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Vacuum Insulation Panel Products: A State-of-the-Art Review and Future Research Pathways

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Abstract

Vacuum insulation panels (VIP) are regarded as one of the most upcoming high performance thermal insulation solutions. At delivery, thermal conductivity for a VIP can be as low as 0.002-0.004 W/(mK) depending on the core material. VIPs enable highly insulated solutions, and a measure to reduce the energy usage in both hot-water applications, cold applications and for the construction industry in general. This study gives a state-of-the-art review of VIP products found available on the market today, and explore the future research opportunities for these products.

VIPs have been utilized with success for applications such as freezers and thermal packaging, and during the last decade they have also been used for building applications in increasing numbers, where one of the main driving forces is the increased focus on e.g. passive houses, zero energy buildings and zero emission buildings. Hence, VIPs are now in the early market stages as a building product. Implementation of VIPs in various building constructions have given an increased interest in the possibilities of this product, both in new and refurbished constructions. Even though there is not enough data to conclude the effect over a lifetime of a building yet, the immediate result in decreased energy usage can be seen. However, the problem of guaranteeing a set lifetime expectancy, along with high costs, are some of the major reasons why VIPs are met with scepticism in the building industry. Aiming to give better quality assurance for the users, make further advances in envelope technologies and the development of core materials, along with a further cost reduction is crucial for VIPs to become a competing thermal insulation solution for buildings.

Keywords: Vacuum insulation panel; VIP; State-of-the-art; Review; Energy; Thermal insulation.

Contents

1 Introduction

The world today relies on a large amount of fossil fuels to produce energy. The continued use of fossil fuels will strain our resources, as well as lead to large amounts of pollution, especially through CO_2 emissions. The heating and cooling of buildings require a considerable amount of energy. A reduction in energy usage for the building sector will have a beneficial effect on CO_2 emissions. In the European Union buildings represent 40% of the total energy usage, and the existing building stock represents the single largest potential sector for energy savings. (European Union [19]) By the principle of the Kyoto Pyramid, the most cost effective method of reducing energy usage is to provide better thermally insulated buildings.

To reach the demanded U-values with traditional insulation materials, buildings are required to have walls up to 50 cm thick. This leads to more complex building details and transportation of thicker materials to the building sites (Jelle [27]).

One of the most promising building insulation materials in its early stages of commercialization now, is vacuum insulation panels (VIP). VIPs have an insulation performance which normally ranges from 0.004 W/(mK) in pristine condition to typical 0.008 W/(mK) after 25 years of aging. This is 5 to 10 times better, depending on aging, than traditional insulation used in buildings today (Jelle [27]). Therefore, VIPs enable highly insulated constructions for walls, roofs and floors, especially within refurbishing of older buildings where space is often limited. Integrating VIPs successfully into constructions requires careful planning with regard to its durability, the lack of flexibility, thermal bridging and lifetime expectations (Tenpierik [56]).

Especially the uncertainties around expected lifetime is a crucial factor for scepticism concerning VIPs. Research is being conducted on determining ways of interpreting in situ measurements and conduct reliable accelerated aging tests. The need to better understand the mechanisms of aging and general loss of thermal resistance over time has been mentioned by Simmler et al. [53] and Baetens et al. [5]. Various forms of accelerated climate aging tests have been described by Wegger et al. [65]. Quality assurance of VIPs is an important factor to promote the use of VIPs the building sector. It is important to be able to differentiate between panel damage as a consequence of production errors, and damages caused by aging and service failure, which hence will help the technology improve further (Brunner et al. [13]).

The objective of this study is twofold, i.e. (a) to present an overview of the different VIP producers and products, and to evaluate the effect and durability of these products, and furthermore (b) to explore possible future research pathways for VIPs. In addition, it is important to know how VIPs are tested with respect to lifetime performance in building applications. These investigations may help form guidelines for a new testing scheme and point to future research opportunities. This work presents many tables with a lot of information, e.g. manufacturers, product names and various properties, both in the main text and in the appendices. Some of these properties are crucial to the performance of the VIPs. The tables provide the readers with valuable information concerning VIPs. Unfortunately, it is currently hard to obtain all the desired information from all the manufacturers. In general, many of the desired property values are not available on the manufacturers' websites or other open information channels, which is hence seen as open spaces in the various tables.

Hopefully, our addressing of these facts could act as an incentive for the manufacturers to state all the important properties of their products at their websites or other open information channels, and also as an incentive and reminder for the consumers and users to demand these values from the manufacturers.

2 Vacuum insulation panel (VIP) concepts

2.1 General

A VIP consists of a porous core enveloped by an air- and vapour tight barrier, which is heat sealed. The core is of an open pore structure to allow all the air to evacuate, and create a vacuum. The envelope needs to be air- and vapour tight for the panel to uphold its thermally insulating properties over time. Figure 1 shows a normal schematic of a VIP. The initial pristine thermal conductivity of the core is normally around 0.004 W/(mK), however increasing with elapsed time due to air and moisture diffusion through the barrier envelope and into the core.

The thermal transport in a VIP may be divided as the following:

$$\lambda_{tot} = \lambda_{sol} + \lambda_{gas} + \lambda_{rad} + \lambda_{conv} + \lambda_{coup} \quad (1)$$

where λ_{sol} is the radiation thermal conductivity, λ_{gas} is the solid state thermal conductivity, λ_{rad} is the gas thermal conductivity, λ_{conv} is the convection thermal conductivity, and λ_{coup} is the thermal conductivity of coupling effects. Coupling accounts for second order effects between the various thermal conductivity terms, and is relevant for powder and fibre materials. This means that the total thermal conductivity will be larger than the sum of the four first terms in Eq.1, due to interactions between them. The coupling effect has been described more closely by Heinemann [26]. Another view on the coupling term stems from the interaction between the gas molecules and the solid material in the pore walls. However, this last coupling term is often included as a factor when the gas conductivity is calculated by the Knudsen effect (Jelle [27]). Coupling effects is a complex effect and is considered to be negligible in most theoretical approaches for the thermal performance of VIPs (Wegger et al. [65]). Conventional insulation can never aim to achieve a thermal conductivity lower than still air at around 0.025 W/(mK). VIPs as a high performance thermal insulation solution by far surpasses this with a much lower value.

Figure 1. Schematic of a VIP (Alam et al. [1]).

The development of VIPs focuses on two main aspects of the panel, the core and the envelope. Hence, a description for the two parts will be given separately in the following.

2.2 The core

2.2.1 Cores in general

The purpose of the core material is to provide the VIP's insulating and mechanical properties. Hence, there is a lot of focus on the core material, as this is important for a VIP to attain the highest possible thermal resistance. To optimize the conditions of the VIPs, the core needs to fulfil certain requirements. These are described in a comprehensive review by Baetens et al. [5].

1. The core material's pore diameter needs to be small. In materials with large pores, the pressure has to be very low to obtain a low thermal conductivity. This is difficult to maintain with methods and materials in use today. By using a nano-porous material the pressure is not required to be as low, and a low thermal conductivity can be reached with a higher pressure. The relation between pressure and thermal conductivity is shown in Fig.2.
2. The pore structure needs to be 100 % open so all the gas in the panel can be easily evacuated.
3. The core material needs to withstand compression. The normal range of the initial internal pressure in VIPs is between 0.2-3 mbar. The external pressure on the panel is around 1 atm, or about 101 kPa.
4. The material has to be impermeable to infrared radiation, which will reduce the radiative heat transfer in the panel.

Several different materials are being tested for use as core materials in VIPs, such as fibre-powder composites (Mukhopadhyaya et al. [40]), polycarbonates (Kwon et al. [36]), phenolic foam (Kim et al. [34]) and ultrafine glass fibres (Di et al. [15]). Different core materials have different advantages and drawbacks. Hence, the type of core material needs to be determined for each application. Core materials found in commercialized VIP products will be presented in the following chapters.

Figure 2. Thermal conductivity versus gas pressure for different core material (Tenpierik [56]).

2.2.2 Fumed silica

Fumed silica is produced by pyrolysis of $SiCl_4$, which is then vaporized and reacts with oxygen, thus forming SiO_2 which is a fine white powder. This powder is pressed into boards, normally with added fibres for structural stability. Figure 3 shows a VIP with fumed silica as a core.

Due to its small pore size, ranging from 30-100 nm, and ability to withstand compression, the fumed silica core fulfils all the criteria stated earlier. The normal material properties for fumed silica are a mass density of around 200 kg/m^3 and a thermal conductivity of 0.003-0.006 W/(mK) under a pressure of 20-100 mbar (Wang et al. [64]). However, fumed silica is not able to block thermal radiation very well. Seeing as the heat transfer through gas conductivity in a vacuum panel is especially low, the contribution from radiation will give a significant increase in the total thermal conductivity. Therefore, it is a common solution to add opacifiers to the fumed silica for it to reach an initial thermal conductivity around 0.004 W/(mK).

Figure 3. VIP with a fumed silica core (va-Q-tec [60]).

Fumed silica is by far the most commonly used core-material for VIPs in the building sector today. Several advantages of fumed silica makes it a good choice for building applications. Silica is non-toxic, incombustible, recyclable and it does not release harmful emissions to the environment. A core of fumed silica works as a desiccant, absorbing water vapour permeating through the envelope.

In the case of panel perforation, fumed silica will still have a rather low thermal conductivity of around 0.002 W/(mK) at atmospheric pressure. Note then that the difference between 0.004 W/(mK) (pristine condition) and 0.020 W/(mK) (punctured) of 0.016 W/(mK) is due entirely to gas thermal conductivity. That is, the combined solid state and radiation thermal conductivity of fumed silica is as low as 0.004 W/(mK) or lower (as there is still a very small concentration of air inside a VIP a small part of the 0.004 W/(mK) value is due to gas conduction), Hence, as it is possible to make materials with such a very low solid state and radiation conductivity, there are rather good opportunities to make a high perforamnce thermal insulation material functioning at atmospheric pressure by lowering the gas thermal conductivity.

