directly applied on the VIP has not been used afterwards (Zwerger and Klein, 2005).

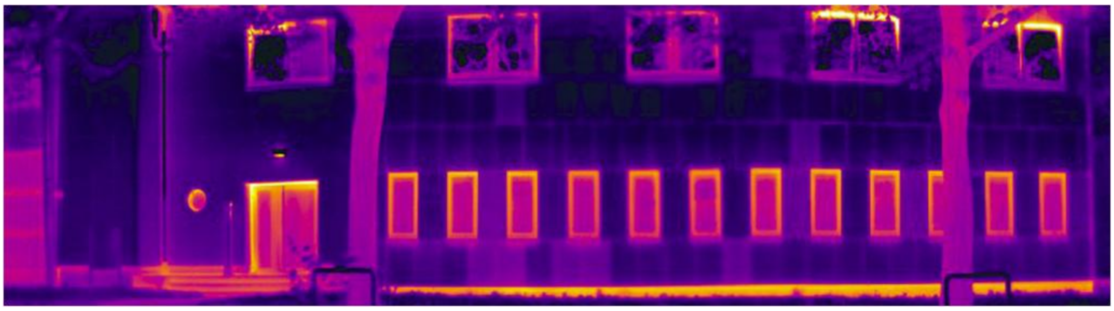

Figure 4.9 Damaged VIP was found on a facade with infrared thermography. The lighter squares show the damaged VIP with the higher surface temperatures (Photo: Zwerger and Klein, 2005).

The exterior wall of a terraced house built in 1956 in Munich, Germany was retrofitted using 40 mm VIP. The panels were attached to the wall by a steel profile system, see Figure 4.10. The U-value of the wall was 0.16 W/(m^{2}K) which would increase to 0.28 W/(m^{2}K) if the VIP was punctured. Infrared thermography showed that at least one panel had been punctured after construction finished (Binz et al., 2005).

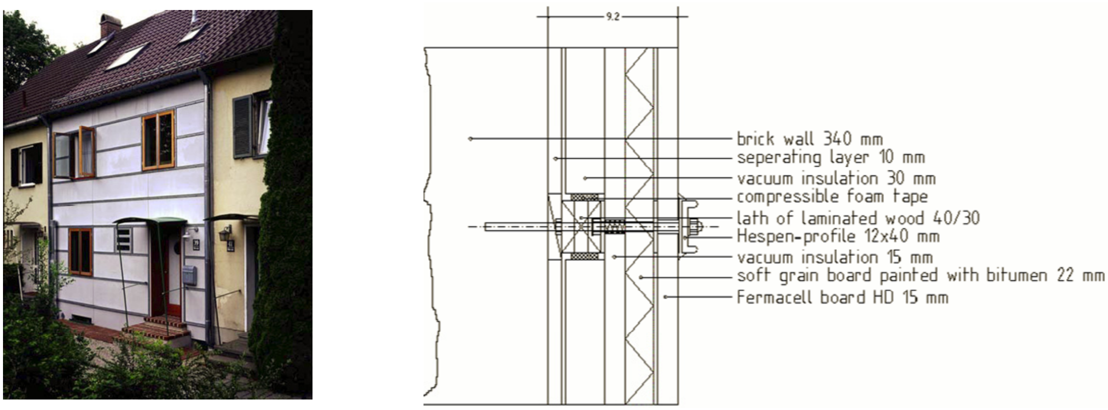

Figure 4.10 Exterior retrofitting of a facade with 40 mm VIP in two layers (Photo: ZAE Bayern).

A gable wall of a listed multi-family building from 1930 in Gothenburg, Sweden was retrofitted with VIP, see Figure 4.11. The building was protected and the façade was not allowed to be altered. Between the 20 mm VIP, stripes of 50 mm wide glass wool laths were fitted to allow the exterior wooden cover boarding to be attached. Mineral wool was also placed around windows and places where VIP could not be fitted. The existing structural wall was covered by a 0.2 mm polyethylene film to which the VIP was glued on. A 30 mm glass wool board was attached on the exterior of the VIP to protect it and make the influence of the thermal bridges less. The U-value before retrofitting was 1.1 W/(m^{2}K) and the final U-value was 0.4 W/(m^{2}K), 0.23 W/(m^{2}K) without considering the parts with mineral wool. The U-value of the wall increased to 0.54 W/(m^{2}K) if the VIP was punctured (Johansson, 2012).

