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REVIEW PAPER

Vacuum insulated panels for sustainable buildings: a review of research and applications

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SUMMARY

New research has identified vacuum insulation panels (VIPs) as highly efficient insulators for use in building construction. They are reported to be several times more effective than conventional materials of a similar thickness in terms of thermal conductivity. Because of their smaller space requirement, VIPs maximize the internal usage area of buildings and so reduce the cost of construction. There are however some obstacles that have hindered the application of VIPs, notably their high cost, susceptibility to perforation and the long-term water and gas effects that worsen their performance. This paper reviews the contemporary research on VIP as a state-of-the-art material for building insulation. The main components and physical principles of VIP performance are discussed. Finally, the review of VIPs available on the market and their performance is provided. © 2013 The Authors. International Journal of Energy Research published by John Wiley & Sons, Ltd.

KEY WORDS
thermal insulation; vacuum insulation panel (VIP); sustainable buildings

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1. INTRODUCTION

In recent years, many developed countries have introduced programmes directed at decreasing energy consumption and improving carbon performance of buildings [1–3]. Development and introduction of energy-efficient materials to the market play a significant role in achieving these goals, because they help decrease building heat losses to the environment, thus reducing the necessary amount of energy used to support the desired heat comfort levels.

Traditional insulation materials, such as cork, mineral wool, cellulose, polystyrene or polyurethane (PUR), are capable of preserving energy to certain extents. Research also indicates use of nontraditional materials for insulation, such as wool-hemp, date palm fibre and phase-change materials [4–6]. However, supporting the required thermal levels in buildings often require the increased thickness of these materials, which is not always feasible with respect to material economy, transportation and use. Recent developments in the physics of construction materials have led to the creation of new building insulation materials that provide lower thermal conductivity rates than the traditional ones. Contemporary research mentions several types of such materials: gas-filled panels (GFPs), polymer skins, aerogels and vacuum insulation panels (VIPs).

Gas-filled panels use a combination of thin polymer films and low-conductivity gases to achieve lower thermal conductivity rates. Visually, GFPs are hermetic plastic bags of different shapes and sizes that are filled with an inert gas having low thermal conductivity, such as argon, xenon or krypton. Inside the outer barrier of GFP is a baffle – a cellular structure that suppresses gas convection and radiation. GFPs, as thermal insulators, have been actively studied in past two decades [7–10]. So far, however, experimental thermal conductivities achieved from GFP (40 mW/mK) have only been comparative with those of the traditional materials, although theoretical investigations predicted values as low as 10 mW/mK [11].

Polymer skins are large films, most commonly ethylene tetrafluoroethylene, that are parts of a pneumatic cushion

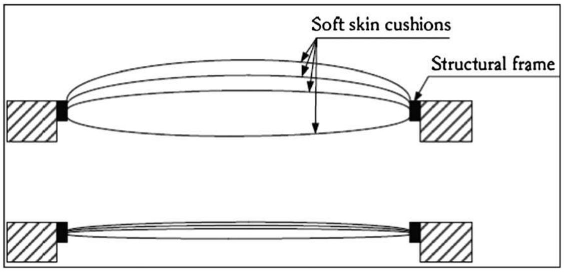

Figure 1. Polymer skins in action [3].

assembly that inflates or deflates the space between the films to increase or decrease the thermal resistance [11]. As such, polymer skins are dynamic thermal insulators that can be adjusted on the basis of the thermal conductivity requirements. Figure 1 schematically shows how the polymer skins are used. They are often designed as a part of a pneumatic cushion assembly, with skins held between the structural frames. The upper picture demonstrates the cushions in an inflated state, and the lower picture in a deflated state. Cushions in an inflated state increase the thermal resistance, which is useful in the cold weather. Polymer skins have been successfully applied in large construction projects, including the Allianz Football Arena in Munich, Germany, and the Beijing National Aquatic Centre in China. However, studies on applicability of polymer skins at smaller building levels are not available [3].

Aerogels are synthetic porous materials derived from drying gels under critical conditions. Gas replaces liquid components of gel, which results in a highly porous structure (over 85% of the total volume) with extremely small pore diameters (5–100 nm) (Figure 2) [12]. This structure not only makes aerogels one of the lightest known solid materials but also limits the three major mechanisms of thermal transport, which results in very low thermal conductivity rates [3]. Aerogels have been relatively popular among the researchers of thermal insulation materials [13–16]. Commercially available aerogels have the thermal conductivity of 13–14 mW/mK at ambient pressures; although under pressures of 50 mbars and with the use of carbon to limit radiative transfer, it is possible to achieve thermal conductivities as low as 4 mW/mK [17,18].

Although aerogels are very promising materials for thermal insulation in buildings, their commercial applications are limited because of extremely high cost of production (€214*/m^2 on average as reported by [19]) and fragility because of low tensile strength.

Vacuum insulation panels have been proposed by a number of researchers as the most promising new age insulation solution for sustainable building [1–3,18,20]. VIPs have a lower *k*-value than both conventional and state-of-the-art insulation materials, meaning that wall construction can be thinner. One analysis indicated that a traditional mineral wool or PUR foam insulation board with a thickness of 185 is equivalent to a VIP only 20 mm thick [1]. There is potential for mass-scale application of VIPs in buildings because of their low *k*-value, and hence, the small wall thickness required. A high barrier laminate covers the microporous core of the VIP, and the vacuum inside the core minimizes thermal conductivity. However, despite the growing number of studies on these potentially auspicious materials, the research on their application for buildings remains somewhat disorganized and localized. The main contributions of this paper to the state-of-the-art insulation systems research for buildings include the following: (i) systematisation and organization of information regarding VIPs as an insulation material for sustainable buildings; (ii) identification of the most perspective VIP components; (iii) practical review of the current market for VIPs in buildings; and (iv) providing an outlook for VIP potential within the new energy initiatives in the European Union.

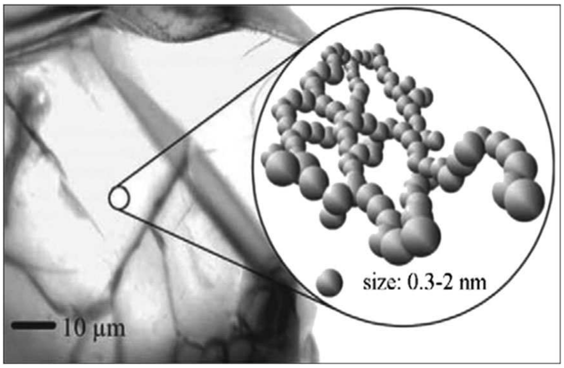

Figure 2. Aerogel under electronic microscope [12].

2. VACUUM INSULATION PANELS

2.1. Vacuum insulation panel overview

Vacuum insulation panels represent an evacuated, open-porous material that is enveloped into a multilayer film. A special structure of VIP makes it the best material in terms of thermal conductivity in pristine condition: 3–4 mW/mK [18]. Figure 3 demonstrates a VIP with its key components and shows how it compares to a traditional insulation material based on thermal conductivity [21,22].

In recent years, research interest in VIPs increased, as the studies covered such topics as thermal conductivity and gas pressure in VIPs [23–26], analytical and optimisation models [27,28], application of various materials in VIP manufacturing [1,29–32] and applications of VIPs in building construction became growing areas of research [3,20,33,34].

As any other material for thermal insulation of buildings on the market, VIPs have its advantages and disadvantages. On the positive side, they have the lowest thermal conductivity rate, and they allow for significant space economy. On the negative side, they are relatively fragile, their performance significantly decreases with time and they are not adaptable for construction sites without

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[*] All prices in the paper are presented in euros. Whenever cited sources used other currencies, they were converted to euros based on the currency rates established on 24 June 2013 (£1 = €1.18; $1 = €0.76)

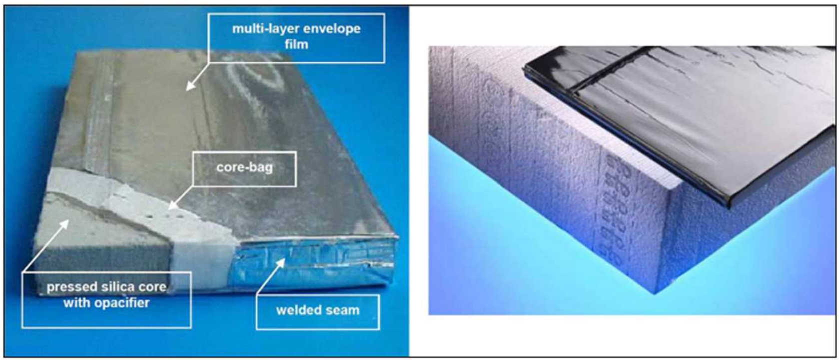

Figure 3. Visual presentation of a vacuum insulation panel (left) and a comparative material thickness with a traditional insulation (extruded polystyrene) achieving the same thermal conductivity level (right) [21,22].

losses in thermal conductivity. VIPs are also relatively expensive to produce, costing €168/m^2 on average [19,20]. Table I compares VIPs with the traditional and other state-of-the-art insulation materials.

Despite the current difficulties that VIPs are facing in becoming a thermal building insulation material of choice, they represent one the most promising thermal insulation technologies on the market today. Even if it will not be possible to create a market for them as for a standalone material for building insulation, it is likely that using VIPs in combination with other materials will be beneficial. Theoretical and practical research on VIPs is also likely to contribute to development of the optimal thermal insulation solutions for the future.

2.2. The scheme of vacuum insulation panel work

A typical VIP represents an insulation system that includes an inner core material, barrier envelope (film), a getter and/or desiccant and a heat seal (Figure 4).

Core materials serve as the main filler of VIPs. Barrier films serve as protectors from environmental and physical damages resulting from the panel handling. Getters and/or desiccant adsorb water vapours and other gases that may break through the barriers. As a system, a VIP's performance depends on the performance of each of these components. This section continues with the discussion of various materials used

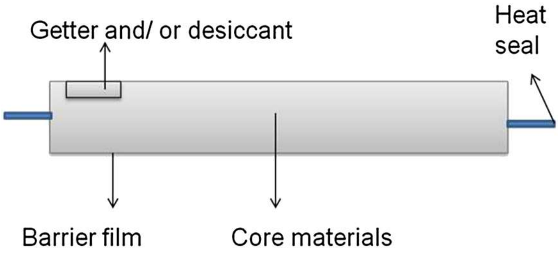

Figure 4. The structure of a vacuum insulation panel.