2.2.3 Aerogels

Aerogels are produced in two steps. First, wet gel formation by acidic condensation or sol-gel process. Second, the wet gel is dried by using supercritical or ambient drying. This produces a nanoporous material with pore sizes around 20 nm and a mass density that can vary from 3-350 kg/m^3. When used as a core material for VIPs, aerogel delivers a low thermal conductivity. At an ambient pressure of 50 mbar, and with an addition of carbon black to suppress the radiative transfer, aerogel has a thermal conductivity of 0.004 W/(mK). At ambient pressure the thermal conductivity rises to 0.0135 mW/(mK) (Baetens et al. [3]).

Aerogel is non-flammable and non-reactive. However, due to its high cost, aerogel-core VIPs are not yet an economically reasonable product for building applications. Nevertheless, aerogel may be used as a heat bridge breaker in buildings and structures where space is restricted. Furthermore, in its translucent or transparent state aerogel has and added value which may be exploited in several building applications.

2.2.4 Polyurethane foam

Polyurethane (PUR) foam is a widely used thermal insulation material by its own. The first vacuum insulation panels were created with PUR foams as the core material. PUR has the mechanical strength and the open pore structure required for a core material. However, the pore size in the PUR is larger than in fumed silica and aerogel. That is, PUR requires a lower vacuum to reach the same low thermal conductivity as the fumed silica and aerogel. For a PUR core VIP to maintain its designed low thermal conductivity value, the pressure has to stay below 1 mbar, over this value it will rise sharply (Yang et al. [66]). This is not feasible with the envelopes of today. PUR foam core VIPs are less expensive to produce, but the short effective lifetime of these panels do not make them as fit for building applications.

2.2.5 Glass fibre

Glass fibre cores have similar issues as PUR foam cores. Because of the relatively large pore size, ranging from 1-12 µm, the gas pressure needs to be very low for the panel to maintain its low thermal conductivity. At a gas pressure of about 0.1 mbar the thermal conductivity is as low as 0.0015 W/(mK). Because of its high thermal stability, Araki et al. [2] have investigated the use of glass fibre cored VIPs for high-temperature applications. The core material itself is relatively inexpensive, but Di et al. [15] concluded that the lifetime expectancy for a glass fibre cored vacuum insulation panel is about 15 years. This is far too low for glass fibre VIP cores to be considered as a choice for building applications. As of today it is still mostly used for shipping containers, freezers etc.

Using ultrafine glass fibre cored VIPs for building applications have recently been mentioned in an article by Boafo et al. [7]. However, no monitoring tests have been found with these VIP types.

2.2.6 Opacifiers, getters and desiccants

A major and crucial drawback of VIPs, are that their thermal conductivity increases over time. The low conductive heat transfer of VIPs is highly dependent on a low gas pressure inside the panel. Vapour and gases that permeate through the envelope therefore contribute to a lower effectiveness of VIPs. To counteract this, the core is often mixed with, desiccants and getters.

Opacifiers are added to the core of the panel to reduce the heat loss through radiation. With added opacifiers the radiative thermal conductivity can be decreased to a value below 0.001 W/(mK) (Bouquerel et al. [8]).

To increase the expected service lifetime of VIPs, getters and desiccants are added to the core. These are components or chemicals that adsorb residual or permeating gases or water vapour. They will maintain a steady thermal conductivity inside the core until their capacity is reached. Getters are highly porous structures with large surfaces. They work by attracting and bonding with permeating gases to maintain a low pressure inside the panel. Desiccants are made of highly hydroscopic materials and work by entrapping moisture. Some core materials have properties that fulfils the functions of getters and desiccants themselves, so they are not always necessary to add. Even though these materials slightly increase the solid state thermal conductivity and increase the costs of a panel they are important to add (Thorsell [58]).

2.3 The envelope

2.3.1 Envelopes in general

The main purpose of the envelope is to provide an air and vapour tight enclosure for the core material, i.e. to maintain a vacuum in the VIP core. As the thermal performance of VIPs are highly dependent on the conservation of the vacuum inside, any gases or water vapour that permeate through the barrier will diminish the effectiveness of VIPs. This makes a VIP a fragile thermal insulation material compared with conventional insulation (Wegger et al. [65]). Permeation through the envelope is also affected by the outer environment. Changes in temperature and relative humidity will affect the permeation rate (Simmler et al. [53]).

Depending on the choice of envelope, thermal bridging around a VIP is also a factor to consider. The core material has great insulating properties, however thermal bridging from the envelope material will increase the panels total thermal conductivity. An increase in panel dimensions will lead to a decrease in the thermal bridging effect. Hence, one should aim to use the largest panel dimensions possible (Wakili et al. [62]). Further studies on the thermal bridging effect of VIPs in both single and double layers have been conducted by Wakili et al. [63]. Note that with larger panel dimensions larger areas and volumes of the building envelope will have a reduced thermal resistance when some of the VIPs are punctured.

The envelope is often divided into the sealing layer, the barrier layer and a protective layer as seen in Fig.4. These layers are described by Alam et al. [1].

The inner layer is the sealing layer. This layer seals the core material in the envelope, and traditionally consists of low or high density polyethylene. The film surfaces are heat sealed by two hot bars under pressure to bond together.

The middle layer is the barrier layer. As seen in Fig.4, this layer may be an aluminium foil or a multilayer laminate. The purpose of the barrier layer is to protect against water vapour and air transmission through the envelope.

The outer layer is the protective layer. Environmental and handling stresses may damage the panel, so a protective layer aims to make the panel more robust. The material chosen for the envelope should also be able to withstand general handling through transportation and installation without tearing. It also works as a substrate for the barrier layer.

The sealed edges in a panel may often be a weak point in maintaining the vacuum. The sealing is a complex process which it is important to develop a further understanding for in order to maximize the lifetime of VIPs. Important factors in the heat sealing process is mentioned by Marouani [39].

Figure 4. Illustration of an Al foil and multilayer foils (Wegger et al. [65]).

2.3.2 Metal laminate

The solution with a metal laminate, most commonly aluminium laminate, consists of a central aluminium foil (with a thickness of 5-10 µm) as a barrier layer, laminated between an outer polyethylene terephthalate (PET) protective layer for better scratch resistance and an inner polyethylene (PE) sealing layer.

Aluminium laminate as a barrier layer lowers the permeation through the envelope, increasing the lifetime of a panel. However, the thickness of the metal laminate contributes to a higher thermal bridging effect as the thermal conductivity for aluminium is 210 W/(mK), compared to the core at around 0.004 W/(mK), and the polymer layers at 0.25-0.30 W/(mK). For a high-performance insulation material this thermal bridge effect will have severe effects on the total thermal resistance of VIPs (Bouquerel et al. [9], Brunner et al. [12]).

2.3.3 Metalized multilayer polymer laminate

The metalized multilayer foil (MF) solution consists of up to three barrier layers of metal coated PET films and an inner sealing layer of PE. The coating is performed with aluminium with a thickness of 20-100 nm.

The MF solution is, as of today, the common solution for VIPs intended for building applications. The multiple aluminium layers gives the envelope a better protection from permeation, while the polymers reduce the thermal bridging effect. The MF consists of two to three barrier layers, though triple layered MF is most common among VIPs for building applications as of today. However, the reduced total metal layer thickness for MFs compared to AFs leads to a considerably faster moisture and air permeation through the VIP envelope and into the core for VIPs with MF envelopes. Hence, during several years the thermal conductivity will increase much faster in VIPs with MF envelopes than with AF envelopes. For thermal conductivity versus time up to 100 years for various VIP dimensions and envelopes, it is referred to the studies by Baetens et al. [3] and Wegger et al. [65], see Fig.5 (various VIP envelopes).

Figure 5. Thermal conductivity versus time for different envelope solutions (Wegger et al. [65]).

3 State-of-the-art vacuum insulation panel products

3.1 Vacuum insulation panel products

Vacuum insulation panels (VIP) are most commonly used for shipping containers for temperature sensitive materials, domestic appliances like freezers etc. However, for the last decade the most interesting aspect of VIPs have been their introduction to the building sector. In the following a short explanation of the use of VIPs in appliances will be given. Thereafter, the use of VIPs in constructions up until today will be looked upon. Both laboratory experiments and in situ measurements will be treated. As it would be too extensive to show all the possible buildings that have been tested with VIPs till now within this study, only a handful of selected examples will be given. Through these examples, the use of VIPs, experiences learned during construction and monitoring after completion will be explored.

Tables 1-3 show different vacuum insulation panel products available on the market today. The tables have been divided into VIPs for appliances (Table 1) and VIPs specified as possible to use in buildings (Table 2 and 3). The VIPs for building applications have been further divided into VIPs that are delivered as unprotected panels (Table 2), and VIPs that are delivered with various protective coverings (Table 3). These tables gives a short overview of the different products. Further information about the manufacturers and the products are given in the appendices.

The core materials for VIPs that are intended for appliances mostly consist of materials with larger pores or aerogel. As explained earlier aerogel is still too expensive to be a reasonable choice for most building applications, but its excellent thermal properties at a higher pressure gives aerogel a higher expected lifetime. Core materials with larger pore sizes are expected to lose the low thermal conductivity earlier than materials with a smaller pore size due to permeation through the envelope. However, these materials with larger pore sizes are also less expensive. More detailed information about the manufacturers and products can be found in Table A1.

Table 1. Literature data for manufacturers of VIPs for appliances.