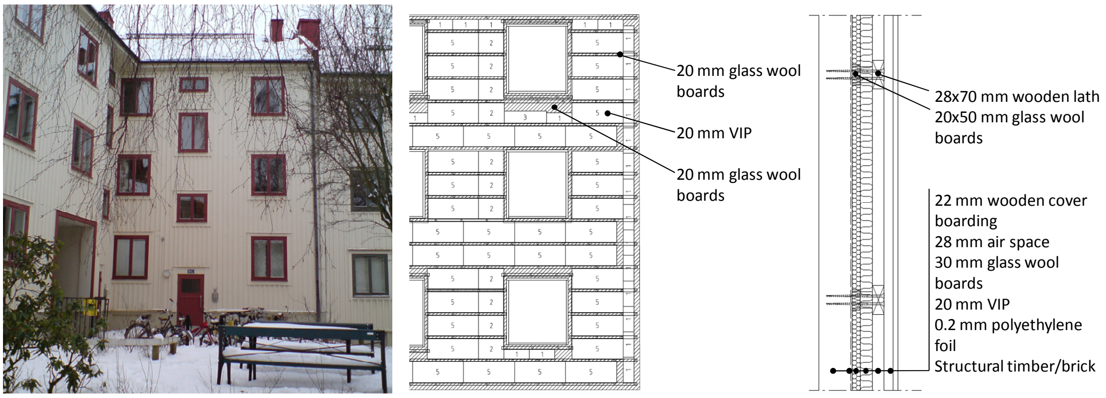

Figure 4.11 Multi-family building retrofitted with 20 mm VIP separated by 50 mm thick glass wool boards. The VIP was covered by 30 mm glass wool boards to protect it from damages from exterior (Photo: Pär Johansson).

Another design approach was used in two multi-family buildings in Karlsruhe, Germany, built in the 1950s with 30 apartments each which were retrofitted using VIP, see Figure 4.12. The panels were attached to the wall in a rail system to reduce the thermal bridges between the panels. 40 mm thick VIP covered on both sides by a 4 mm protective layer was used which means the total thickness of the panels were 48 mm. The panels were of sizes 80x40 cm, 40x40 cm, 30x40 cm and 20x40 cm. The gaps where VIP could not be fitted, 9 cm maximum, were filled with EPS. A double layer of 25 mm EPS boards was used as exterior protection which makes the total thickness of the system to be 10 cm. The U-value of the wall was approximately 0.13 W/(m^2K). The balconies were changed and the connection with the wall was specially designed to minimize the thermal bridges (Bauphysik, 2011).

Figure 4.12 Two multi-family buildings were insulated with 40 mm VIP covered by 4 mm protective cover and 50 mm EPS. The balconies were removed and new attachments were installed to minimize the thermal bridges (Photo: Schöck Balkonsysteme GmbH; Brillux GmbH & Co. KG).

To protect the VIP from damages on the construction site, an external thermal insulation composite system (ETICS) with VIP integrated in EPS, 10 mm thick, has been developed and tested by Kubina (2010) since 2007. The system can be used in new buildings and in retrofitting of façades as shown in Figure 4.13. The basic standardized panels are of sizes 500x500 mm and 1000x500 mm which are covered by an overlapping panel 1000x250 mm. The panels can be adjusted on the construction site by a cutting zone around the panels of maximum 40 mm. The two layers of panels close the gap between the first layers of panels and reduces the thermal bridges around the VIP which were described in Section 2.2 (Kubina, 2011).

Figure 4.13 VIP integrated in EPS boards (Photo: Libor Kubina).