Table I. Comparison of vacuum insulation panel to the traditional and other state-of-the-art thermal insulation materials.

Material	Thermal conductivity (mW/mK)	Cutting to adapt for construction	Resistance – fire, water and chemicals	Resistance – physical damage	Performance if perforated	Cost per thermal resistance	Environmental impact of production and use
Vacuum insulation panel	4–8	No	Low	Low	Worse	High	Moderate
Traditional materials							
Cellulose	40–50	Yes	Low	Low	Same	Low	Low
Fibreglass	30–40	Yes	High	High	Same	Low	Moderate
Expanded polystyrene	30–40	Yes	Low	Moderate	Same	Low	High
Extruded polystyrene	30–32	Yes	Moderate	Moderate	Same	High	High
Polyurethane	20–30	Yes	Moderate	High	Same	High	High
State-of-the-art materials							
Gas-filled panel	10–40	No	Low	Low	Worse	High	Moderate
Aerogels	13–14	Yes	Moderate	Low	Same	High	Moderate

Sources: [6,19,20]

for inner core, barriers and getters in VIPs and the physical processes that determine performance of VIPs.

2.3. Core materials for vacuum insulation panels

The major function of core materials in VIPs is to support the required vacuum level to ensure low thermal conductivity of a panel. To meet this objective effectively, a core material has to possess a number of specific characteristics. Firstly, as was discussed previously, core materials with smaller pores are preferable, because they allow to decrease the gaseous conductivity to insignificant levels even at normal pressure conditions. Secondly, core materials with open cell structures are preferable because they allow evacuation of gas [20]. Thirdly, specific geometry of skeleton is required of core materials to maintain small contact points between the structures, consequently minimizing conductive heat transfer [3]. Finally, core materials have to ensure the lowest possible radiation transfer between the panels themselves [3,20]. Some of the most common types of core materials used for VIPs are briefly discussed in the succeeding texts and compared on the basis of these requirements.

2.3.1. Fumed silica

Fumed silica is the most commonly used core material for VIPs [3]. It is a porous material produced in a flame where silicon chloride ($SiCl_2$) is transformed into silicon dioxide (SiO_2) aggregates (Figure 5).

Fumed silica is a stable material that endures pressures of up to 10 t per square metre, which is required for evacuation of the core [3]. At the same time, this material has a relatively low density of 150–200 kg/m^3 and surface area of 50–600 m^2/g, which allow it to achieve a remarkably low thermal conductivity levels of 3–6 mW/mK at pressures in the range of $20–100 \times 10^{-3}$ bar [2,35]. Finally, fumed silica material achieves low radiative heat conductivity of 0.001–0.004 W/mK at 1 mbar gas pressure levels depending on temperature [20].

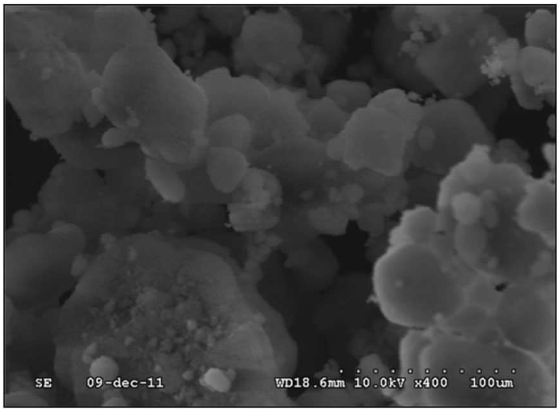

Figure 5. Fumed silica under electronic microscope [3].

2.3.2. Silica aerogel

Silica aerogels are the aerogels derived from silicate. Like other aerogels, this material is notable for its extremely low density (up to 3 kg/m^3), high internal surface area (600–1000 m^2/g) and small pore size (1–100 nm) [20]. This allows silica aerogels to achieve very low thermal conductivity rates: 1–3 mW/mK under evacuated and opacified conditions and certain temperatures and up to 4 mW/mK under 50 mbar pressure or less, whereas values of 13.5 mW/mK are possible at regular pressures [36]. Silica aerogels are also nonreactive and nonflammable materials, and they have the tendency to absorb infrared radiation. The major disadvantage of these materials for VIP applications remain relatively the high cost of production: with €25/m^2 and €3000/m^3, they cost nearly 10 times more than the traditional insulation materials of the same thermal resistance [36]. Further, silica aerogels, like other aerogels, are also very fragile because of poor tensile strength.

2.3.3. Expanded polystyrene and polyurethane foams

Open cell expanded polystyrene (EPS) and PUR foams represent another core materials applied in VIPs [29]. The low cost, small pore size (30–250 nm) and low density (60–100 kg/m^3) of these foams make them suitable for use in VIPs [29]. PUR foams are nearly three times more expensive than EPS foams (€7.10 vs €2.81/m^2), but they offer higher thermal resistance [20]. However, to maintain the acceptable low thermal conductivity of both PUR and EPS foams as core materials, relatively low gas pressures are required (10^{-4} bar and lower). As [37] showed, at this pressure, the total thermal conductivity of PUR foams with 100 nm pore size can reach as low as 7.8 mW/mK. However, pressures that low are extremely difficult to maintain over the life time of a VIP. The same study demonstrated that even if the gaseous thermal conductivity can be eliminated, EPS and PUR foams at densities of 70 kg/m^3 will have total thermal conductivities of 5.7–9.7 mW/mK [37], which are higher than the values demonstrated by fumed silica.

2.3.4. Fibreglass

As a core material for VIP, fibreglass has advantages of high temperature applications, which are possible because of its high thermal stability (over 1000 °C) and density. The internal structure of fibreglass (Figure 6) ensures small contacts between the particles, which leads to low conductive heat transfer rates even when the material is compressed. Average cost of fibreglass is about €2.81/m^2 [20]. [37] experimentally demonstrated the solid thermal conductivity and the radiative conductivity of 2.1 and 0.7 mW/mK, respectively, for fibreglass of density 250 kg/m^3 and diameter of fibre 0.5–0.7 nm at 300 K. [37] also showed that the theoretical total thermal conductivity of 3.6 mW/mK is possible; although, as with the foams, it would require low pressure at 0.1×10^{-3} bar. Therefore, fibreglass as a core material for VIP has the same disadvantage in terms of long-term applications.

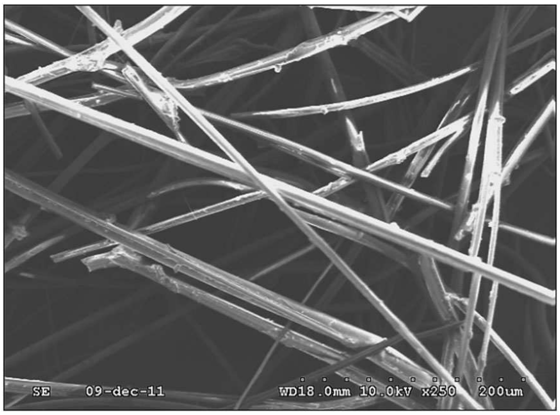

Figure 6. Fibreglass under electronic microscope [3].

2.3.5. Staggered beam

Kawaguchi and Nagai have proposed by using the staggered beam structure (Figure 7) in vacuum insulation for reducing the solid thermal conduction, thus decreasing the total conduction value [37]. The structure makes the use of parallel beams having rectangular cross-sections to make the thermal conduction path as long as possible.

[37] experimentally demonstrated that a polycarbonate staggered beam structure allows to achieve very low solid thermal conductivity of about 0.9 mW/mK; however, because of large pore size, the gaseous conductivity and the radiative conductivity of the staggered beam is higher than that of the other VIP core materials presented previously.

2.3.6. Composite materials

National Research Council Institute for Research in Construction researchers have developed an alternative type of core material, which they refer to as low cost. Thin slices of fibre insulation board and fine insulating powdered material are layered together in a composite material [38]. Figure 8 shows how the movement of powders inside the fibre structures results in smaller pore sizes in the fibre-powder composite structure.

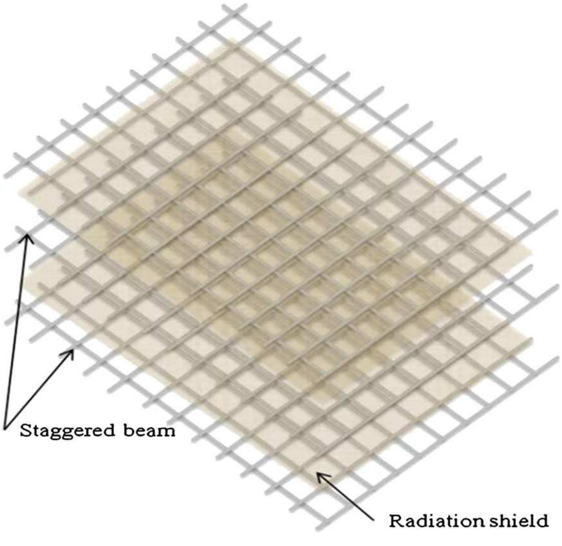

Figure 7. Multilayered staggered beam with radiation shields redrawn from [37].

Although the total thermal conductivity of the composite materials has been found comparative with that of precipitated silica for pressure ranges $0.25–100 \times 10^{-3}$ bar [38], there is still little research available to report on the suitability of using these materials for VIP cores.

2.4. The envelope

2.4.1. Function and materials

Envelopes preserve vacuum in the VIP by creating barriers for water vapour and other gases entering the panels and protect the panel from the damages caused by the environment and handling procedures. VIP envelopes usually consist of several layers: the outer protective layer protects the panel from handling and environmental stresses, the barrier layer protects the core material from water vapour and gas transmissions and the inner layer seals the core material of the panel [2]. The envelope is formed by joining these layers with an adhesive, most commonly, PUR [2]. Double envelopes that use additional porous material between the envelopes have been investigated [32], although their application may not be feasible because of the greater panel thickness and additional costs of production.