Manufacturer	Product	λ_{tot}^{e} [W/(mK)]	Initial gas pressure	Core	Envelope
Jinko	VIP	0.001-0.006[a]			
Rparts	VIP				
Va-Q-tec	va-Q-pur	0.007-0.009[a]	< 1 mbar	PUR-foam	Al foil
	va-Q-mic	0.0028-0.0035[a]	< 1 mbar	Micro fleece	
Foamcore INC	Therm-max	R-40 per inch[a]		Aerogel	MF
Nanopore	VIP	0.004		Silica, titania and/or carbon	MF
Guangdong	VIP				
Xiamen Goot	VIP	0.004[a]	< 0.1 Pa	Fibre glass	
American Aerogel	Aerocore VIP	0.0019-0.0042[a]		Organic aerogel	MF
Fujian Supertech	VIP	0.0025[a]			
Unifrax	Exelfrax 200	0.00375		Fumed silica, opacifiers	Laminated PE film

a) No specific information given, b) Aged value allowing for edge effect, c) Initial value, d) Rated value, e) Aged thermal conductivity values and lifetimes are not given for most of the VIP products, although these are very crucial properties for the VIPs.

Table 2 shows manufacturers of VIPs that can be applied for building constructions. The general choice for core material among these VIPs are dominantly fumed silica. One important factor which is lacking for almost all producers are an expected lifetime of the VIP. As mentioned earlier, the difficulty in predicting a useful lifetime for VIPs is one of the main reasons VIPs are still struggling to become a renowned choice for thermal building insulation. Some manufacturers do however mention a theoretical rise in gas pressure per year. This value is in the range of 0.5-4 mbar/year.

Note that VIPs applied for building constructions does may also be used for other purposes. More information about the manufacturers of VIPs intended for buildings and their products can be found in Table A2.

Table 2. Literature data for manufacturers of VIPs for building applications.

Manufacturer	Product	λ_{tot}^{e} [W/(mK)]	Initial gas pressure	Core	Envelope
va-Q-tec	va-Q-vip	0.005[a]	< 5 mbar	Fumed silica	High gas barrier film
	va-Q-plus	0.0035[a]	< 5 mbar	80% fumed silica, Opacifiers, organic fibres	
	va-Q-plus A	0.0035[a]	< 5 mbar		
Panasonic USA	U-Vacua	R-60 per inch[a]			
Neofas AG	Vakutherm	0.0045[c]-0.008[b]		Pyrogenic silica	MF
Qingdao	Creek VIP	0.0035[a]	< 0.001 Pa	Fibre glass	
ThermoCor	VIP				
Caralon Global	CG Max-Thermic	0.0038[a]	< 1 mbar	Iner alkaline earth silicate glass wool	Al_2O_3
LG Hausys	VIP	0.004[a]		Glass fibre board	Al laminated film
Porextherm	Vacupor NT-B2-S	0.005[c]	< 5 mbar	Fumed silica, opacifiers and fibre filaments	MF
	Vacupor RP-B2-S	0.005 [c]	< 5 mbar	Fumed silica, opacifiers and fibre filaments	Al laminate
Porextherm	Vacupor PS-B2-S	0.005[c]	< 5 mbar	Fumed silica, opacifiers and fibre filaments	Al laminate
	Vacupor TS-B2-S	0.005[c]	< 5 mbar	Fumed silica, opacifiers and fibre filaments	Al laminate + sound absorbing plastic board

Manufacturer	Product	λ_{tot}^{e} [W/(mK)]	Initial gas pressure	Core	Envelope
	Vacuspeed	0.0043[c]	< 5 mbar	Fumed silica, opacifiers	Al laminate
	Vacupor NT		< 5 mbar		
Dow Corning	VIP	0.00369[c]		Fumed silica	MF
Microtherm	Slimvac	0.0042[c]	< 5 mbar	Filament reinforced silica and opacifier	MF
Vaku-isotherm	Standard	0.005[c]		Fumed silica, opacifiers and cellulose fibres	MF
	VakuVIP B2	0.005[c]		Fumed silica, opacifiers and cellulose fibres	MF
Variotec	QASA	0.007[a]	< 7 bar	Pyrogenic silica, Opacifiers	
Suzhou VIP	VIP	0.008[a]		Glass fibre	
Kingspan	OPTIM-R	0.007[b]			
Nanopore insulation	VIP				

a) No specific information given, b) Aged value allowing for edge effect, c) Initial value, d) Rated value, e) Aged thermal conductivity values and lifetimes are not given for most of the VIP products, although these are very crucial properties for the VIPs.

Table 3 shows manufacturers which produce VIPs with added protective coverings for building applications. The benefits of such sandwich panels are explained in more detail later. More information about the manufacturers of sandwich VIPs and their products can be found in Table A3.

Table 3. Literature data for manufacturers of VIPs with added protective coverings, i.e. sandwich VIPs, for building applications

Manufacturer	Product	λ_{tot}^{e} [W/(mK)]	Initial gas pressure	Core	Envelope
va-Q-tec	va-Q-vip B	0.0043[c]	< 5 mbar	Fumed silica	Foil and glass fibre
	va-Q-plus B	0.0035[c]	< 5 mbar	80% fumed silica, Opacifiers, organic fibres	Foil and glass fibre
Porextherm	Vacupor XPS-B2-S	0.005[c]	< 5 mbar	Fumed silica, opacifiers and fibre filaments	Al laminate + EPS
Vaku-isotherm	Gum-1	0.005[c]		Fumed silica, opacifiers and cellulose fibres	MF + rubber Granulate
	SP-1	0.005[c]		Fumed silica, opacifiers and cellulose fibres	MF + polystyrene
	SP-2/E	0.005[c]		Fumed silica, opacifiers and cellulose fibres	MF + polystyrene plates and sides covered with EPS
	Protekt-1	0.005[c]		Fumed silica, opacifiers and cellulose fibres	MF + fleece
	Bauplatte	0.005[c]		Fumed silica, opacifiers and cellulose fibres	MF + plastic plates and sides covered with EPS
	Sandwich Paneel 1	0.005[c]		Fumed Silica, opacifiers and cellulose fibres	MF + Glass plates and sides covered with EPS.
	Sandwich Paneel 2	0.005[c]		Fumed Silica, opacifiers and cellulose fibres	MF + glass/Al and sides covered with EPS
	Sandwich Paneel 3	0.005[c]		Fumed Silica, opacifiers and cellulose fibres	MF + Al/Al and sides covered with EPS
Variotec	QASA	0.007[a]	< 7 mbar	Pyrogenic silica, Opacifiers	

a) No specific information given, b) Aged value allowing for edge effect, c) Initial value, d) Rated value, e) Aged thermal conductivity values and lifetimes are not given for most of the VIP products, although these are very crucial properties for the VIPs.

From the products found on the market it is clear that fumed silica is the current choice for building applications, while various core materials are used for all other applications. Product-related requirements that separate VIPs intended for buildings from other VIPs have been discussed by Tenpierik et al. [57]. These are requirements concerning structural stability, fire protection, hygiene, health and environment, application safety and fitness for use, acoustical performance, thermal performance and service life. VIPs for building applications put more requirements on the core material.

As seen in Fig.2, fumed silica cores can maintain a stable thermal conductivity up to about 10 mbar and has a centre of panel thermal conductivity of about 0.008 W/(mK) at 100 mbar. This gives VIPs with silica cores a higher expected lifetime. Further advantages of fumed silica for building applications have been discussed earlier in this review. Even though the costs of fumed silica is higher than glass fibre or PUR foam, it is necessary to fulfil the requirements for building applications.

VIPs have been used with success in applications for some years. Glass fibre and PUR foam give the same initial thermal conductivity as silica core VIPs, but the expected lifetime is lower and various other requirements are not so strict for VIP cores of glass fibre or PUR foam. Glass fibre or PUR foam cores are also less expensive to produce, making these VIP cores a better choice whenever they are possible to use.

In this study, it is found that producers of building intended VIPs from Europe offers a large variety of different covering solutions for their products, which is well intended for use in buildings as they make the products more robust. However, the VIP coverings may also represent some drawbacks. For example, covering a VIP with expanded polystyrene (EPS) makes it more difficult to detect loss of vacuum, and furthermore the EPS has a higher thermal conductivity than the VIP area and thickness (volume) it replaces (Jelle [27]).

Overall, there are very few producers who state an expected lifetime and a guarantee for their panels. Some manufacturers state a lifetime which is only valid for specific conditions, and therefore not possible to compare with conditions in use. Many of the thermal conductivities are given without stating anything else. For the customers of this product, an aged value or an intended design value is important. However, as this study will discuss later, these values rely on many factors concerning the environment in which the product is used. Therefore, many manufacturers state that the values are only for guidance, and that each case has to be considered specifically.

3.2 VIPs in appliances

VIPs have shown good results in domestic appliances and for logistic purposes. Recently, research on VIPs that can withstand higher temperatures have also been performed. These VIPs have been introduced to insulate hot-water equipment and other high-temperature applications (Araki et al. [2]). For most typical appliances like refrigeration, thermal packaging and so on the normal lifetime expectancy for these panels are seldom required to exceed 15 years. This makes it possible to use glass fibre or polyurethane cores for these VIPs. Requirements are not so strict for general applications as broken panels rarely leads to anything else than replacing a broken ware.