4.7 Façade insulation interior retrofit

Interior insulation on an existing wall is a more challenging task than to place the insulation on the exterior. However, with interior insulation it is possible to preserve the existing façade, which in many cases is protected for its aesthetics and historical features. The hygrothermal performance of the wall will change when a larger part of the heat flow through the wall is stopped by the insulation which can lead to moisture damages caused by moisture accumulation from the exterior (Künzel, 1998). There are also thermal bridges at the connections between e.g. wall and intermediate floors that has to be considered. A very large heat loss can be created through these insufficiently insulated parts if not proper care is taken during the design process. The surface temperature at these locations can also mean that the relative humidity approaches critical levels for mold growth. For VIP as interior insulation there is also a risk of puncturing of panels caused by the occupants who want to hang paintings and shelves on the wall.

A stone masonry wall was investigated for VIP on the interior. Thermal bridges caused by the connection between wall and ceiling was investigated and calculated with numerical three-dimensional software for three different cases of attachment detail. The linear thermal transmittance coefficient ranged between 0.21 and 0.37 W/(m·K) for the three cases. The thickness of the VIP was 20 or 30 mm in the calculations, but showed to have little influence on the linear thermal transmittance coefficient. The U-value for the wall was 0.35 W/(m^{2}K) for the case with 20 mm VIP and 0.25 W/(m^{2}K) for 30 mm (Ghazi Wakili et al., 2005).

A building from 1907 in Zürich, Switzerland was retrofitted internally. In the ground floor wall towards the street, 30 mm VIP was used as wall insulation. The VIP was covered by 60 mm plaster boards separated by a 10 mm thick air space to protect the VIP from mechanical damages, see Figure 4.14. The VIP was attached to the wall on a smoothing layer of plaster and an adhesive was used to keep the VIP in place. Aluminum tape was used to seal the joints between the VIP and at the attachments of wall and floor, 200 mm cork insulation was placed to have some tolerance to imperfections in the old construction. On the upper floor walls, 80 mm cork insulation was used (Binz and Steinke, 2006; Viridén, 2007). At least one of the VIP had been punctured when parts of the walls were reopened. If the damage had happened during or after construction could not be determined (Viridén et al., 2004).

Figure 4.14 Interior retrofitting of brick wall with 30 mm VIP covered by 60 mm plaster boards (Photo: Viridén + Partner AG).

4.8 Structural façade sandwich panels

VIP integrated in some kind of protective layers has been proposed to reduce the risk of damages to the VIP during construction and service life. There are four main concepts developed: panels with an exterior protective layer, panels with an interior layer, an edge spacer construction and a sandwiched panel. The protection from mechanical damages is best for the edge spacer construction and the sandwiched panels. It is the resistance towards shear stresses that is the main difference between the two concepts, the sandwich panel acts as a composite system of three plates while the edge spacer acts as a single plate with a frame of columns. This difference will cause larger deformations in the edge spacer compared to the sandwich panel for the same load (Tenpierik et al., 2009).

Three main types of sandwich panels have been investigated: structural sandwich panel, panel with stainless steel casing and panels using membrane action. The panels can be evaluated according to their thermal resistance, fragility, complexity and practical usability. Development of a façade panel was done in three steps and finally a panel which was 1200x3600 mm^2 and had a U-value of 0.15 W/(m^{2}K) was proposed. The thickness of the panel was 49.5 mm which gave an average thermal conductivity of 0.007 W/(m·K) whereof 40 mm was the VIP. Stainless steel was used to encapsulate the panel and mechanical fasteners were used to stabilize it. Main advantages are the slimness, high thermal performance and robustness (Tenpierik et al., 2009).

At the Royal Institute of Technology, KTH, in Stockholm, research has been focused on the possibilities of using VIP in prefabricated building systems; special interest was focused on the use of VIP in precast concrete. The VIP should be produced in atmospheric conditions and evacuated through a valve. The more robust VIP might consist of metal plates which are connected with a thin foil at the edges (Gudmundsson, 2009).

Prefabricated sandwich elements with VIP were used in a building located in Neumarkt in der Oberpfalz in Germany. The three storey building was constructed in 2005 to demonstrate different solutions for prefabricated construction elements with integrated VIP, see Figure 4.15.