Vacuum insulation panel envelope layers are made of films, which are generally 100–200 nm thin [20]. Plastics and metal foils are common materials used for the films. Metal foils, such as aluminium, have advantage of sturdiness and extremely low gas and water permeating rates; however, their disadvantage is high thermal conductivity rates. It is typical, therefore, for VIP manufacturers to use plastics and metals in combination by producing metallized plastics and multilayer laminated foils. Three types of multilayer films are available on the market today: (i) metal foils, which consist of an outer polyethylene terephthalate (PET) layer, aluminium barrier layer and a PE inner layer; (ii) metallized films consisting of up to three layers of aluminium-coated PET for the outer and barrier layers and a PE sealing layer; and (iii) polymer films based on nylon, polyester or polypropylene. However, the application of the polymer films on their own is limited because of higher gas and vapour permeability rates. Figure 9 demonstrates some of the most commonly used films for VIP.

Because it is common to use a combination of film types in VIP envelopes, there is no specific envelope permeance rate. Instead, two empirical values are used to determine envelope material properties: the gas transmission rate (GTR) and the water vapour transmission rate (WVTR).

2.4.2. Gas transmission rate

Gas transmission rate can be defined as the total volume of gas that passes through a unit area of material per unit of

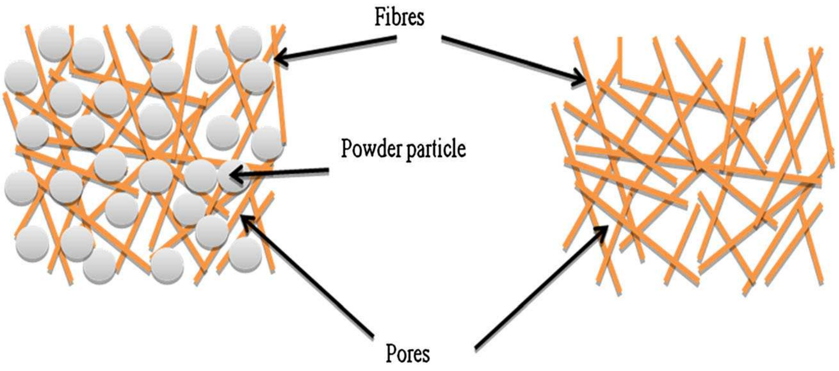

Figure 8. Fibre pore structures packed with powder particles (redrawn from [38]).

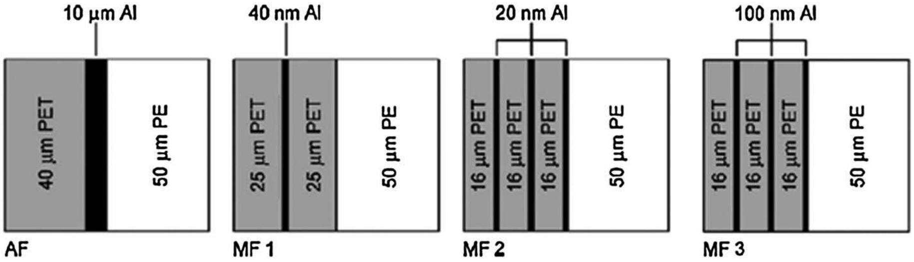

Figure 9. Some typical films for vacuum insulation panel: a metal film (AF), a single layer metallized film (MF1) and three layer metallized films (MF2, MF3) [20].

time under unit partial pressure difference. [20] Measured GTR is measured as follows [39]:

$$\mathrm{GTR_{tot}} = \mathrm{GTR_A}(\mathrm{T}, \varphi) \times \mathrm{A} + \mathrm{GTR_L}(\mathrm{T}, \varphi) \times \mathrm{L} \qquad (1)$$

where

$\mathrm{GTR_{tot}}$	is the total gas transmission rate of material;
$\mathrm{GTR_A}$	is the GTR of the surface of the laminate cover per panel area;
A	is the total area of the panes, including front and back sides;
$\mathrm{GTR_L}$	is the length-related GTR along the panel's circumference;
L	is the panel circumference.

The total GTR relates to the laminate permeance through the pressure difference across laminate barrier:

$$\mathrm{Q_{totg}} = \frac{\mathrm{GTR_t}}{\Delta \mathrm{p_g}}, \qquad (2)$$

where

$\mathrm{Q_{totg}}$	is the laminate permeance;
$\Delta \mathrm{p_g}$	is the pressure difference across laminate barrier.

Using the law of mass conservation and the ideal gas equation, the relationship between the gas pressure increase and the total GTR can be written as follows:

$$\frac{\mathrm{dp_g}}{\mathrm{dt}} = \frac{\mathrm{Q_{totg}} \times \Delta \mathrm{p_g}}{\mathrm{Veff}}\left(\frac{\mathrm{Tmp0}}{\mathrm{T0}}\right) = \frac{\mathrm{GTR_t}}{\mathrm{V_{eff}}}\left(\frac{\mathrm{Tm} \times \mathrm{p_0}}{\mathrm{T_0}}\right), \qquad (3)$$

where

$\frac{\mathrm{Tm} \times \mathrm{p_0}}{\mathrm{T_0}}$	is the conversion factor from standard to measurement conditions (0–m);
V_{eff}	is the effective pore volume in the panel.

If assumed that the initial internal pressure is negligible, then pressure difference across laminate barrier would initially be equal the atmospheric pressure. Consequently, using (3), gas pressure increase over time can be defined as follows:

$$\mathrm{p(t)} = \frac{\mathrm{Q}_{air} \times \mathrm{p}_{atm}}{\mathrm{V}_{eff}}\left(\frac{\mathrm{Tm} \times \mathrm{p_0}}{\mathrm{T_0}}\right)\mathrm{t} = \frac{\mathrm{GTR}_t}{\mathrm{V}_{eff}}\left(\frac{\mathrm{Tm} \times \mathrm{p_0}}{\mathrm{T_0}}\right)\mathrm{t} \qquad (4)$$

Figure 10 shows this dependence on a graph for the envelope materials identified in Section 2.3.1. The lines marked 50 are for the panel sizes $50 \times 50 \times 1\,\mathrm{cm}^3$, and the lines marked 100 are for the panel sizes $100 \times 100 \times 2\,\mathrm{cm}^3$. This is a simplified version based on [39], which assumes the initial internal air pressure 0 bar, no getters are used and that the envelope properties do not change over time.

2.4.3. Water vapour transmission rate

Water vapour transmission rate refers to the total volume of water vapour that passes through a unit area of material per unit of time. It is measured in the following way [40,41]:

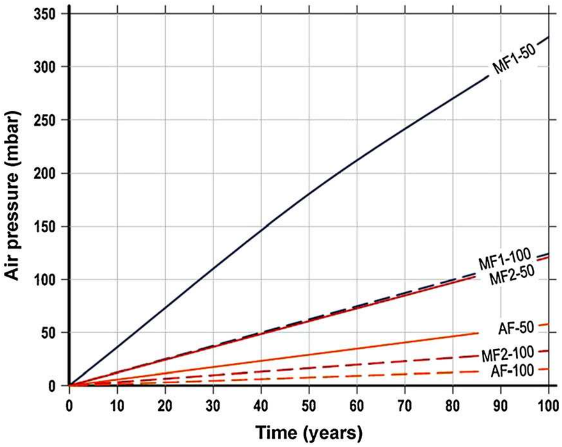

Figure 10. Increase in internal gas pressure over time for some envelope materials and panel sizes [20].

$$\mathrm{WVTR} = \frac{\mathrm{dmv}}{\mathrm{dt}} = Q_{wtot} \times \Delta p_{wv}, \tag{5}$$

where

$\frac{dmv}{dt}$	is the panel's mass increase over time;
Q_{wtot}	is the total water permeance;
Δp_{wv}	is the water vapour pressure across the film.

Applying the inverse function of sorption isotherm ($\varphi(Xw)$):

$$pw = \varphi(Xw) \times pw_{sat}(T), \tag{6}$$

where

pw	is the partial water vapour pressure;
$pw_{sat}(T)$	is the saturation of the water vapour based on temperature;
$\varphi(Xw)$	is the water vapour saturation pressure based on relative humidity level.

Then, the change in water content over time can be expressed as [40]:

$$\begin{aligned}\frac{dXw}{dt} &= \frac{Q_{wtot}}{md}(pw_{out} - pw_{in}) \\ &= \frac{Q_{wtot}}{md} \times pw_{sat} \times (\varphi_{out} - \varphi_{in}(Xw)),\end{aligned} \tag{7}$$

where

md	is the mass of VIP dry;
pw_{out} and pw_{in}	are the water vapour pressures outside and inside of VIP, respectively;
φ_{out} and φ_{in}	are the relative humidity outside and inside of the panel. respectively.

Considering the sorption isotherm linear as $Xw = k\varphi$, where *k* is the coefficient representing the degree of slope, Equation (10) can show water saturation over time as follows:

$$Xw(t) = k\varphi_{out}\left(1 - e^{-\frac{Qwt \times pw_{sat}(T)}{md^{k}}t}\right) \tag{8}$$

Figure 11 shows a graphical representation of the function for the envelope materials identified earlier in the paper. The lines marked 50 are for the panel sizes $50 \times 50 \times 1\,\mathrm{cm}^3$, and the lines marked 100 are for the panel sizes $100 \times 100 \times 2\,\mathrm{cm}^3$. This is a simplified version based on Schwab *et al.* (2005), which assumes that no getters are used and that the envelope properties do not change over time.

2.4.4. Factors affecting gas transmission test and water vapour transmission rate

As follows from Equations (4)–(11), GTR and WVTR in VIPs depend on temperature and panel size, whereas WVTR is also dependent on the factor of humidity. Figures 12 and 13 demonstrates the differences in GTR and WVTR based on panel sizes: smaller size VIPs had higher

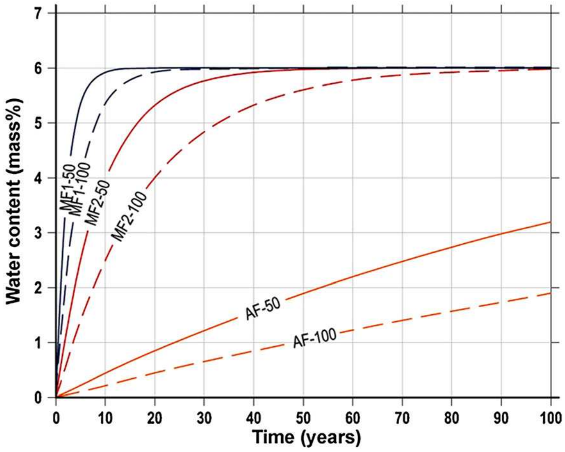

Figure 11. Increase in water content over time for some envelope materials and panel sizes [20].