3.3 VIPs in the building sector

3.3.1 VIPs in monitoring projects

Even though VIPs show great promise as a thermal insulation material solution of tomorrow there are several drawbacks that have to be addressed when considering VIPs for building applications. A VIP requires a low pressure inside. If the panel is perforated or broken in any way which leads to a loss of this vacuum, the thermal conductivity will increase to about 0.020 W/(mK) for VIPs containing fumed silica. Cutting and adapting the panel on-site is not possible. Insulating a building with VIPs therefore requires detailed planning from an early stage and a layout plan of how and where the panels shall be put into place. Practice also shows that the most common cause of damage to the panels occur before and during installation (Kunic [35]). Extra precautionary matters needs to be taken with the handling of VIPs as they are a fragile construction material. Damaged panels do not only decrease the thermal resistance of the building, but depending on how the VIPs are implemented there is also a risk of condensation and possibly mould growth (Parekh et al. [48]).

In Germany there have been a lot of test projects with constructions implementing VIPs, both refurbished and new constructions. Some were built as early as 2001 and have been monitored on a regular basis since. Bayerisches Zentrum für Angewandte Energieforschung (ZAE Bayern) in collaboration with various VIP producers have many interesting projects which show how the implementation of VIPs into buildings have proceeded. ZAE Bayern conducted a research project called VIP Prove, where the aim was to see how VIPs behaved under practical conditions. To choose these projects ZAE Bayern had certain criteria the buildings had to fulfil, giving them a score of up to 85 points, where the higher the score was the more suitable a construction was for monitoring.

The first criteria depended on how suited the construction elements were for a thermographic scanning. When conducting a thermographic scan of the building element the VIPs should not be covered with heavy building elements or air-filled spaces that would disrupt the measurements and give unclear results to whether the panels are functioning as planned or not. Figure 6 shows a termographic scan which clearly shows a broken panel, where it is also seen that many of the joints between the panels have been poorly executed.

The second criteria was how many different areas the VIPs could be applied to. More areas which could be applied with VIPs were to prefer, as this would give more and comparable results within the same building.

The third criteria was the age of the panel. Preferably VIPs that had been implemented before 2005 should be monitored. The longer the panels have been in the building the more interesting it is to see how their properties have changed, that is, if they had changed at all.

The fourth criteria was the possibility to conduct other measurements to show the results of the thermal performance of the panels. These results could be used in comparison with the thermography measurements.

(Heinemann et al. [25]).

For the VIP Prove project a total of 29 objects, with an area of 8206 m^2 installed with VIPs were assessed. Out of these, 19 objects with an area 3224 m^2 installed with VIPs were investigated by termographic scanning. The results showed that 12.8 % of the VIPs were classified as faulty. However, three buildings were particularly faulty and stood out in the statistical evaluation. By removing these three buildings the percent of broken panels fell to 4.9 %. This might mean that these three projects have failed to handle the panels properly, that they have been installed wrongly or that a production error has affected many of the panels (EnOB [17]).

Some of these monitoring projects will be mentioned in the following chapters about new and refurbished constructions.

Figure 6. Thermography of a VIP facade from the outside. The green square (auffälliges VIP) shows a broken VIP and the green lines shows poorly executed joints (Heinemann et al. [25]).

3.3.2 Lifetime predictions

The useful lifetime can be explained as the time until the centre of panel thermal conductivity reaches a critical level. Usually this point is at around 0.008 W/(mK), meaning that when U-values are being calculated this should be the design value (Simmler et al. [53]). The VIPs will still function when this value is reached, but the thermal conductivity will continue to increase, thus also increasing the U-value and heat loss.

For VIPs meant for building applications the lifetime is one of the most important and crucial properties. Buildings should be dimensioned with a lifetime of up to at least 50 years in mind, preferably up to 100 years. Today most VIPs using a MF3 laminate can be said to have a lifetime of over 25 years under specific conditions (Simmler et al. [53], Baetens et al. [5] and Heinemann et al. [25]).

The uncertainties surrounding the exact lifetime of VIPs when they are in use, are still major factors for scepticism. Predicting the useful lifetime of VIPs have therefore been an aim of many studies. Accelerated climate ageing and comparative ageing of in situ panels and panels kept in laboratories have been conducted. The focus here is on permeating gases and water vapour through the envelope, as this increases the thermal conductivity. VIPs for building purposes should never have an increase of more than 2 mbar/year (Schwab et al. [52]). For a panel with fumed silica an increase of 2 mbar/year would equal a lifetime of almost 50 years.

A laboratory age test of 20 VIPs performed by The National Research Council - Institute for Research in Construction (NRC-IRC) in Canada over seven years showed that the average loss of R-value was about 2 % per year. In a test hut wall of the NRC construction 18 months of field exposure was performed with 5 different VIP products, 15 specimens from different manufacturers showed 5% aging in 4 out of 5 products and 2 out of 15 specimens failed. Therefore, they concluded that VIPs show promising longterm performance for service life of 25-50 years (NRC [45]).

Wegger et al. [65] mentioned that there are no standardized ways of performing accelerated ageing tests for VIPs. To get a prediction of a VIPs effective lifetime within a shorter time frame, such tests will be necessary to define. Several factors such as pressure, temperature, ultraviolet and infrared radiation, moisture, water exposure and freezing/thawing were tested, along with various climate cycling test. The results showed that the change in performance was relatively low compared to the initial thermal performance. However, two of the panels which were tested showed signs of failure from other factors than the accelerated ageing testing. This shows that VIPs are still a fragile material when exposed to high moisture and temperature, or that they may have defects from the manufacturing process.

3.3.3 Economics

Modern day passive houses built with traditional thermal insulation require a wall thickness of 35 cm or more, meaning that a large part of the building volume is filled up by insulation. By building with VIPs the required thickness can be reduced, hence increasing the value of a building through increased living space. VIPs are still far more expensive than conventional insulation, however studies have been made to show that the increased living space achieved by decreasing the wall thickness may still make VIP a more economically favourable choice. Studies that mention the cost benefit of the increased living space have been conducted by Jelle [27] and Alam et al. [1]. Alam et al. [1] also show that the payback time for VIPs is drastically reduced if the benefit of the increased usable area is included. This is based on that each square meter gained will lead to increased market value, which is of naturally highly dependent on the value per square meter in the given area.

For frame constructions there is also a possibility to reduce the use of materials where the size of the cavity traditionally has been increased to fit the thickness of conventional thermal insulation beyond what has been required for structural strength, i.e. by applying VIPs instead. This will lead to a reduction in use of materials and also reduce the transportation of materials to the building site. The economical impact of this has so far not been discussed in detail.

3.4 VIP sandwich elements

In the building projects which have been completed so far, it is clear that most of the damaged panels have been damaged during transport or while they are being installed at the building site. To protect VIPs, both under construction and in use, encasing it with other materials is a good solution. Such sandwich elements will reduce the risk of damaging the panel unintentionally. Some of the solutions also completely envelope the sides of the panel with expanded polystyrene (EPS). This is a favourable solution for adapting the panels on site as the EPS can be cut to fit the panels in the construction without harming the VIP. Note that the EPS (or other) covering makes it more difficult to discover loss of vacuum. Besides, EPS has a higher thermal conductivity than the VIP area and thickness (i.e. volume) it replaces (Jelle [27]).

Some producers already manufacture finished sandwich elements of different kinds, with protective layers such as granulated rubber, glass fibre boards, aluminium or glass plates and polystyrene plates. Different sandwich solutions have been given in Table 3. Another solution, where it is possible, is to prefabricate building elements with integrated VIPs. This is by some referred to as a structural vacuum panel (SVP) as demonstrated in Fig.7. Producing SVPs can be performed under controlled conditions where the risk of damaging panels can be reduced. The VIPs inside the finished elements will also be a lot less likely to be damaged during transport.

A prefabricated building from Scotland has been built using SVPs, showing that it is possible to attain a low U-value. This building was built with 125 mm thick SVPs with a 25 mm VIP at its core. The overall U-value for the wall ended up at 0.10 W/(m^2K) for a thickness of

234 mm (Nanopore Insulation [44]). However, prefabrication of buildings and various building elements are an entirely different issue which will have to be addressed for each individual project and the desires of the end users.

Figure 7. Illustration of a SVP (Nanopore insulation [44]).

3.5 Constructing with VIPs

VIPs can be applied to many different areas of a construction. This chapter will shortly describe some of the most common areas which are suited for VIP applications and discuss some important considerations when they are applied to these areas. More detailed information about different areas where VIPs can be implemented, and more detailed descriptions on building details has been made by Johansson, [33].

3.5.1 Facades and walls

For facades it is possible to either insulate the exterior or the interior part of the wall. For frame constructions there is a third possibility to insulate inside the cavity as well.

Internal facade insulation with VIPs may be an excellent choice for retrofitting. The thin layers of VIPs required, compared to conventional insulation, will enable lower U-values after retrofitting without the same loss of indoor space. This is especially interesting for listed buildings where the outside design is not allowed to be altered. However, careful planning concerning low exterior surface temperatures, increased number of freezing/thawing cycles and the risk of condensation has to be made to avoid damages and mould forming.

Insulating the outer facades is beneficial for the reduction of thermal bridging, and can be made easy by using adhesives to stick the VIPs to the facade.

In wall constructions VIPs will not only give positive results in reduced energy usage, but also quite be visible through slimmer wall constructions. As mentioned earlier this is will work towards making VIPs more economically favourable with respect to increased indoor living space.

3.5.2 Glazing structures

For glazing structures, the transition between glass areas and opaque areas can be made more architecturally appealing by insulating with VIPs. The high thermal resistance enables slim facades and smoother transitions (see e.g.Fig.8). In some areas VIPs were integrated into the glazed parts between enamelled glass panes (Pool [50]).

Figure 8. Residential and office building in Munich (DINE informationsdients [6]).

3.5.3 Doors

Doors are a part of a construction which is hard (due to a restricted thickness) to insulate properly with traditional insulation, and therefore the doors become a source for heat to leave the building. By inserting a VIP into a door it is possible to increase the thermal resistance of doors and thus reduce the total heat loss from the building. Nussbaumer et al. [47] showed that a wooden door system with an implemented VIP reduced the energy usage for the doors by 25 %.