Figure 4.15 Prefabricated structural elements were used in a building with 50 mm VIP integrated in various parts of the building envelope (Photo: Variotec GmbH & Co. KG).

The average U-value of the building envelope was 0.15 W/(m^2·K) which was possible due to the 50 mm thick VIP that were integrated in the building. The basement walls, parts of the exterior walls and the ceilings were made of concrete and the remaining exterior walls and roof were made of wood. The foundation slab had a 50 mm thick VIP below the concrete slab, separated from the ground by a layer of gravel and a sealing layer. Three different wall types were used in the building where the concrete wall had a total thickness of 330 mm and a U-value of 0.11 W/(m^2·K) below ground and 270 mm and 0.12 W/(m^2·K) above ground. The wooden wall had a 33 mm wooden panel on the exterior, followed by 51 mm VIP, 94 mm wood and 15 mm plaster board on the interior which gave an U-value of 0.12 W/(m^2·K). The building was monitored in a research project where the temperatures showed that the dew point was on the safe side on two measured locations. The moisture sensors in one of the prefabricated elements showed that the moisture level was stable (BINE Informationsdienst, 2007)

4.9 Attic hatches and stairs

Wooden attic stairs in US residential buildings are usually lacking proper thermal insulation. When the potential market for VIP for this application was investigated in 2002, it was found that around 1.9 km^2 VIP could be installed. However, the additional costs for using VIP were a fact that prevented a large scale implementation of VIP in the attic stair assemblies. Depending on the source of heating fuel, the payback period varied between 5 and 30 years for the VIP stair assembly (NAHB Research Center, 2002).

4.10 Roof and terrace insulation

When designing terraces on the roof of a building, architects and engineers struggle to get an even transition between the indoor and outdoor floor levels. This is a hard task since the outdoor floor requires additional thermal insulation underneath the floor to decrease the heat transfer through the roof. With VIP it is possible to make an even transition between the floors in the building and on the terrace. If VIP is to be used in terrace floor insulation, additional protection layers above and below the panels are necessary to distribute the loads. The protective layers can be polyurethane foam, together with a load-bearing slab underneath the floor. To secure enough moisture sealing on top of the panels, they must be covered with a double sealant layer (Willems and Schild, 2005).

An existing roof in Switzerland was insulated with 10 mm VIP covered by a protective layer, bituminous water barrier and gravel Figure 4.16. Brunner and Simmler (2008) monitored the aging of the panels during two years and measured the temperature and relative humidity in the construction during three years. The measurements showed that the panels were exposed to moisture that penetrated the water barrier leading to condensation below the VIP. The aging of the panels was found to follow the data derived in laboratory with 80% relative humidity and various temperatures. The thermal conductivity of the panels after 25 years of use was expected to increase with 2.9 mW/(m·K) to around 7.4 mW/(m·K) (Brunner and Simmler, 2008).

Figure 4.16 A flat roof equiped with VIP covered by a water repellent layer was monitored during two years and the results were compared to laboratory aging data.

There is a thermal bridge effect caused by the connection of the wall and floor. Ghazi Wakili et al. (2005) investigated three different designs of the wall to floor connection with a guttering in the floor and their effects on the linear thermal transmittance coefficient. The case with the highest linear thermal transmittance was when a vertical aluminum sheet was attached to the door which increased the transmittance from 0.12 to 0.57 W/(m·K). The transmittance decreased to 0.11 W/(m·K) without the guttering (Ghazi Wakili et al., 2005). The large difference caused by the design of the attachment show the importance of studying several options to choose the one with the smallest thermal bridges since these can reduce the benefits of using VIP. Figure 4.17 shows a number of flat and pitched roofs insulated with VIP.

Figure 4.17 Various flat and pitched roofs insulated with VIP (Photo: Neofas AG).

Most often there are no requirements on keeping the construction height down for a pitched roof. In ventilated roofs careful design is needed to avoid thermal bridges. It is possible to use the more rigid vacuum insulation sandwich (VIS) as rafter insulation, preferably in prefabricated roofs (Willems and Schild, 2005).