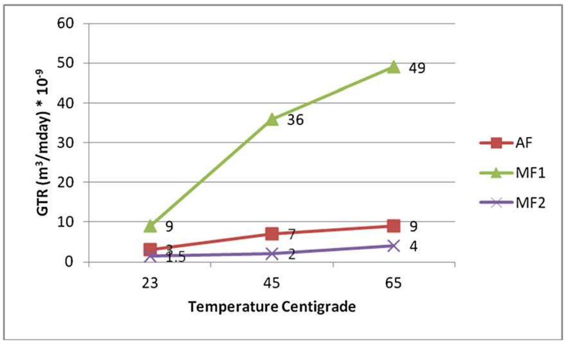

Figure 12. Vacuum insulation panel envelope films' gas transmission rate (GTR) as a function of temperature. On the basis of the empirical numbers provided by[39].

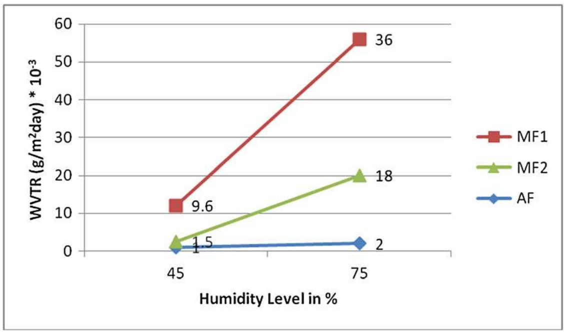

Figure 13. Vacuum insulation panel envelope films' water vapour transmission rate (WVTR) as a function of humidity. On the basis of the empirical numbers provided by[40].

degrees of both. Temperature influence on both GTR and WVTR is commonly expressed as an Arrhenius equation type [34,21]:

$$\mathrm{Q(T)} = Q(To)e^{\left(\frac{Ea}{R}\right)\left(\left(\frac{1}{To}\right)-\left(\frac{1}{T}\right)\right)}, \tag{9}$$

where
Ea is the activation energy;
R is the gas constant.

Different types of films have different levels of sensibility to temperature changes. Figure 12 shows how the film types described in the previous sections react to temperature changes in terms of GTR.

As is seen, a single layer metallized film (MF 1) is the most sensitive to temperature changes, which makes them less suitable for VIP applications. Metal foils (AF) and three layer metallized films with 20 nm aluminium coatings (MF 2) have comparable values. However, thermal conductivity of AF is higher, which makes MF 2 films the most promising multilayer material for VIP use on the basis of temperature increases.

The effect of humidity levels on WVTR were reported by [40,41] and [20]. At the fixed temperature of 25 °C, the differences between various barrier films' WVTR are demonstrated in Figure 13 for humidity levels of 45% and 75%. The graph shows that a single-layer metal foil barriers (MF 1) are, again, inferior because of higher initial level of WVTR and a stronger spike in WVTR at the increased humidity level in comparison with the three-layered metallized films (MF 2) and metal foil films (AF).

2.5. Getters and desiccants

Getters and desiccants are the chemicals added to the core materials to adsorb gases and water vapour. By doing so, they prevent the higher gas and water vapour pressures, thus decreasing the thermal conductivity of VIPs and their lifetime [2]. Silica core materials act as desiccants themselves, but other core materials require additional chemical protection. Silica gels and, sometimes, other chemical such as synthetic zeolites are added to nonsilica core materials for gas adsorption purposes [20]. For silica core materials, opacifiers, such as silicon carbide powder, black carbon, iron oxide (Fe_3O_4) and titanium dioxide (TiO_2) are added to reduce the material's radiative thermal conductivity [20].

3. MEASURING VIP PROPERTIES

3.1. Thermal conductivity

The major property of an insulation material for buildings is the thermal conductivity, which is determined as the material's thickness divided by its thermal resistance.

$$\lambda = \frac{\mathrm{L}}{\mathrm{R}} \tag{10}$$

The materials with the lowest thermal resistance are the best, because they are thinner and retain heat better. In general, thermal conductivity of a material is considered a sum of several units:

$$\lambda_{\mathrm{tot}} = \lambda_{\mathrm{s}} + \lambda_{\mathrm{g}} + \lambda_{\mathrm{r}} + \lambda_{\mathrm{c}} + \lambda_{\mathrm{coup}} + \lambda_{\mathrm{l}}, \tag{11}$$

where

λ_{T}	is the total thermal conductivity;
λ_{s}	is the thermal conductivity of the material skeleton through the atomic bonds;
λ_{g}	is the thermal conductivity accounting for gas in the material pores;
λ_{r}	is the thermal conductivity accounting for the radiation transfer between internal pore surfaces of the material;
λ_{c}	is the thermal conductivity accounting for air and moisture convection within the pores;
λ_{l}	is the thermal conductivity accounting for thermal leakage transport because of pressure differences;
λ_{coup}	is the thermal conductivity accounting for second order effects between the mentioned thermal conductivities.

However, the unique structure of VIP allows it to achieve negligible levels of the last three components, thus reducing the thermal conductivity equation to [12]:

$$\lambda_{\mathrm{tot}} = \lambda_{\mathrm{s}} + \lambda_{\mathrm{g}} + \lambda_{\mathrm{r}} \tag{12}$$

Therefore, achieving lower conductivity levels for VIPs is possible by reducing these components. Solid conductivity can be defined as a function of the core material structure, density and external pressure [2]:

$$\lambda_s = \rho^a, \quad (13)$$

where

ρ is the core material density;

a is a value of foam unity.

From Equation (13), it is clear that materials with lower density will achieve lower solid conductivities.

Gas conductivity for VIP can be measured by using the Knudsen number [2]. [37] estimated gas conductivity for VIPs at temperature 25 °C as follows:

$$\lambda g = \lambda o/(1 + 0.0032/p\Phi), \quad (14)$$

where

λo is the thermal conductivity of air at atmospheric pressure;

p is the gas pressure;

Φ is the pore width of insulation material.

As follows from Equation (14), lower pressures provide a positive influence on reducing the thermal conductivity of gas. Further, the gaseous thermal conductivity decreases with smaller pore size of insulation material [20]. This relationship is shown in Figure 14.

The final component of the VIP thermal conductivity value is radiative conductivity. As was noted previously (Section 2.5), opacifiers are commonly used in VIPs to reduce radiative conductivity of core materials. The positive results of opacifiers' applications were noted by [42], who demonstrated that at a room temperature, opacified precipitated silica has from 0.002 to 0.003 W/m/K lower conductivity than pure silica.

3.2. Ageing and service life

Time has an important effect on VIP's thermal conductivity by decreasing it because of effects of water and gas permeance into the panel. [43] proposed that the function of the total thermal conductivity change over time is as follows:

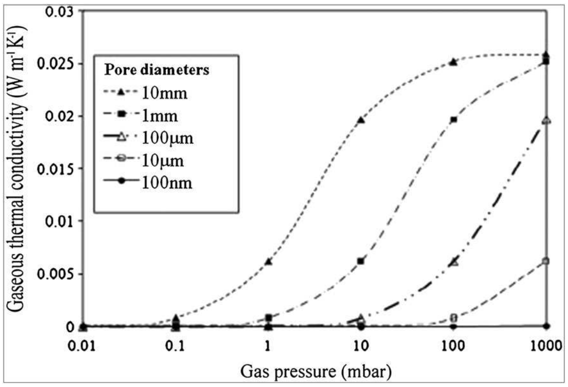

Figure 14. The gaseous thermal conductivity as a function of gas pressure and pore size of an insulation material [2].

$$\lambda_{tot}(t) = \lambda e(t) + \lambda g(t) + \lambda wv(t) + \lambda w(t), \quad (15)$$

where

$\lambda e(t)$ is the thermal conductivity of the evacuated VIP in the beginning of service;

$\lambda g(t)$ is the thermal conduction caused by GTR over time;

$\lambda wv(t)$ is the thermal conduction caused by WVTR over time;

$\lambda w(t)$ is the thermal conduction over time based on adsorbed water within the core material.

Envelopes and panel size play an important part in reducing the effects of time on thermal conductivity of VIPs. Figure 15 shows the total thermal conductivities as functions of time for the VIPs using fumed silica as the core material, aluminium (AF) and metallized (MF) envelopes for panels of two sizes: 50 × 50 × 1 and 100 × 100 × 2 cm. AF, larger size VIPs, shows slower thermal conductivity reduction over time.

Literature defines two approaches to measuring the useful life of a VIP [33]. The first approach is the one used by VIP manufacturers and incorporated into the American Standard C1484 for VIPs. This approach defines service life as a time span from the panel manufacturing to the time when the effective thermal conductivity of the panel exceeds the established limiting value:

$$\lambda eff|t = tSL = \lambda_{lim} \quad (16)$$

The second approach defines service life as a time span from the panel manufacturing to the time when the time-average thermal conductivity exceeds the established critical value. This approach takes into account the non-linear nature of ageing and can be expressed formulaically as follows:

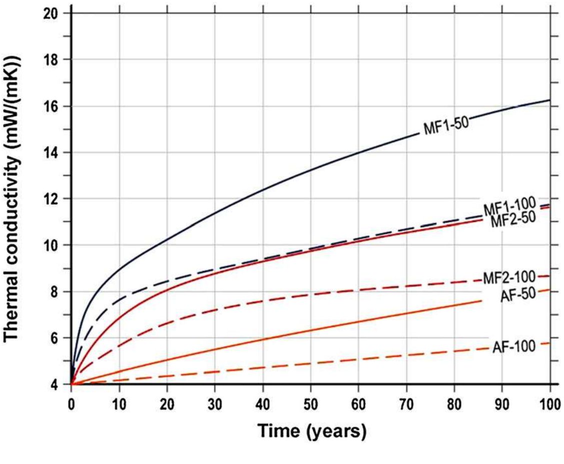

Figure 15. Vacuum insulation panel thermal conductivity as a function of time [20]. Temperature, humidity and porosity are assumed constant. Gas pressure is set at 0 bar. No getters, desiccants or pacifiers are used.

$$\lambda\text{eff}|\text{t} = \text{t}_{\text{SL}} = \lambda_{\text{Crit}} \quad \text{where} \quad \lambda\text{eff} = \frac{1}{t}\int_0^t \lambda\text{eff}(\text{t})\text{dt} \qquad (17)$$

Both approaches to VIP service life assume it as a function of several factors [2,3,20]:

- size: larger panels have longer life spans,
- manufacturing quality: higher quality panels have longer life spans,
- core materials: materials with lower pore sizes have longer life spans,
- environment and conditions of use: high moisture, humidity and temperature decrease the life span,
- use of opacifiers, getters and desiccants increases life span,
- physical handling: scratches and cracks reduce life span of VIPs.