3.5.4 Roofs

VIPs for roofing purposes have been tested for both flat roofs and sloped roofs. VIPs have shown to be especially good for roofs under terrace floors, where conventional insulation often makes it hard to get the entrance in line with the outer floor because of the requirements for insulating properly over the room below. Here the VIPs enable a slimmer insulation layer making it possible to insulate within the requirements and at the same time enabling an entrance in line with the outside floor.

Brunner et al. [10] have monitored VIPs in a flat roof construction over a three year period. Assuming that the initial thermal conductivity was 0.0045 W/(mK) and the practical service life ended when the thermal conductivity exceeded 0.008 W/(mK) the panels used had an expected lifetime of about 25 years.

3.5.5 Floors

Gaining space through insulating with VIPs in the floor is not highly economically beneficial. However, for rooms with large temperature difference demands such as e.g. cold storages the use of VIPs can be a good choice for reducing energy demands. In heated floors VIPs may increase the efficiency of the floor heating system. VIPs may also represent a good choice when there are different space or thickness restrictions, e.g. restricted floor to ceiling height. Furthermore, transitions between floors and outdoor areas can be made stepless by insulating with VIPs.

Refurbishing poorly insulated floors can also be accomplished with VIPs. An example from UK showed that insulating over an existing concrete floor slab could reduce the U-value from 0.78 W/(m^{2}K) to 0.15 (W/m^{2}K) by using 20 mm VIPs. The new floor had a minimal increase in thickness (Nanopore insulation [43]).

3.6 New constructions examples

A few examples of new constructions with VIPs will be shown here. These examples will be given to illustrate how VIPs can be implemented in new buildings. General considerations and experiences that were learned from these examples will be given as well. Building details will not be discussed in detail as these vary from each individual project. As VIPs are still considered a new material solution in the construction sector, there are still a lot of uncertainties about how they actually perform when implemented in a building, and how to plan the construction phase with VIPs. Different forms of buildings affect the way VIPs have to applied to the construction. In Nordic countries the most common way to build houses is by building with a lightweight timber-frame construction. However, central European countries such as Germany and Switzerland, where most studies on VIPs have been conducted, rely more on massive structures like brick and concrete for housing purposes.

Munich

The first building over two storeys to be entirely insulated with VIPs was a residential and office building in Munich (Fig.8 and Fig.9). Here the goal was to show the economic benefit of achieving a slimmer facade through VIPs. With a total area of 1350 m^2 the building's heating requirement is just 22 kWh/(m^2year). This project was also a part of the earlier discussed ZAE Bayerns VIP Prove project. Under an inspection in 2009, 450 m^2 out of a total of 750 m^2 of VIPs were monitored with termographc scans. None of these showed any signs of damage. (BINE Informationsdienst, [6]).

This project showed that a big hurdle for VIPs, in addition to the uncertainties considering lifetime, is the lack of certified building systems. Getting the required certifications took several months and added extra costs to the project. Planners took on a lot of extra risk and work to make this happen (Pool [50]).

Figure 9. Termographic scan of the the VIP project from Munich (Pool [50]).

Freiburg

Figure 10 shows the Sun Ship from Freiburg, completed in 2006. The supporting structure is made from reinforced concrete and the facade is constructed from a wooden post-beam construction. A total of 1198 m^2 of VIPs are fit into place within the facade. Energy efficient design, along with the VIPs and installation of photo voltaic solar cell modules have made the Sun Ship the first commercial plus-energy building. The building has won several awards for its energyefficient profile. (SolarArchitektur [54]). This shows that VIPs can be implemented and acknowledged in the aim for a more energyefficient architecture.

Figure 10. The Sun Ship in Freiburg (VIP-Bau [61]).

Leipzig

In Leipzig in 2006 a single family house was built using a total of 265 m^2 of VIPs (Fig.11). The VIPs were implemented in the outer part of the wall construction. The building was raised with a steel skeleton. The goal was to build a light construction that was energy efficient, ecologically flexible and of materials that were recyclable. When the construction was finished the energy used for heating was under 15 kWh/m^2.

Figure 11. Single family house in Leipzig (VIP-Bau [61]).

Laboratory examples with timber-frame constructions

Hot box measurements on a timber frame construction with 40 mm thick VIPs demonstrated that it was possible to reach a U-value of 0.10 W/(m^{2}K) with a wall thickness of ~20 cm. However, it was clear that building with VIPs requires more effort in the planning phase because of the lack of adaptability (Haavi et al. [24]). Hot box experiments with VIPs in a timber frame construction were also conducted by Grynning et al. [23], including single and double layers, tape, and stacking/overlapping effects. Furthermore, accelerated climate ageing of VIPs in a timber frame construction was carried out by Wegger et al. [65].

3.7 Retrofitting examples

VIPs hold great possibilities within the refurbishing of existing constructions. High-performance thermal insulations such as VIP can be applied even where space is limited and help to reduce the heat loss from the building considerably. That is, reducing the total energy usage. In constructions where it is difficult to modify the thickness of the building, implementation of high-performance insulation is an efficient option to achieve a greater energy efficiency through insulation. The efficient use of space also opens up for possibilities of renovating listed buildings, which are not allowed to be renovated at the expense of changing the building design.

ZAE Bayern has also conducted monitoring projects on retrofitted buildings. From the VIP Prove project of ZAE Bayern, the highest score for a refurbished construction was achieved from a project in Berlin. For this project a total area of 96 m^2 of wall were built with VIPs.

Laboratory example with a timberframe construction

An investigation of retrofitting with VIPs in a timberframe structure has been conducted by Sveipe et al. [55]. This study looked at the potential to retrofit old Norwegian buildings with VIPs, thus lowering the energy usage to that of a passive house. A test module was built between two climate rooms to test how the VIP constructions performed with respect to oisture transport and risk of condensation, both when applied on the inside and outside of the wall.

Insulating the outside will enable the reduction of thermal bridges, which is one reason this is normally the preferred solution with conventional vapour open solution. However, vapour tight VIPs retrofitted at the exterior side, there may be a risk of condensation on the inner side of the VIPs. With 100 mm mineral wool retrofitted with 30 mm VIPs, the wall achieved an U-value of 0.143 W/(m^2K) for VIPs in pristine condition. When ageing of the panels were considered (panels reaching a thermal conductivity of 0.008 W/(mK)) the wall had an U-Value of 0.181 W/(m^2K). These results did not account for the small thermal bridging of the vertical VIP joints.

Practical example from Canada

During the 10th international vacuum insulation symposium (IVIS-X) in Canada in 2011 a few construction retrofit examples from Canada were presented. One of these was the retrofitting of an institutional building in Yukon. The interest for a new and high performing insulation material with high insulation values per units of thickness and weight is increasing. Determining the VIP qualities in the harsh environment of northern Canada was of interest. Initially, one exterior facade was insulated using VIPs. As costs were high, contractors were hesitant to insulate an entire building with this new technology. By testing one section of the building first, the results might lead to increased trust and willingness to conduct more projects with VIPs.

After the project, the construction experience was positive. Local interest around VIPs was said to increase. The low weight and small thickness made the installation easy, and as a result the labour was completed under budget. The VIPs were easily installed with adhesives, i.e. they were stuck directly on the wall as shown in Fig.12. However, the project is still being monitored further so there are no conclusive results of the VIP performance yet, even though the initial indications are positive.

Some important points that were highlighted during this project was the need to train all staff on how to install and handle VIPs. The panels are still expensive and difficult to replace. At the end of a workday the VIPs should always be covered by some form of protective layers. The areas where the VIPs are to be installed must always be investigated for elements that may harm the envelope through mechanical rubbing. (MacLean et al. [38]).

Figure 12. Installation of VIPs with adhesives (MacLean et al. [38]).

4 Future research pathways

4.1 Other state-of-the-art insulation materials

Though VIPs show great promise as an insulation material for tomorrow, it is not the only one under development. Other interesting materials that may compete with VIPs in the future will be mentioned in the following chapters.

4.1.1 Aerogel

Aerogels are dried gels with a very high porosity, high specific surface area, low apparent density and a low refraction index. The pore volume of aerogel may vary from 85 up to 99.8 %. This gives the material a bulk density as low as 3 kg/m^3, making it the lightest solid state material known. For building applications the density is in the range of 70-150 kg/m^3. At ambient pressure the thermal conductivity may be as low as 0.0135 W/(mk), which can be reduced down to 0.004 W/(mK) at a pressure of 50 mbar (Baetens et al. [3]).

Figure 13. A photo of translucent/transparent aerogel (Dornob, [16]).

Aerogel at ambient pressure has thermal conductivity values 2-3 times lower than conventional insulation, and unlike VIPs, it can be cut and adjusted at the building site. However, aerogel has a very low tensile strength, making the material very fragile.

The optical properties of aerogel are quite remarkable. It is possible to produce aerogel which is opaque, translucent or transparent, (Fig.13) making it possible to use it for a wide spectrum of applications, such as windows, facades and roofs which will allow solar radiation and daylight to pass through (Baetens et al. [3]).

4.1.2 Gas-filled panels (GFP)

Gas-filled panels (GFP) consist of a gas between reflective layers sealed within a low-emissivity barrier envelope. The reflective layers inside a GFP is called a baffle. Figure 14 shows the cross-section of a normal GFP. The gas inside the core can either be air or other heavier gases that further reduces the thermal conductivity. Theoretical values of 0.020 W/(mK) and 0.012 W/(mK) for argon and krypton filled panels, respectively, have been found. However, prototype GFPs have given a thermal conductivity of 0.040 W/(mK) for panels filled with argon in practical use in a building construction. As a technology with the same fragility and lack of flexibility as VIPs, but still showing a higher thermal conductivity, the future of GFPs is questionable (Baetens et al. [4]).