4.11 Saunas

Saunas placed indoor require thick insulation layers. With vacuum insulation panels it would be possible to make the construction much slimmer. The extreme temperature difference increases the ageing of the VIP and also the moisture from the sauna has to be taken into account.

5 Conclusions

VIP has been used in various parts of the building envelope where the requirements on the thermal resistance are high or where the construction thickness is limited. The major challenges have been how to reduce the influence of the thermal bridge created by the metalized multi-layered polymer film around the VIP and how the VIP should be attached to the construction. The durability of the VIP is dependent on a well thought out design where the VIP is protected both during the construction phase and during the service life.

Another issue is the cost of the VIP which is dependent on the core material. The prizes could be reduced if a cheaper core material is used in the VIP. With a high additional income for the space saved using VIP compared to EPS decreases the PBP for VIP which can be shorter than for EPS.

VIP could be used in new buildings, both in light-weight timber frame walls and in heavy concrete walls. In old buildings, VIP could be used on the exterior or interior of the existing wall. So far, the most common wall application with VIP is on the exterior of the existing wall. It is also possible to integrate the VIP in a structural sandwich panel, e.g. made of concrete, to increase the protection of the VIP.

Accelerated ageing experiments have shown that VIP in roof constructions could be expected to have a service life of at least 25 years. In case the VIP is punctured the thermal conductivity increases fivefold, but is still half the thermal conductivity of mineral wool. A way to protect the VIP from damages is by integrating it in boards of EPS on all sides. This measure increases the thickness of the insulation layer, but with a decreased risk of damages to the VIP.

Despite the obstacles which have to be overcome to use VIP in building applications, it is an interesting component that may play an important role on the path to reduce the energy use for heating of buildings. In the literature it is recommended to integrate the VIP in a way that they are easy to exchange after their service life has expired. By doing so and by educating the builder and designer in the special considerations when working with VIP the energy use for heating in the existing building stock could be reduced.

6 References

Alam, M., Singh, H., and Limbachiya, M. C. (2011). Vacuum Insulation Panels (VIPs) for building construction industry - A review of the contemporary developments and future directions. *Applied Energy, 88*(11), 3592–3602.

Bauphysik. (2011). Aktuell. *Bauphysik, 33*(1), 73.

Binz, A., Moosmann, A., Steinke, G., Schonhardt, U., Fregnan, F., Simmler, H., Brunner, S., Ghazi, K., Bundi, R., Heinemann, U., Schwab, H., Cauberg, J. J. M., Tenpierik, M. J., Jóhannesson, G. A., Thorsell, T. I., Erb, M., and Nussbaumer, B. (2005). *Vacuum Insulation in the Building Sector. Systems and Applications (Subtask B)*: IEA/ECBCS Annex 39 High Performance Thermal Insulation (HiPTI).

BINE Informationsdienst. (2007). Vacuum-insulated prefabricated elements in construction. *Projektinfo, 09*(07).

Binz, A. and Steinke, G. (2006). Fassadendämmung mit Vakuum. *applica, 113*(6), 22-30.

Boverket. (2010). *Energi i bebyggelsen - tekniska egenskaper och beräkningar - resultat från projektet BETSI*. Karlskrona, Sweden: Boverket.

Boverket. (2011). *Regelsamling för byggande, BBR 2012*. Karlskrona, Sweden: Boverket.

Brunner, S. and Simmler, H. (2008). In situ performance assessment of vacuum insulation panels in a flat roof construction. *Vacuum, 82*(7), 700-707.

European Commission. (2008). *Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions - 20 20 by 2020 - Europe's climate change opportunity*. Retrieved from http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:52008DC0030:EN:HTML:NOT.

Fricke, J., Heinemann, U., and Ebert, H. P. (2008). Vacuum insulation panels - From research to market. *Vacuum, 82*(7), 680-690.

Ghazi Wakili, K., Bundi, R., and Binder, B. (2004). Effective thermal conductivity of vacuum insulation panels. *Building Research and Information, 32*(4), 293-299.