The second approach also takes into account the building construction heat loss through thermal bridges. Thermal bridges are heat transfers where a noninsulating, heat transmitting material is placed between the conditioned space and the exterior environment of a building assembly [44]. For VIPs, bridge transfers occur at the panel level, building components level and facade level [45]. The linear thermal transmittance that represents thermal bridge effect depends on the thickness of a VIP, its length and perimeter area [2]. The effect of the thermal transmittance on the total thermal conductivity of a VIP can be expressed as follows [21,26]:

$$\lambda\text{eff} = \lambda_{\text{cop}} + \Psi_{\text{edge}} \times \text{d}_{\text{p}} \times \text{I}_{\text{p}}/\text{S}_{\text{p}}, \qquad (18)$$

where

λ_{cop}	is the thermal conductivity of VIP centre;
Ψ_{edge}	is the linear thermal transmittance;
d_{p}	is the panel thickness;
I_{p}	is the perimeter length of VIP;
S_{p}	is the surface area of VIP.

The effect of thermal bridges on thermal conductivity and, therefore, service life of VIPs was a subject of both numerical [26,45–48] and analytical [27,48,49] investigations. In general, the studies showed that VIPs with aluminium foil envelopes have higher (up to 50 times) thermal transmittance rates than VIPs with multilayer foils or metallized polymer films [50,51]. Studies also showed high measures of thermal transmittance (0.170 W/mK) for such types of panels even if there was no air space between the panels [51]. For these reasons, [20] did not recommend use of VIPs with laminated aluminium foils (type AF in Figure 10) for buildings if their size is less than 1 m^2. Some studies suggested encapsulating AF-VIPs with EPS or extruded polystyrene to reduce the total thermal conductivity [51,52]. Although the results of those studies showed improvements in thermal conductivity, the obtained measurements were still higher than for the coated multilayer foils. Another proposed solution has been the use of serpentine edges [53] to increase the path for the heat flux. Theoretically, it was shown that the linear thermal conductivity of the panel edge could be significantly reduced [3]; although no practical investigations were conducted to confirm the feasibility of these innovations.

Studies on thermal transmittance of VIPs also showed that VIP envelopes with higher thermal conductivity have stronger thermal bridge effect [27]. This means that the materials with lower thermal conductivity are preferable for VIP envelopes. [2] suggested application of thin films of SiO_x and SiN_x coated on a polymer substrate for these purposes. It was also found that larger panels are thermally advantageous over smaller ones, although the effect decreases with the size. According to [3], a 2.5 m^2 VIP panel provides a nearly 10% thermal efficiency increase over a 1 m^2 panel, although further increasing the size to 4 m^2 only provided increase by a few percent.

A typical VIP has two protecting facings on each side that are linked with a spacer. Use of EPS for VIPs with aluminium foil and aluminium-coated envelopes was shown to reduce thermal transmittance losses [54,55]. However, [45,49] showed that thermoplastic spacers showed lower transmittance rates. Further, it was found that EPS along the encapsulated VIP perimeter provided additional thermal bridge effects [56]. [2] suggested by using a better insulator or minimizing EPS strips to reduce the thermal bridge effects.

4. ECONOMICAL FEASIBILITY OF VACUUM INSULATION PANELS

As was discussed previously, the major advantage of VIPs is its extremely low thermal conductivity rate, which allows to apply thin panels to ensure the same level of thermal resistance as with the traditional insulation materials. Therefore, the benefit of VIPs comes in form of space savings. At the same time, VIPs are rather costly in comparison with the traditional materials. Therefore, applications of VIPs for buildings need to be evaluated also from the economic point of view. [57] showed that the life cycle costs for VIPs and a traditional insulation material, such as mineral wool, are comparable (Figure 16). Their simulation analysis was based on the insulation of a 15 cm brick wall, energy costs of €0.06/m^2, floor height of 2.8, land cost of €400/m^2 and space renting cost of €200/m^2.

[57] proposed that the economic benefit of using VIP in buildings shows up whenever there is high cost of building rent so that the saved wall thickness compensates for the high cost of VIPs. [18] expressed the same idea with regards to space driven savings achieved with VIPs. Jelle applied economic analysis for replacement of a 35 cm mineral wool insulation (p = €20/m^2) with a 6 cm VIP (€200/m^2) on a 9 cm timber frame to maintain the required wall thickness for the load-bearing building properties. The simulated interior wall area and floor area were 100 m^2 each. Figure 17 shows the expected cost savings using

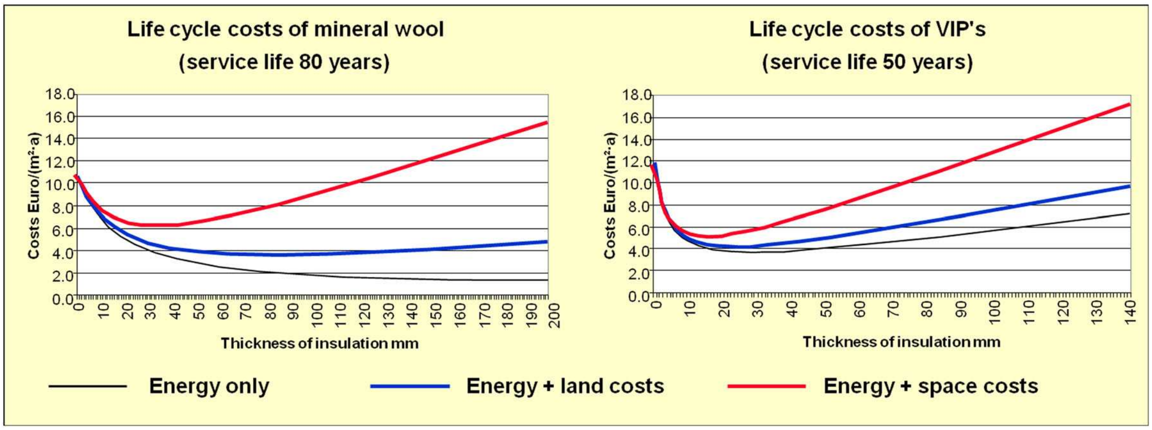

Figure 16. A comparative analysis of life cycle costs of mineral wool ($\lambda = 0.036$; $p = €100/\text{m}^3$) and vacuum insulation panel (VIP) ($\lambda = 0.008$; $p = €2000/\text{m}^3$, service life 50 years. Land cost is $€400/\text{m}^2$, energy costs are €0.06 kWh, space renting costs $€200/(\text{m}^2 \cdot \text{a})$, floor height 2.8 m, and capital costs 5% p.a.) [57].

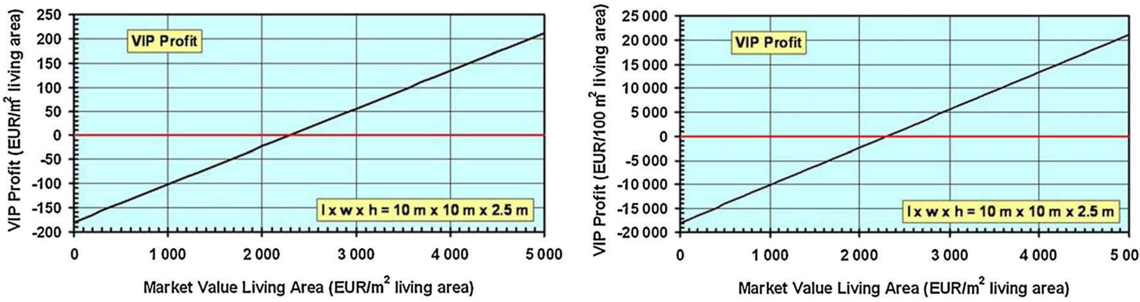

Figure 17. Vacuum insulation panel (VIP) profit as a function of market value living area [18].

VIPs instead of mineral wool as a function of living area cost. As is seen, the higher the cost of living area, the more savings are provided with VIP applications. At about $€2400/\text{m}^2$ living area, installation of VIP represents a break point of costs.

[2] used a payback analysis to determine economic feasibility of VIP applications in buildings. The payback period was calculated as follows:

$$\text{PP} = \frac{\text{C}_{ins}}{\text{C}_{A,cur} – \text{C}_{A,impr}}, \tag{19}$$

where
C_{ins} is the cost of insulation material;
$\text{C}_{A,cur}$ is the annual heating costs for the current thermal conductivity (traditional material);
$\text{C}_{A,impr}$ is the annual heating costs for the improved thermal conductivity (VIP).

Annual costs of heating are calculated as follows:

$$\text{Ca} = (86{,}400 \times \text{HDD} \times \text{Cf} \times \text{U} \times \text{DF})/(\text{Hv} \times \eta), \tag{20}$$

where
HDD is the heating degree day;
Cf is the cost of fuel;
U is the average U-value;
PWF is the discounting factor $N/(1+i)$ where N is the life time in years and i is the inflation rate;
Hv is the heating value of fuel;
η is the efficiency of the heating system.

Four scenarios (Table II) were considered by [2] for a VIP and an EPS panel for comparative purposes. The analysis was conducted on the basis of the values for the UK buildings and, therefore, cannot be generalized onto other countries. However, similarly to [2] and [57], it showed that the economic benefit of VIPs in buildings (this time in the form of shorter payback) significantly improves (Figure 18) the value of space savings is taken into account.

As is seen, the initial payback period of VIPs is higher in comparison with EPS, which is dictated by their high initial costs. Therefore, decreasing the costs of production is the priority for VIP manufacturers in order to make VIPs a cost-effective alternative to the commonly used insulation materials. However, even considering the current costs

Table II. Payback period scenarios for vacuum insulation panel and expanded polystyrene in buildings [2].