Figure 14. Technology cross-section of a GFP (Fi-Foil company [20]).

4.1.3 Nano insulation materials (NIM)

Figure 15. Conceptual model of a NIM based on hollow nanospheres (left), TEM image of actual hollow silica nanospheres (right) (Sandberg et al. [51]).

Nano insulation materials (NIM) can be described as materials that are basically homogenous and which achieve high-performance thermal insulating qualities mainly due to their open or closed nanoporous structure. By reducing the pore size until the maximum pore size in the material is lower than the mean free path of air the gaseous thermal conductivity can be substantially reduced. From the conceptual ideas of NIMs (Jelle et al. [28], Jelle et al. [29], Baetens et al. [5] and Jelle [27]), the first experimental steps have been carried out in order to actually make NIMs in the laboratory (Jelle et al. [30], Gao et al. [21], Gao et al. [22], Sandberg et al. [51]). One main focus for trying to make NIMs today is manufacturing of hollow silica nanospheres (Fig.15). Production and measurements on the thermal insulation ability of hollow silica nanospheres are further described by Liao et al. [37], Sandberg et al. [51].

4.2 Possible future research on current VIP technologies

4.2.1 Various requirements

When addressing the future possibilities of VIPs the problem areas of today should be considered. Thermal insulation materials intended for building applications should fulfil several requirements as suggested by Jelle et al. [28], Jelle et al. [29] and Jelle [27].

It is proposed that the initial thermal conductivity should be 0.004 W/(mK) or below, whereas it should not exceed 0.005 W/(mK) after 100 years. Perforation should not affect the thermal performance of the material, and it should be robust when considering climate stresses such as freezing/thawing cycles and ageing. The thermal insulation material should be adjustable on the building site and furthermore it should have a low negative environmental impact. In addition, the insulation material should be cost-competitive in comparison with other products.

For VIPs of today, a lot of the suggested requirements are not met. The path forward can either focus on improving the current technologies or explore new technologies based on similar principles as those that have been used while working with VIPs. In the following some of the work and reflections about the future of VIPs will be discussed.

As mentioned earlier the two main components that lead to and maintain the low thermal conductivity of VIPs are the core and the envelope. However, they are not directly depending on each other. That is, improving one of the two individually will contribute positively to a VIP. Hence, research being conducted on improving the core and envelope can be explored separately.

4.2.2 The core

There are several factors with the current core technology that can be addressed to make VIPs more attractive.

1. Developing core materials that better resist permeating gases and water vapour. Introducing getters and desiccants to the core is not a permanent solution to gases permeating through the envelope. They will eventually reach their capacity for adsorbing water vapour and gases and the core material will begin to lose its thermal

properties. New core materials with smaller pores, a stronger structure and generally better resistance may increase the expected lifetime of a VIP.

2. Producing core materials that can achieve a lower solid and radiative conductivity. Further reduction of the thermal conductivity may be achieved through reducing the heat loss from conduction in the solid material and the radiative heat transfer through the voids in a VIP. However, as noted earlier, the solid state conductivity and radiation conductivity are already very low, i.e. 0.004 W/(mK) or lower.

3. Reducing the production cost of the current core materials or seek new materials that can be produced at less costs. For VIPs manufactured for the building sector, the core materials are mainly nanopourous materials. As of today the production costs for these materials are still very high. Exploring new methods to produce the core materials can therefore make VIPs more cost competitive.
4. Developing core materials that are better at maintaining a vacuum, and less vulnerable towards perforation and cutting (e.g. vacuum insulation materials VIM), and ultimately core materials that have low thermal conductivities at atmospheric pressure (e.g. nano insulation materials, NIM) (Jelle et al. [28], Jelle et al. [29], Baetens et al. [5], Jelle [27]). That is, such core material developments are moving beyond the very concept of *vacuum* insulation *panels*, i.e. not requiring vacuum or (enveloped) panels.

The National Research Council - Institute for Research in Construction (NRC-IRC) has noted the costs of VIPs to be one of the major factors that is stopping the wide use of VIPs in the construction sector. To meet this challenge, they have started ongoing research to find less expensive core materials. By using a vacuum guarded hot plate (VGHP) different open porous insulating materials can be tested at different pressure levels. None of the materials tested so far have been commercialized, but work is still ongoing (Mukhopadhyaya et al. [41]).

4.2.3 The envelope

The envelope is the weak point of VIPs as of today. Permeation through the envelope leads to an increase in thermal conductivity, heat bridging contributes to a higher thermal conductivity and the envelope is fragile and can easily be perforated. These are some of the major issues that need to be further improved. One aim is to develop an envelope without the aluminium layers. The aluminium in todays laminates leads to an increase in thermal bridging. However, they are necessary to reduce the permeability through the envelope as polymers do not have the same resistance against permeation. If a polymer material with better resistance could be introduced this would work favourably for the reduction of thermal bridging. Reducing the permeation sufficiently would also allow for less expensive materials such as glass fibres and PUR foams to be used as core materials with an extended life time. Note the earlier discussion herein concerning the faster increase in thermal conductivity for thin metalized foils (MF) than the thicker aluminium foils (AF).

The production method may also lead to flaws with todays envelopes. Material imperfections and processing errors need to be handled to increase the trust in VIPs. Material imperfections such as pinholes are impossible to notice by just a visual inspection, but may reduce the lifetime of the panel. New methods of assuring the quality should be considered. This will also be beneficial as it will allow monitoring of panels without results being affected by a faulty production process.

There is also the problem with the lack of robustness for the envelope. Steel casings have already been tried for use as envelopes. Stainless steel makes for an almost impermeable envelope with only a few mm thickness. The steel will also represent a robust panel, which is not easily perforated. However, there is the issue of a greatly increased thermal bridging. A method with serpentine edging to minimize edge loss, has been investigated by Thorsell [59]. Figure 16 shows an illustration of how serpentine edges works. For a steel casing with 11 serpentines with a depth of 20 mm, the thermal bridging effect was found to be 0.010 W/(mK).

Figure 16. Serpentine edging in VIPs (Thorsell [59])

Further research must also be made on the sealing technique for the envelope. The heat sealed flange is often considered as a weak point in the modern VIPs. Understanding the processes around the sealing process may help to improve the seals and reduce the permeation through it. There are also investigations going on as to where it is most beneficial to put the seal, i.e. either along the panel edges, or on one of the large area surfaces on the panel.

4.3 Further reflections

One important factor to consider is the 'economies of scale'. VIPs have not yet been widely used as a thermal insulation material, and even though there are a variety of manufacturers, the production scale is not comparable to conventional insulation. As VIPs gain confidence as an insulation material, the scale of production will increase and most likely lead to a reduction of production costs for VIPs (Mukhopadhyaya et al. [42]).

As mentioned earlier, there are other insulation materials in development that may end up competing with VIPs in the future. The outlook is interesting for both aerogels and nano insulation materials (NIM), and further studies are being conducted on these materials. Their ability to be adapted at the building site, lack of inherent thermal bridges, and generally higher robustness makes them more suited for building applications. The nature of the construction industry is known to be conservative. Introducing VIPs, that are a fragile and not a very flexible material, will put new demands on contractors and building planners for how to plan, handle and implement the VIPs correctly. Aerogels and NIMs however, could be implemented much like conventional insulation today, and would make for a much more seamless adaption (Tenpierik [56]).

4.4 Producing vacuum insulation with new technology

The general idea of VIPs is that the vacuum greatly reduces the gaseous conductivity through a material. However, with the current manufacturing technology, an open porous structure is a requirement for panels to be totally evacuated to a vacuum. A new thought is to create a material with a closed pore structure in combination with vacuum (Fig.17). This would give the same low thermal conductivities as a VIP, but without the need for a sealing envelope. Should a material like this be perforated the result would just be a local thermal bridge, and the material could also be cut and adjusted at the building site. Such a material is referred to as a vacuum insulation material (VIM) (Jelle et al. [28], Jelle et al. [29], Baetens et al. [5], Jelle [27]).

Figure 17. Illustration of a vacuum insulation material (VIM) (Baetens et al. [5]).

However, a problem for this solution would be that gases and water vapour would also permeate through the solid state pore walls similar to as it would through the envelope of a VIP.

Synthesis of a closed porous silica has been studied by Pei et al. [49]. A challenge concerning a closed pore structured material is that the material can no longer be evacuated. Therefore, a material like this may have to be manufactured under vacuum to create an evacuated closed pore structure or a material blowing itself up from withon or pore walls absorbing all of the initial gases in the pores (Jelle et al. [28], Jelle et al. [29]).

4.5 The path forward for VIPs in the construction sector

As VIPs improve and becomes a part of the building envelope of tomorrow, it will be necessary to create standards for their use. As of today, the building projects which have been completed have had to be approved individually. Applying for approval for each individual building from local building regulators is time consuming and makes it harder for VIPs to gain access to the building sector at a larger scale. As we have seen however, many of the reference projects have given positive results. New standards should include how to properly handle, store and install VIPs. As mentioned by Brunner [11] a standard which is in line with the other European product standards EN13162 to EN 13171 on how to handle thermal insulation, should be made for VIPs as well. These standards do, among other issues, state initial testing and production control for the materials. Other important factors that needs to be described are design guidelines, more clear material specification standards, and handling instructions.