Ghazi Wakili, K., Nussbaumer, T., and Bundi, R. (2005). Thermal performance of VIP assemblies in building constructions. *Proceedings of the 7th International Vacuum Insulation Symposium*, September 28-29, 2005, Duebendorf/Zurich, Switzerland. pp. 131-138.

Ghazi Wakili, K., Stahl, T., and Brunner, S. (2011). Effective thermal conductivity of a staggered double layer of vacuum insulation panels. *Energy and Buildings, 43*(6), 1241-1246.

Grynning, S., Baetens, R., Jelle, B., Gustavsen, A., Uvsløkk, S., and Meløysund, V. (2009). *Vakuumisolasjonspaneler for bruk i bygninger – Egenskaper, krav og muligheter [Vacuum insulation panels for building applications: Properties, requirements and possibilities]* (Project number: B22479.18 Report ISSN 1504-6958 ISBN 9788253610504). Oslo: SINTEF Byggforsk.

Gudmundsson, K. (2009). A Parametric Study of a Metal Sandwich VIP. *Proceedings of the 9th International Vacuum Insulation Symposium*, September 18-19, 2009, London, UK.

Haavi, T., Jelle, B., Gustavsen, A., Uvsløkk, S., and Baetens, R. (2010). Vacuum Insulation Panels in Wood Frame Wall Constructions - Hot Box Measurements and Numerical Simulations. *Proceedings of the 2nd Biennial International Conference on Building Enclosure Science and Technology*, April 12-14, 2010, Portland, USA.

Heinemann, U. and Kastner, R. (2010). *VIP-PROVE Ergebnisse der wissenschaftlichen Begleitforschung. Project Final Report ZAE 2-1210-11*. Würzburg, Germany: Bayerisches Zentrum für Angewandte Energieforschung e.V. ZAE Bayern.

Jasim, S. (2010). VIP i portgångar. Internal meeting, September 28, 2010. Gothenburg, Sweden: Göteborgs Egnahems AB.

Johansson, P. (2012). *Retrofitting of old Exterior Wall with Vacuum Insulation Panels: Meaurements of Thermal Properties, Moisture Performance and Practical Considerations (Lic. Thesis)*. Gothenburg, Sweden: Chalmers University of Technology, Department of Civil and Environmental Engineering.

Korjenic, A. and Dreyer, J. (2003). Untersuchungen zur thermisch-hygrischen Eignung von Vakuumdaemmplatten zur Sanierung von Gebaeuden der Wiener Gruenderzeit [Investigations thermal-hygral suitability of vacuum insulation panels for reinstatement of buildings from the 19th century in Vienna]. *Bauphysik, 25*(6), 344-349.

Kubina, L. (2010). Etics with Integrated Vacuum Insulation Panels. *Proceedings of the International Conference Central Europe towards Sustainable Building CESB*, June 30-July 2, 2010, Prague, Czech Republic.

Kubina, L. (2011). LockPlate System ETICS with Integrated VIP - Experience from Building Practice. *Proceedings of the 10th International Vacuum Insulation Symposium*, September 15-16, 2011, Ottawa, Canada.

Künzel, H. (1998). Effect of interior and exterior insulation on the hygrothermal behaviour of exposed walls. *Materials and Structures, 31*(2), 99-103.

Microtherm. (2009). SlimVac Safety Data Sheet. Sint-Niklaas, Belgium: Microtherm N V.

NAHB Research Center Inc. (2002). *Accelerating the Adoption of Vacuum Insulation Technology in Home Construction, Renovation, and Remodeling, Project Final Report*. Upper Marlboro, MD: Prepared for U.S. Department of Housing and Urban Development, Office of Policy Development and Research.

Nussbaumer, T., Bundi, R., Tanner, C., and Muehlebach, H. (2005). Thermal analysis of a wooden door system with integrated vacuum insulation panels. *Energy and Buildings, 37*(11), 1107-1113.

Pool, M. (2005). Neubau eines Wohn- und Geschaeftshauses mit Ultra-Niedrigenergiehaus-Standard unter Verwendung von Vakuumisolationspaneelen [Construction of a new residential and business building in line with the ultra-low-energy house standard using vacuum insulation panels]. *Bauphysik, 27*(6), 363-368.