	Parameters	Value
Scenario 1	Average building U-value	0.40 W/m^2/K
VIP	Thickness	10 mm
	Cost	€82.37/m^2
EPS	Thickness	48.3 mm
	Cost	€2.82/m^2
Scenario 2	Average building U-value	0.31 W/m^2/K
VIP	Thickness	25 mm
	Cost	€164.74/m^2
EPS	Thickness	113 mm
	Cost	€7.28/m^2
Scenario 3	Average building U-value	0.27 W/m^2/K
VIP	Thickness	40 mm
	Cost	€164.74/m^2
EPS	Thickness	180 mm
	Cost	€9.86/m^2
Scenario 4	Average building U-value	0.24 W/m^2/K
VIP	Thickness	60 mm
	Cost	€164.74/m^2
EPS	Thickness	256 mm
	Cost	€12.69/m^2
	Fuel	Natural gas
Other parameters	Emission conversion factor	0.2
	HDD	1931 °C day
	C_f	€0.47/m^3
	H_v	39.5×10^6 J/m^3
	η	0.9
	N	25 years
	i	10%

VIP, vacuum insulation panel; EPS, expanded polystyrene; HDD, heating degree day; C_f, cost of fuel; η, efficiency of the heating system; N, panel life time; i, inflation rate.

of production, VIPs could be an attractive alternative for listed buildings where insulation of outer surfaces is impractical. In this case, the economic value of space saved increases with the required degree of insulation. As scenario 4 demonstrates, under high insulation requirements, VIPs could have even lower payback in comparison to EPS.

5. VACUUM INSULATION PANELS IN BUILDINGS

5.1. Recent progress in applications

Research shows that VIPs for buildings are being produced in many parts of the world [3,20]. VIPs reduce the space required for insulation in most common applications. Installation of VIPs successfully combines high thermal performance and a sleek building structure. The multilayered metallized polymer VIP provides a high barrier material for long-lasting performance in buildings, as it minimizes the thermal bridge effect through edge zones. For wet, alkaline environments at high temperature VIPs are not yet suitable recommended to use in buildings.

The research in VIPs and their applications has also been growing rapidly in several countries including Scandinavian countries, Switzerland, Germany, the UK, Canada, USA and a number of Asian countries [58]. Several types of applications of VIPs in buildings have been studied so far. Internal [47] [59] and external [22,46,52] insulations of buildings have been researched because of VIPs' potential to increase available living space. VIPs have also been researched for their applications in window frames and door frames, where reduction of thermal transmittance of

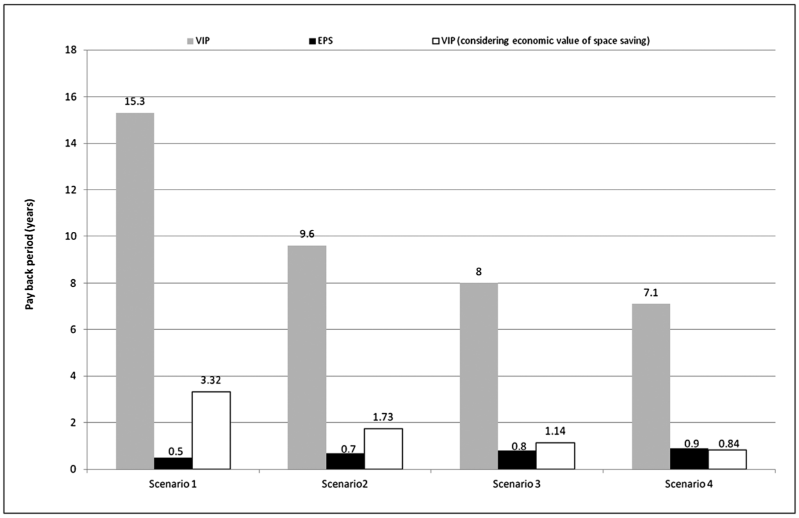

Figure 18. Payback period of vacuum insulation period (VIP) and expanded polystyrene (EPS) boards based on scenarios from Table II (redrawn from [2]). The calculations were performed by using a base rent of €506/m^2.

Table III. Vacuum insulation panel available on the market.

Producer	Title	Core	Barrier	Thickness (mm)	Initial thermal conductivity (mW/mK)*	Actual thermal conductivity (mW/mK)	Regular size (cm)	Maximum size (cm)	Service life (years)
va-Q-tec	va-Q-vip B	Fumed silica	High barrier film	10–50	4.3	7–8	50 × 60	100 × 60	60
	va-Q-pur	PUR foam	Aluminum foil laminate	10–40	-	7–9	50 × 50	120 × 100	15
	va-Q-mic	Microfleece	Aluminum foil laminate	14–20	2.8–3.5	-	50 × 50	130 × 100	5
LG Hausys		Fibreglass	Aluminum foil laminate	1–30	4	-	50 × 50	180 × 70	-
EnviroHomes	Vacupor PS	Mix (SiO2, SiC, others)	Aluminum foil laminate	10–30	4	5–19	50 × 50	100 × 50	40–50
	Vacupor RP	Mix (SiO2, SiC, others)	Aluminum foil laminate, rubber	10–50	4	5–19	60 × 50	220 × 100	50
	Vacupor NT B2	Mix (SiO2, SiC, others)	Aluminum foil laminate	10–50	4	5–19	60 × 50	220 × 100	40–50
Dow Corning		Fumed Silica	Aluminum metallized laminate	6.3–38	2.13	-	60 × 90	-	60
ThermalVisions	THRESHHOLD	-	-	5–51	2.88	-	50 × 50	100 × 127	-
Microtherm	SlimVac	Fumed silica	Multilayer polymer	6–40	4.2	9	50 × 50	140 × 80	30–50
American Aerogel	Aerocore	Aerogel	Aluminized PES	12–25	1.9–4.2	-	-	-	10–15
Xiamen Goot	GOOT	Fibreglass	Aluminum foil, multilayer polymer	10–35	4	-	50 × 50	170 × 80	10–15
Sokkull	Qasa	Pyrogenic silica	Metallized high barrier	10–50	4	8–19	50 × 50	125 × 300	-
Suzhou	HD-002	Fibreglass	Metal foil laminate	8–35	3.5–4	-	50 × 50	-	10–15

PUR, polyurethane; PES, polyester foil.

*Thermal conductivities, both initial and actual, are given for 20-mm-thick 50 × 50 cm panels.

up to 50% was reported [27,60]. Investigations of VIP applications for roof and terrace insulation were conducted, where the expected service life of several decades were shown for VIPs [34,61]. VIPs were also investigated as a sustainable insulation material for the new buildings [34,62]. [63] showed 20 different building applications of VIPs being applied on practice.

5.2. Performance of various vacuum insulation panels on the market

5.2.1. Vacuum insulation panels market for building sector

Although the research on VIPs has progressed in the recent years, there are very few prefabricated VIP systems available specifically for building sector today [64]. Types of VIP are generally determined by the type of core materials, envelopes, as well as by the presence of getters, desiccants and opacifiers, and the presence of additional cladding materials.

Table III shows the most common types of VIP currently available for building applications. The manufacturers represented are from different parts of the world, including the UK (EnviroHomes), USA (LG Hausys, Dow Corning, ThermalVisions, Microtherm and AmericanAerogel), Germany (va-Q-tec), Iceland (Sokkull) and China (Xiamen Goot and Suzhou). The data for each type of VIP is obtained from the companies' websites and personal communication with the company representatives where possible. Fumed silica and mixed silica VIPs are the most common core materials used by the manufacturers, although some manufacturers prefer fibreglass as a core material. Rarely offered are the panels with PUR foam, aerogels and other materials such as microfleece as cores. It is clear, however, that these panels offer short service lives comparatively with the silica panels. For silica panels, several variations of envelopes are offered, although multilayer aluminium envelopes seem to be the most common material applied.

The numbers demonstrated in Table III for each type of panels are provided by manufacturers. In many cases, only information on initial, postproduction thermal conductivities is available. However, studies have been conducted to evaluate the actual performance of various VIP systems, some of which are already commercially produced. The following sections review the performance of various panels based on the independent researches.

5.2.2. Fumed silica vacuum insulation panels for buildings

Fumed silica VIPs are the most popular among the commercially produced panels for building applications and also the most researched ones [20,65]. Fumed silica is commonly chosen for its low thermal conductivity at normal pressures.

A number of studies have been conducted to determine the optimal envelope material for fumed silica boards. Among the envelopes, variations in metal foils, metallized polymers and laminated materials were investigated. Researchers also noted the difference in silica VIP performance based on the panel sizes and thickness. [66] conducted hot box measurements for fumed silica va-Q-tec VIPs with seven variations based on panel envelopes and thickness: 2 and 4 cm single layer metal foil, single layer 2 cm, double layer 2 cm and double layer 2 cm with staggered joints and two 18 mm VIPs with tapered edges. The results of the analysis demonstrated that the real thermal conductivity values (U-values) were higher than the numerically predicted. At the same time, the performance of 20 mm double layer VIPs was comparable with 40 mm VIPs.

[20] investigated the performance of four different types of fumed silica VIPs for buildings: a metal film panel, a single layer metallized film panel and two multilayer metallized film panels. The authors also conducted measurements for different thickness values of the panels. In general, it was determined that single metal foil VIPs performed worst in terms of thermal conductivity. The VIPs with multilayered aluminium/polymer envelopes showed the best performance, whereas the single layer metallized film VIP had worse measurements of GTR, WVTR and service life. Notably, the study showed that 100 × 100 cm multilayer envelope VIP maintained the thermal conductivity value of 8 mW/mK after 60 years of a lifetime (generally quoted by the manufacturers), whereas 50 × 50 cm VIP of the same kind would have around 10 mW/mK [20]. This indicates the effect of panel size on its lifetime performance.

5.2.3. Other vacuum insulation panel types for buildings

Although silica VIPs remain the most popular type of panels on the market for building applications, research continues for other types of panels as well. However, so far, the results demonstrate the superiority of silica panels. [64] demonstrated that PUR-core VIPs have worst performance because of high outgassing rates. [29] showed that the use of low density polyethylene with polystyrene at some temperatures may provide thermal conductivities as low as 6.5 mW/mK, which, however, is still higher than those demonstrated by silica VIPs. [32] proposed by using double envelopes and three-sided sealing envelopes with getters with PUR foams as cores for VIPs. However, despite the relatively low thermal conductivities achieved, the service life of the panels was only about 20 years. [67] investigated the application of steel-clad VIP systems and found them to be much better suited for building applications because of high durability rates. However, in terms of thermal conductivity, the sheet steel cladding VIPs demonstrated values of 14.7–20.0 mW/mK [67].