Another goal for the building sector may also be to innovate how constructions are being built around VIPs. It is a weak point of VIPs that the thermal conductivity increases by a factor of about 5 times should the panel be punctured. New planning of constructions to make it possible to monitor the VIPs and easily replace broken VIPs might make them more suitable and desired for constructions. For various experimental tests on VIPs for building applications it is referred to the investigations by Grynning et al. [23], Haavi et al. [24], Sveipe et al. [55] and Wegger et al. [65], whereas for more general information about accelerated climate ageing of building materials, components and structures, including new materials and solutions (e.g. VIPs), it is referred to the studies by Jelle [31] and Jelle et al. [32].

The manufacturers of VIPs and contractors should also work together to establish a common norm for the use of VIPs in buildings. Enabling standard formats for VIPs would be beneficial for all participants. Allowing VIPs to be stored in the factory after production may enable the manufacturers to notice broken panels before they are shipped out. Broken panels will be easier to re-order from stock and a standardized production process may lead to fewer defect panels. As of today, production problems are still critical for faith in the VIP technology (Zimmermann [67]). The need for quality assurance is present in the market. Standardized tests to assure there are no microscopical damages or relatively large leakages through weak seals should be guaranteed to the customers through a quality label (Erbenich [18]).

Measuring the gas pressure inside the panels is still difficult. When defect panels are discovered the only solution is to exchange the panels. Caps et al. [14] have demonstrated that technology for measuring the gas pressure inside the panels is available. For the future, the use of measuring technology has to be more common so that the quality of all VIPs can be assured.

In Europe a Common Understanding of Assessment Procedure (CUAP) and globally an ISO Working Group have been established to deal with testing procedures for VIPs. The definition of clear test methods will help to define when panels are damaged because of faults in production versus bad handling during transport and installation (Brunner et al. [13]).

5 Conclusions

This study shows and presents a variety of vacuum insulation panel (VIP) manufacturers on the market today, offering a wide variety of VIP products. VIPs in general applications have already been used on the market for nearly two decades with success. For the construction sector there are still challenges to overcome. The lack of certified building systems and official approvals from governmental agencies are providing hurdles that will need to be handled. Education and further promotion of VIPs are important in order to accelerate the implementation of VIPs in constructions. Thus, the challenges lies with the manufacturers. They need to improve the quality assurance of their VIP products, and to be able to give a guarantee the end users can rely on.

For the future it is important that data from already finished constructions are gathered and shared, so that the uncertainty of how VIPs perform at practical conditions can be reduced. Removing uncertainties around VIPs, and reducing the costs, will be an important factor for a larger commercialization of this product.

VIPs show great promise as a building insulation material in the near future. Many projects have already been completed with VIPs, where many show good initial results. If the technology can be further improved, and the current lifetime can be extended and guaranteed, VIPs will become a more trusted choice for thermal insulation. However, even if the moisture and air diffusion into the VIP core somehow could be reduced to almost zero (which is far from the situation today), the lack of flexibility and the risk of perforation will always be major drawbacks for the use of VIPs. Other high-performance insulation solutions have been described briefly. Some show great promise, combined with the possibilities of increased flexibility and being able to adapt at the building site. These may become a favourable choice over VIPs if or when they are able to be commercialized.

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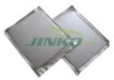
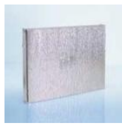
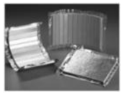
Appendix

Table A1. Manufacturers of VIPs for appliances or applications that are not specified

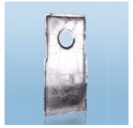
Manufacturer	Product	Illustration	Thermal conductivity[e] (W/(mK))	Mass density (kg/m^3)	Initial gas pressure (mbar)	Spesific heat-capacity (kJ/(kgK))	Standard dimensions (LxW) (mm x mm)	Thickness (mm)	Core/ Envelope	Additional information
JINKO Qingdao Jinko New Materials Co.,Ltd Haier Rd, High-tech industrial zone, Laoshan Section, Qingda, Shandong Province China Tel: 86-532-88964006 jinkovip@gmail.com http://www.jinkovip.com	Vacuum insulation panel		0.001-0.006[a]							Does not mention building applications http://jinkovip.com/product/detail.php/id-35.html [Accessed 04.06.2013]
Rparts Refrigeration Parts Solution, LLC Santa Cruz, CA 95066 USA Tel: (831)600-7878 sales@rparts.com http://www.rparts.com	VACUUM INSUL:082-1817						18 inch x 18 inch	1 inch		Produced for refrigeration http://www.rparts.com/index.php?cPath=9_32 [Accessed 04.06.2013]
va-Q-tec AG-Würzburg, Headquarters Karl-Ferdinand-Braun Strasse 7 97080 Wuerzburg / Germany Tel.: +49 (0)931 35 942 0 Fax: +49 (0)931 35 942 10 info@va-q-tec.com http://www.va-q-tec.com/	va-Q-pur		0.007-0.009[a]	65	< 1 mbar		max 1200 x 1000 ,	10-40	**Core** Polyurethane foam **Envelope** Aluminium foil/film	Developed for applications, freezers etc. Service life up to 15 years http://www.va-q-tec.com/va-q-pur_en,2756.html [Accessed 04.06.2013]
	va-Q-mic		0.0028-0.0035[a]	220	< 1 mbar		max 1300 x 1000	14 and 20	**Core** Micro fleece	For applications with extremely little space Service life approx 5 years http://www.va-q-tec.com/va-q-mic_en,2757.html [Accessed 04.06.2013]

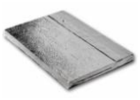
Manufacturer	Product	Illustration	Thermal conductivity[e] (W/(mK))	Mass density (kg/m^3)	Initial gas pressure (mbar)	Spesific heat-capacity (kJ/(kgK))	Standard dimensions (LxW) (mm x mm)	Thickness (mm)	Core/ Envelope	Additional information
Foamcore, Inc. 1704 Wayneport Road Macedon, New York 14502 USA Phone: 315-986-4390 Fax:315-986-4391 sales@foamcoreinc.com http://foamcoreinc.com/	Therm-Max Panels		R-40 at 1 inch[a]						**Core** Aeroblack (aerogel) **Envelope** Aluminized polyester laminate	For thermal packaging http://foamcoreinc.com/public/Panels.html [Accessed 04.06.2013]
Nanopore NanoPore Incorporated 2501 Alamo Avenue SE Albuquerque, New Mexico 87106 USA Tel: (505) 247-4041 Fax: (505) 247-4046 info@nanopore.com http://www.nanopore.com	Vacuum insulation panel		< 0.004[a], 0.008[b]	170			25-900 x 25-600	6-30	**Core** Silica, titania and/or carbon **Envelope** Three-layer laminate with aluminium metalization on two of the layers to enhance barrier performance.	Use for building applications not specified http://nanopore.com/vip.html [Accessed 04.06.2013]
Guangdong Alison Hi-Tech Co.,Ltd. Rm 1202, Golden Lake Building, No.2 Donghu Road West, Guangzhou, China Tel : 86-20-8386-0079 Fax : 86-20-8384-7308 ydalison@hotmail.com http://www.ydalison.com	Alison Aerogel Insulation									For refrigerant insulation http://alisonaerogel.en.ecplaza.net/alison-aerogel-vacuum-insulation-panel--237903-2182851.html [Accessed 04.06.2013]
Xiamen Goot Advanced Material Co., Ltd. 99 Liantang Road, North Jimei Industrial Region, Xiamen City, Fujian Province. China Tel: 86-592-6688857/66866 Fax: 86-592-6689988 market@goot.com.cn http://www.goot.com.cn	Vacuum insulation panel		< 0.004[a]	230	< 0.1 Pa		Max 1600 x 700	10-35	**Core** Fibre glass	10-15 years service life http://xgamcl.en.china.cn/selling-leads/detail,1067096931,Vacuum-Insulation-Panels-VIP.html [Accessed 04.06.2013]

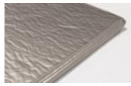
Manufacturer	Product	Illustration	Thermal conductivity[e] (W/(mK))	Mass density (kg/m^3)	Initial gas pressure (mbar)	Spesific heat-capacity (kJ/(kgK))	Standard dimensions (LxW) (mm x mm)	Thickness (mm)	Core/ Envelope	Additional information
American Aerogel 460 Buffalo Rd. Suite 200A Rochester, NY 14611 USA Tel: (585) 328-2140 Fax: (585) 785-8624 info@americanaerogel.com http://americanaerogel.com/	Aerocore VIP		0.0019-0.0042[a]	0.15-0.2 g/cc	O2TR < 0.0005 cc/m^{2}day		up to 500 x 600	12-25	**Core** Organic aerogel **Envelope** Aluminized polyester laminate	Building applications not mentioned http://americanaerogel.com/wordpress/wp-content/uploads/2012/02/Aerocore-Properties.pdf [Accessed 04.06.2013]
Fujian supertech advanced material Co, Ltd Lianguan Industrial Area, Liancheng County ,Longyan City,Fujian Province, China Tel：+86-0592-6199925 market@supertech-vip.com http://www.supertech-vip.com/En/	Vacuum insulation panel		< 0.0025[a]	240-314						http://www.supertech-vip.com/En/products.aspx [Accessed 04.06.2013]
Unifrax Corporation 2351 Whirlpool Street Niagara Falls, N.Y. 14305-2413 USA Tel: 716-278-3800 Fax: 716-278-3900 http://www.high-temperature-insulation.com/	Exelfrax 200 VIP Insulation		0.00375[a]	185			490-980 x 490-1225	10-30	**Core** Fumed silica, opacifiers **Envelope** Laminated PE film	Building applications not mentioned http://www.high-temperature-insulation.com/files/Excelfrax-200-VIP-Insulation.pdf [Accessed 06.06.2013]