Porextherm. (2010). Vacupor Safety Data Sheet (91/155/EEC). Kempten, Germany: Porextherm Dämmstoff GmbH.

Pramsten, E. and Hedlund, M. (2009). *Ekonomisk analys av vakuumisoleringspaneler i ytterväggar*. Stockholm: Skolan för arkitektur och samhällsbyggnad, Kungliga Tekniska högskolan.

Schonhardt, U., Binz, A., Wohler, M., and Dott, R. (2003). *Ökobilanz eines Vakuum-Isolations-Paneels (VIP)*. Muttenz, Switzerland: Institut für Energie, Fachhochschule beider Basel.

Schwab, H., Stark, C., Wachtel, J., Ebert, H.-P., and Fricke, J. (2005). Thermal Bridges in Vacuum-insulated Building Façades. *Journal of Thermal Envelope & Building Science, 28*(4), 345-355.

Schwab, H., Wachtel, J., Scheuerpflug, H., Stark, C., Heineman, U., Ebert, H.-P., and Fricke, J. (2004). *Entwicklung und Anwendung von evakuierten höchsteffizienten Dämmungen für Gebäude (Vakuumdämmung für Gebäude). Project Final Report ZAE 2-1203-21*. Würzburg, Germany: Bayerisches Zentrum für Angewandte Energieforschung e.V. ZAE Bayern.

Simmler, H., Brunner, S., Heinemann, U., Schwab, H., Kumaran, K., Mukhopadhyaya, P., Quénard, D., Sallée, H., Noller, K., Kücükpinar-Niarchos, E., Stramm, C., Tenpierik, M. J., Cauberg, J. J. M., and Erb, M. (2005). *Vacuum Insulation Panels. Study on VIP-components and Panels for Service Life Prediction of VIP in Building Applications (Subtask A)*: IEA/ECBCS Annex 39 High Performance Thermal Insulation (HiPTI).

Tenpierik, M., Van Timmeren, A., Van Der Spoel, W., and Cauberg, H. (2009). Vacuum Insulation Panels and Architecture: Cradle-to-cradle Fadace Systems. *Proceedings of the 3rd International Conference on Smart and Sustainable Built Environments (SASBE 2009)*, June 15-19, 2009, Delft, The Netherlands.

Tenpierik, M. J., Cauberg, J. J. M., and Thorsell, T. I. (2007). Integrating vacuum insulation panels in building constructions: an integral perspective. *Construction Innovation, 7*(1), 38-53.

Thorsell, T. I. (2006a). Edge loss minimization in vacuum insulation panels. *Research in Building Physics and Building Engineering*, 251-256.

Thorsell, T. I. (2006b). *Vacuum Insulation in Buildings - Means to Prolong the Service Life*. Stockholm: Division of Building Technology, Department of Civil and Architectural Engineering, Royal Institute of Technology.

Willems, W. and Schild, K. (2005). Vacuum Insulated Constructions in Detail. *Proceedings of the 7th Symposium on Building Physics in the Nordic Countries*, June 13-15, 2005, Reykjavík, Iceland. pp. 928-936.

Viridén, K. (2007). Retrofit Buildings close to Passive House Standard. *Proceedings of the International Conference Central Europe towards Sustainable Building CESB*, September 24-26, 2007, Prague, Czech Republic. pp. 411-415.

Viridén, K., Ammann, T., and Büsser, A. (2004). Herausforderung Gebäudehülle bei Passivhäusern im Umbau Erfahrungen aus realisierten P+D-Projekten.

Proceedings of the 13. Schweizerisches Status-Seminar 2004 "Energie- und Umweltforschung im Bauwesen", September 9-10, 2004, Zürich, Switzerland.

Zwerger, M. and Klein, H. (2005). Integration of VIP's into external wall insulation systems. *Proceedings of the 7th International Vacuum Insulation Symposium*, September 28-29, 2005, Duebendorf/Zurich, Switzerland. pp. 173-179.