6. CONCLUSIONS AND OUTLOOK

In 2011, the European Council acknowledged that the Union's target for energy efficiency and greenhouse emissions is not on track [68]. One of the major actions recommended by the council to attain the required energy efficiencies is achieving higher energy savings in buildings, which represent 40% of the Union's final energy consumption. The Energy Efficiency Directive 2012 binds the member states to establish a long-term strategy for residential and commercial building innovations to improve their energy performance. These new requirements establish the need for new, highly efficient insulation methods and materials. VIPs represent one of the most promising technological innovations in this regard. These state-of-the-art insulation systems provide a lower degree of thermal conductivity than the traditional insulation materials. They help achieve the desired energy standards while at the same time saving living space because of thinner building walls.

So far, however, these materials are not in the widespread use in buildings because of their high cost, susceptibility to perforation and the effects that worsen their performance (GTR, WVTR and thermal bridging). The currently available on the market VIPs are not numerous in variations. VIPs with silica cores and multilayered envelopes are the most popular types of VIP systems, although other variations in terms of both are present. Silica based VIPs with multilayered envelope structure provide low thermal conductivity rates (4–10 mW/mK) and have relatively long service lifetime of about 60 years for standard 50 × 50 cm panels with 20 mm thickness. Larger and thicker panels have even better analytically and practically measured performances. Moreover, some manufacturers, such as va-Q-tec and EnviroHomes, are already providing customized VIPs in terms of size and shape. This allows to eliminate one of the disadvantages of VIPs based on the inability to cut the material without losing its thermal conductivity performance.

Yet, many unresolved issues remain. Fumed silica, while having the best thermal performance, is also one of the most expensive materials, which drives VIP cost to about €2000/m^3. Other core materials, such as fibreglass or PUR foams, are cheaper, but they provide worse thermal conductivity and have shorter service lifetime. The analysis performed in this paper showed that current VIPs can be economically feasible only in cases of rental costs starting at around €2400/m^2 considering that the saved space contributes to the rental savings. In order to spur the widespread application of VIPs in buildings, it is of utmost importance to reduce the cost of their production without sacrificing the high level of thermal performance. In this regard, research considering both core materials and envelopes is needed to answer the question whether more efficient solutions are possible than the currently existing on the market.

The European Union member states are obligated to implement the major Energy Efficiency Directive 2012 points by June 2014. This means that the importance of energy efficiency research, including thermal insulation initiatives, is higher than ever. This review demonstrated that under certain conditions VIPs could be economically feasible and provide short payback periods after their installation. This means that these insulation materials deserve further consideration for sustainable building construction. It is expected that with more manufacturers entering the market and with improvements in the manufacturing process, the market price on VIPs will decline, making them more attractive for wider applications in buildings.

NOMENCLATURE

AF = metal film
EPS = expanded polystyrene
GFP = gas filled panels
MF1 = a single layer metallized film
MF2, MF3 = three layer metallized films
PE = polyethylene
PET = polyethylene terephthalate
PUR = polyurethane
VIP = vacuum insulation panel
XPS = extruded polystyrene

Formulae variables

A = total area of the panes, including front and back sides (m^2)
C = cost (€/m^3)
C_{acur} = annual heating costs for the current thermal conductivity (traditional material)
C_{aimpr} = annual heating costs for the improved thermal conductivity (VIP)
C_f = cost of fuel
C_{ins} = cost of insulation material

E_a = activation energy (J/mol)
H = heating value (J/m^3)
H_v = heating value of fuel

K = coefficient representing the degree of slope
L = panel circumference (m)
N = panel life time (years)
Q = permeance (m^3(STP)/(m^2/day/Pa))
Q_{totg} = laminate permeance
Q_{wtot} = total water permeance

R = the gas constant (J/(mol K))
S = surface area of VIP (m^2)
T = temperature (K)
U = average thermal conductivity (W/m^2/K)
V = pore volume (m^3)
V_{eff} = effective pore volume in the panel

X_w = water content (% mass)
P = core material density
p = pressure (Pa)
p_{wout} = water vapour pressure outside of VIP
p_{win} = water vapour pressures inside of VIP
p_w = partial water vapour pressure

Δp_g = pressure difference across laminate barrier.
Δp_w = water vapour pressure across the film

a = a value of foam unity
d = panel thickness (m)
i = inflation rate (%)
l = perimeter length of VIP (m)
m = mass (kg)
m_d = the mass of VIP dry
m_v = the mass of VIP panel

GTR = gas transmission rate, ($m^3/(m^2$ day))
GTR_A = GTR of the surface of the laminate cover per panel area
GTR_L = length-related GTR along the panel's circumference
GTR_t = total gas transmission rate of material

HDD = the heating degree day (°C day)
PWF = discounting factor ($N/(1+i)$)
WVTR = water vapour transmission rate (g/(m^2 day))
φ = relative humidity (%)
$\varphi(X_w)$ = water vapour saturation pressure based on relative humidity level
φ_{out} = relative humidity outside and inside of the panel
φ_{in} = relative humidity inside of the panel

λ = thermal conductivity (W/m/K)
λ_T = total thermal conductivity
λ_s = thermal conductivity of the material skeleton through the atomic bonds
λ_g = thermal conductivity accounting for gas in the material pores
λ_r = thermal conductivity accounting for the radiation transfer between internal pore surfaces of the material
λ_c = thermal conductivity accounting for air and moisture convection within the pores
λ_l = thermal conductivity accounting for thermal leakage transport because of pressure differences
λ_{coup} = thermal conductivity accounting for second order effects between the mentioned thermal conductivities
λ_0 = thermal conductivity of air at atmospheric pressure
$\lambda_e(t)$ = thermal conductivity of the evacuated VIP in the beginning of service
$\lambda_g(t)$ = thermal conduction caused by GTR over time
$\lambda_{wv}(t)$ = thermal conduction caused by WVTR over time
$\lambda_w(t)$ = thermal conduction over time based on adsorbed water within the core material
λ_{cop} = thermal conductivity of VIP centre
Φ = the pore width of insulation material (m)
Ψ = the linear thermal transmittance (m/K)
ρ = the core material density (kg/m^3)
η = the efficiency of the heating system

Subscripts

A = annual
atm = atmospheric pressure
c = convection
cop = centre of panel
crit = critical value
cur = current
e = evacuated VIP
edge = edge
eff = effective
g = gas
impr = annual heating costs for the improved thermal conductivity
ins = insulation
lim = limiting value
p = panel
r = radiation
s = the material skeleton through the atomic bonds
sat = saturation
tot = total
totg = total gas
w = water
wtot = total water
wv = water vapour

Superscripts

Ea = activation energy (J/mol)
R = the gas constant (J/(mol/K))
a = a value of foam unity

REFERENCES

1. Mukhopadhyaya P, Kumaran MK, Normandin N, van Reenen D, Lackey JC. High performance vacuum insulation panel: development of alternative core materials. *Journal of Cold Regions Engineering* 2008; **22**(4):103–123.
2. Alam M, Singh H, Limbachiya MC. Vacuum insulation panels (VIPs) for building construction industry – a review of the contemporary developments and future directions. *Applied Energy* 2011; **88**(11):3592–3602.
3. Thorsell T. Advances in thermal insulation – vacuum insulation panels and thermal efficiency to reduce energy usage in buildings. PhD Research, 2011.

4. Ye Z, Wells C, Carrington C, Heweiit N. Thermal conductivity of wool and wool–hemp insulation. *International Journal of Energy Research* 2006; **30**:37–49.
5. Al-Sulaiman F. Date palm fibre reinforced composite as a new insulating material. *International Journal of Energy Research* 2003; **27**:1293–1297.
6. Ismail K, Castro J. PCM thermal insulation in buildings. *International Journal of Energy Research* 1997; **21**:1281–1296.
7. Griffith BT, Arasteh D, Türler D. Gas-filled panels: an update on applications in the building thermal envelope. *Proceedings of the BETEC Fall Symposium, Superinsulations and the Building Envelope*, Washington, DC, 14 November, 1995.
8. Mills GL, Zeller CM. The performance of gas filled multilayer insulation, advances of cryogenic engineering. *Transactions Of The Cryogenic Engineering Conference* 2008; **53**:1475–1482.
9. Griffith BT, Türler D, Arashteh D. Optimizing the effective conductivity and cost of gas-filled panel thermal insulations. *Proceedings of the 22nd International Thermal Conductivity Conference*, Arizona State University, 7–10 November, 1993.
10. Baetens R, Jelle BP, Gustavsen A, Grynning S. Gas-filled panels for building applications: a state-of-the-art review. *Energy and Buildings* 2010; **42**:1969–1975.
11. Trubiano F (ed.). *Design and Construction of High Performance Homes*. Routledge: Oxon, UK, 2013.
12. Fricke J, Schwab H, Heinemann U. Vacuum insulation panels – exciting thermal properties and most challenging applications. *International Journal of Thermophysics* 2006; **27**:1123–1139.
13. Hostler SR *et al*. Thermal conductivity of a clay-based aerogel. *International Journal of Heat and Mass Transfer* 2009; **52**(3–4):665–669.
14. Schultz JM, Jensen KI, Kristiansen FH. Super insulating aerogel glazing. *Solar Energy Materials & Solar Cells* 2005; **89**:275–285.
15. Schultz JM, Jensen KI, Kristiansen FH. Evacuated aerogel glazings. *Vacuum* 2008; **82**:723–729.
16. Soleimani Dorcheh A, Abbasi MH. Silica aerogel; synthesis, properties and characterization. *Journal of Materials Processing Technology* 2008; **199**(1–3): 10–26.
17. Ramakrishnan K, Krishnan A, Shankar V, Srivastava I, Singh A, Radha R. Modern aerogels 2007. Retrieved April 11, 2012, from www.dstuns.iitm.ac.in.
18. Jelle BP. Traditional, state-of-the-art and future thermal building insulation materials and solutions – properties, requirements and possibilities. *Energy and Buildings* 2011; **43**(10):2549–2563.
19. Aegerter M, Leventis N, Koebel M (eds.). *Aerogels Handbook*. Springer: London, 2011.
20. Baetens R *et al*. Vacuum insulation panels for building applications: a review and beyond. *Energy and Buildings* 2010; **42**(2):147–172.
21. Simmler H, Brunner S, Heinemann U, Schwab H, Kumaran K, Mukhopadhyaya P, Quénard D, Sallée H, Noller K, Kücükpinar-Niarchos E, Stramm C, Tenpierik MJ, Cauberg JJM, Erb M. Vacuum insulation panels. Study on VIP components and panels for service life prediction in building applications (subtask A). *Final Report for the IEA/ECBCS Annex 39 HiPTI-project (High Performance Thermal Insulation for Buildings and Building Systems)*, 2005.
22. Zwerger M, Klein H. Integration of VIPs into external wall insulation systems. *Proceedings of the 7th International Vacuum Insulation Symposium*, EMPA, Dübendorf, Switzerland, 28–29 September, 2005; 173–179.
23. Beck A, Frank O, Binder M. Influence of water content on the thermal conductivity of vacuum panels with fumed silica kernels. *Proceedings of the 8th International Vacuum Insulation Symposium*, ZAE Bayern, 18–19 September 2007; 1–9.
24. Caps R *et al*. Quality control of vacuum insulation panels: methods of measuring gas pressure. *Vacuum* 2008; **82**(7):691–699.
25. Kim J, Jang C, Song T-H. Combined heat transfer in multi-layered radiation shields for vacuum insulation panels: theoretical/numerical analyses and experiment. *Applied Energy* 2012; **94**(0):295–302.
26. Ghazi Wakili K, Stahl T, Brunner S. Effective thermal conductivity of a staggered double layer of vacuum insulation panels. *Energy and Buildings* 2011; **43**(6):1241–1246.
27. Tenpierik M, Cauberg H. Analytical models for calculating thermal bridge effects caused by thin high barrier envelopes around vacuum insulation panels. *Journal of Building Physics* 2007; **30**(3):185–215.
28. Araki K, Kamoto D, Matsuoka S-i. Optimization about multilayer laminated film and getter device materials of vacuum insulation panel for using at high temperature. *Journal of Materials Processing Technology* 2009; **209**(1):271–282.
29. Wong CM, Hung ML. Polystyrene foams as core materials used in vacuum insulation panel. *Journal of Cellular Plastics* 2008; **44**(3):239–259.
30. Tseng PC, Chu HS. The effects of PE additive on the performance of polystyrene vacuum insulation panels. *International Journal of Heat and Mass Transfer* 2009; **52**(13–14):3084–3090.
31. Marouani S. Investigation of the resistance welding of multilayers aluminum-coated polymer complexes used

as envelopes of vacuum insulation panels. *Materials & Design* 2012; **36**(0):546–556.

32. Kwon J-S *et al*. Vacuum maintenance in vacuum insulation panels exemplified with a staggered beam VIP. *Energy and Buildings* 2010; **42**(5):590–597.
33. Tenpierik MJ, Cauberg JJM, Thorsell TI. Integrating vacuum insulation panels in building constructions: an integral perspective. *Construction Innovation* 2007;**7**(1):38–53.
34. Brunner S, Simmler H. In situ performance assessment of vacuum insulation panels in a flat roof construction. *Vacuum* 2008; **82**(7):700–707.
35. Wang X, Walliman N, Ogden R, Kendrick C. VIP and their applications in buildings: a review. *Proceedings of the Institution of Civil Engineers. Construction Materials* 2007; **160**(4):145–153.
36. Baetens R, Jelle BP, Gustavsen A. Aerogel insulation for building applications: a state-of-the-art review. *Energy and Buildings* 2011; **43**(4):761–769.
37. Kwon J-S *et al*. Effective thermal conductivity of various filling materials for vacuum insulation panels. *International Journal of Heat and Mass Transfer* 2009; **52**(23–24):5525–5532.
38. Mukhopadhyaya P, Kumaran MK, Normandin N, Van Reenen D, Lackey JC. Fibre-powder composite as core material for vacuum insulation panel. *9th International Vacuum Insulation Symposium*, London, UK, 17–18 September 2009; 1–9.
39. Schwab H *et al*. Permeation of different gases through foils used as envelopes for vacuum insulation panels. *Journal of Thermal Envelope and Building Science* 2005; **28**(4):293–317.
40. Schwab H *et al*. Dependence of thermal conductivity on water content in vacuum insulation panels with fumed silica kernels. *Journal of Thermal Envelope and Building Science* 2005; **28**(4):319–326.
41. Schwab H *et al*. Predictions for the increase in pressure and water content of vacuum insulation panels (VIPs) integrated into building constructions using model calculations. *Journal of Thermal Envelope and Building Science* 2005; **28**(4):327–344.
42. Caps R, Fricke J. Thermal conductivity of opacified powder filler materials for vacuum Insulations1. *International Journal of Thermophysics* 2000; **21**(2):445–452.
43. Wegger E, Jelle BP, Sveipe E, Grynning S, Gustavsen A, Baetens R, Thue JV. Aging effects on thermal properties and service life of vacuum insulation panels. *Journal of Building Physics* 2011; **35**(2):128–167.
44. Allen E, Iano J. *Fundamentals of Building Construction: Materials and Methods*. John Wiley & Sons Inc.: Hoboken, NJ, 2009.
45. Quenard D, Sallee H. From VIP's to building facades: three levels of thermal bridges. *Proceedings of the 7th International Vacuum Insulation Symposium*, EMPA, Duebendorf, Switzerland, 28–29 September 2005; 113–120.
46. Willems MK, Schild K, Hellinger G. Numerical investigation on thermal bridge effects in vacuum insulating elements. *Proceedings of the 7th International Vacuum Insulation Symposium*, EMPA, Duebendorf, Switzerland, 28–29 September 2005; 145–152.
47. Ghazi K, Nussbaumer T, Bundi R. Thermal performance of VIP assemblies in building constructions. *Proceedings of the 7th International Vacuum Insulation Symposium*, EMPA, Duebendorf, Switzerland, 28–29 September 2005; 131–138.
48. Van den Bossche N, Moens J, Janssens A, Delvoye E. Thermal performance of VIP panels: assessment of the edge effect by experimental and numerical analysis. *1st Central European symposium on Building Physics*, Cracow, Poland, 13–15 September 2010; 279–286.
49. Tenpierik M, Van Der Spoel W, Cauberg H. An analytical model for calculating thermal bridge effects in high performance building enclosure. *Journal of Building Physics* 2008; **31**(4):361–387.
50. Ghazi K, Bundi R, Binder B. Effective thermal conductivity of vacuum insulation panels. *Building Research and Information* 2004; **32**(4):293–299.
51. Schwab H *et al*. Thermal bridges in vacuum-insulated building façades. *Journal of Thermal Envelope and Building Science* 2005; **28**(4):345–355.
52. Willems W, Schild K. The use of vacuum insulated sandwiches (VIS) in building constructions.
53. Thorsell TI, Källebrink I. Edge loss minimization in vacuum insulation panels. *Proceedings of the 7th Symposium on Building Physics in the Nordic Countries*, 13–15 June 2005, The Icelandic Building Research Institute, Reykjavik, 2005; 945–952.
54. Schwab H *et al*. Prediction of service life for vacuum insulation panels with fumed silica kernel and foil cover. *Journal of Thermal Envelope and Building Science* 2005; **28**(4):357–374.
55. Nussbaumer T, Wakili KG, Tanner C. Experimental and numerical investigation of the thermal performance of a protected vacuum-insulation system applied to a concrete wall. *Applied Energy* 2006; **83**(8):841–855.
56. Tenpierik MJ, Cauberg JJM. Encapsulated vacuum insulation panels: theoretical thermal optimization. *Building Research & Information* 2010; **38**(6): 660–669.
57. Zimmerman M, Brunner S. VIP market development recommendations based on the SELF experimental building. EMPA, 2011. Available from: http://www.ivis2011.org/pdf/T4-4%20VIP%20as%20standard%20insulation.pdf [accessed on April 11, 2012].

58. Mukhopadhyaya P. Progress in the use of vacuum insulation panels in construction. *Home Builder* 2012; **6**:10.
59. Bundi R, Ghazi K, Frank Th. Vacuum insulated panels in building applications. *International Conference, CISBAT, EPFL*, Lausanne, 2003.
60. Nussbaumer T *et al*. Thermal analysis of a wooden door system with integrated vacuum insulation panels. *Energy and Buildings* 2005; **37**(11): 1107–1113.
61. Simmler H, Brunner S. Vacuum insulation panels for building application: basic properties, aging mechanisms and service life. *Energy and Buildings* 2005; **37**(11):1122–1131.
62. Jordi M. Development of a low energy house with vacuum insulation. Renggli AG Suree and Schotz, Switzerland, 2008. Available from: http://www.vip-bau.ch/ [accessed on April 11, 2012].
63. Symons W, Erb M. Vacuum insulation panel properties and building applications. ECBCS Annex 39 Project Summary Report, 2010.
64. Yang CG *et al*. Outgassing of rigid open-celled polyurethane foam used in vacuum insulation panels under vacuum condition. *Journal of Cellular Plastics* 2007; **43**(1):17–30.
65. Fricke J, Heinemann U, Ebert HP. Vacuum insulation panels – from research to market. *Vacuum* 2008; **82**(7):680–690.
66. Grynning S *et al*. Hot box investigations and theoretical assessments of miscellaneous vacuum insulation panel configurations in building envelopes. *Journal of Building Physics* 2011; **34**(4):297–324.
67. Labory F, Cajot L, Mees C, Decluve F, Doring B, Kuhnhenne M, Kesti J, Lawson M, Baddoo N. Energy efficient buildings through innovative systems in steel. European Commission. Available from: http://www.arcelormittal.com/sections/fileadmin/redaction/pdf/Research_reports/Sustainability/EEBIS.pdf [accessed on March 11, 2013].
68. Council E. Directive 2012/27/EU of the European Parliament and of the Council. *The Official Journal of the European Union*. Available from: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2012:315:0001:0056:EN:PDF [accessed on March 27, 2013]