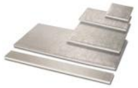
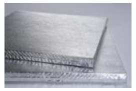
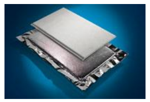
a) No specific information given, b) Aged value allowing for edge effect, c) Initial value, d) Rated value, e) Aged thermal conductivity values and lifetimes are not given for most of the VIP products, although these are very crucial properties for the VIPs

Table A2. Manufacturers of VIPs specified for building applications

Manufacturer	Product	Illustration	Thermal conductivity[e] (W/(mK))	Mass density (kg/m^3)	Initial gas pressure (mbar)	Spesific heat-capacity (kJ/(kgK))	Standard dimensions (LxW) (mm x mm)	Thickness (mm)	Core/ Envelope	Additional information
va-Q-tec AG-Würzburg, Headquarters Karl-Ferdinand-Braun Strasse 7 97080 Wuerzburg / Germany Tel.: +49 (0)931 35 942 0 Fax: +49 (0)931 35 942 10 info@va-q-tec.com http://www.va-q-tec.com/	va-Q-vip		< 0.0043[a]	180-210	< 5 mbar, Pressure rise approx. 1 mbar/year	0.8	1000 x 600, 500 x 600	10-50	**Core** Fumed silica **Envelope** High gas barrier film	Triangle, trapezium, special shape, cornet cut, hole cut and recessed surface Lifetime, extrapolated, depending on application up to 60 Years. http://www.va-q-tec.com/va-q-vip_en,2754.html [Accessed 04.06.2013]
	va-Q-plus		< 0.0035[a]	170-200	< 5 mbar, Pressure rise approx. 1 mbar/year	0.8	400-1750 x 250-1000	3-35	**Core** 80% fumed silica, Opacifiers, organic fibres	Can be made in various shapes Lifetime, extrapolated, depending on application up to 60 Years. http://www.va-q-tec.com/va-q-plus_en,2758.html [Accessed 04.06.2013]
	va-Q-plus A		< 0.0035[a]	170-200	< 5 mbar	0.8				Lifetime, extrapolated, depending on application up to 60 Years. http://www.va-q-tec.com/en/va-Q-plus-A-277,30322.html [Accessed 04.06.2013]
Panasonic USA Panasonic Industrial Company Applied Technologies Group 3 Panasonic Way, 7E-2 Secaucus, NJ 07094 USA Fax: (201) 271-3068 Vip@us.panasonic.com http://www.panasonic.com	U-Vacua		R-60 per inch[a]							http://www.panasonic.com/industrial/appliances-hvac-devices/vacuum-insulation/panel.aspx [Accessed 04.06.2013]

Manufacturer	Product	Illustration	Thermal conductivity[e] (W/(mK))	Mass density (kg/m^3)	Initial gas pressure (mbar)	Spesific heat-capacity (kJ/(kgK))	Standard dimensions (LxW) (mm x mm)	Thickness (mm)	Core/ Envelope	Additional information
NEOFAS AG Vogelsangstrasse 14 CH- 8307 Effretikon Switzerland Tel: +41 52 354 51 00 Fax: +41 52 354 51 01 info@neofas.ch http://www.neofas.ch	Vakutherm		0.0045[c]- 0.008[b]	180-220			300-1000 x 200-800	15-45	**Core** Pyrogenic silica **Envelope** Multiple metalized polymer foil	http://www.neofas.ch/produkte/vakutherm/vakutherm.html [Accessed 04.06.2013]
Qingdao Kerui New Environmental Materials Co., Ltd. 39 Donghai West Road Qingdao, 30th Floor, Century House China Tel：400-670-8338 Fax：0532-80778338 qingdaokerui@163.com http://www.cncreek.net	Creek VIP		< 0.004[a]		< 0.001 Pa		150-1800 x 100-600	10-50	**Core** Fibre glass	http://cncreek.net/en/product.aspx?id=2 [Accessed 04.06.2013]
ThermoCor 2900 Dryden Road Dayton, OH 45439 USA Tel: (937) 312-0114 http://www.thermocorvip.com	Vacuum insulation panel									http://www.thermocorvip.com/vacuum-insulation-panels/ [Accessed 04.06.2013]
Caralon Global Bletchley Park Science and Innovation Centre Bletchley Park Milton Keynes MK3 6EB United Kingdom Tel: +44 (0)1908 880721 http://www.caralonglobal.com	CG Max-Thermic		0.0038[a]	150-300	< 1 mbar		300-1200 x 250-1000	3-20 mm	**Core** Inert alkaline earth silicate glass wool **Envelope** Al_2O_3	Lifetime up to 45 years http://www.caralonglobal.com/index.php/products [Accessed 04.06.2013]

Manufacturer	Product	Illustration	Thermal conductivity[e] (W/(mK))	Mass density (kg/m^3)	Initial gas pressure (mbar)	Spesific heat-capacity (kJ/(kgK))	Standard dimensions (LxW) (mm x mm)	Thickness (mm)	Core/ Envelope	Additional information
LG Hausys EUROPE (Frankfurt) Lyoner str 15, Atricom C8, D-60528, Frankfurt/m, Germany Tel: 49-69-58302-9400 VIPinfo@lghausys.com http://www.lghausys.com	Vacuum insulation panel		< 0.004[a]	175			max 1800 x 700	1-30	**Core** Glass Fibre Board **Envelope** Al foil laminated film	http://www.lghausys.com/eng/product/highfunctional/vacuum/subindex.jsp [Accessed 04.06.2013]
Porextherm Dämmstoffe GmbH Heisinger Straße 8/10 D-87437 Kempten Germany Tel: + 49(0)831-575360 Fax: + 49(0)831-575363 info@porextherm.com http://www.porextherm.com	Vacupor NT-B2-S		< 0.005[c], 0.007[d]	170-210	< 5 mbar, pressure rise 1.0 mbar/year (theoretical)		150-2200 x 150-1000	10-50	**Core** Fumed silica, opacifiers **Envelope** Metalized, multilayer plastic film	http://www.porextherm.com/en/products/vacupor/vacupor-nt-b2-s.html [Accessed 04.06.2013]
	Vacupor RP-B2-S		< 0.005[c], 0.007[d]	150-300	< 5 mbar, pressure rise 0.5 mbar/year (theoretical)		150-1500 x 150-1000	10-50	**Core** Fumed silica, opacifiers, fibre filaments **Envelope** Aluminium foil	http://www.porextherm.com/en/products/vacupor/vacupor-rp-b2-s.html [Accessed 04.06.2013]
	Vacupor PS-B2-S		< 0.005[c], 0.007[d]	150-300	< 5 mbar, pressure rise 0.5 mbar/year (theoretical)		150-1500 x 150-1000	10-50	**Core** Fumed silica, opacifiers, fibre filaments **Envelope** Aluminium foil	authorities http://www.porextherm.com/en/products/vacupor/vacupor-ps-b2-s.html [Accessed 04.06.2013]
	Vacupor TS-B2-S		< 0.005[c], 0.007[d]	170-210	< 5 mbar, pressure rise 1,0 mbar/year (theoretical)		150-1500 x 150-1000	10-50	**Core** Fumed silica, opacifiers, fibre filaments **Envelope** Aluminium foil and sound absorbing plastic board	http://www.porextherm.com/en/products/vacupor/vacupor-ts-b2-s.html [Accessed 04.06.2013]

Manufacturer	Product	Illustration	Thermal conductivity[e] (W/(mK))	Mass density (kg/m^3)	Initial gas pressure (mbar)	Spesific heat-capacity (kJ/(kgK))	Standard dimensions (LxW) (mm x mm)	Thickness (mm)	Core/ Envelope	Additional information
Porextherm Dämmstoffe GmbH Heisinger Straße 8/10 D-87437 Kempten Germany Tel: + 49(0)831-575360 Fax: + 49(0)831-575363 info@porextherm.com http://www.porextherm.com	Vacuspeed		0.0043[c], 0.008[e]	170-210	< 5 mbar Pressure rise 1.0 mbar/year (theoretical)		250-1000 x 250-500	15-25	**Core** Fumed silica, Opacifiers **Envelope** Aluminium Foil, double-middle seam	http://www.porextherm.com/en/products/vacupor/vacuspeed.html [Accessed 04.06.2013]
	Vacupor NT		< 0.005[c]	150-300	< 5 mbar, pressure rise 0.5 mbar/year (theoretical)		150-2200 x 150-1000	10-30	**Core** Fumed Silica, Opacifiers **Envelope** Aluminium Foil	http://www.porextherm.com/en/products/vacupor/vacupor-nt.html [Accessed 04.06.2013]
Dow Corning Corporation Corporate Center PO Box 994 MIDLAND MI 48686-0994 USA Tel: 49 611 2371 Fax: 49 611 237620 http://www.dowcorning.com	Vacuum Insulation Panel		0.00369[c]	150-300			up to 900 x 600		**Core** Fumed Silica **Envelope** Aluminized multilayer barrier	80% of initial thermal resistance after 30 years Nonrectangular shapes are possible http://www.dowcorning.com/content/publishedlit/62-1556-01.pdf [Accessed 04.06.2013]
Microtherm Microtherm N.V. Industriepark-Noord 1 9100 Sint-Niklaas Belgium Tel (+32) 3 7601980 Fax (+32) 3 760 1999 info@microthermgroup.com http://www.microthermgroup.com	SlimVac		0.0042[c]	160-220	< 5 mbar		up to 1400 x 800	6-40	**Core** Filament reinforced silica and an opacifier **Envelope** Multiple metalized polymer layers	http://www.microthermgroup.com/low/EXEN/site/vip-intro.aspx [Accessed 04.06.2013]

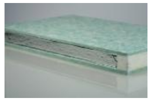
Manufacturer	Product	Illustration	Thermal conductivity[e] (W/(mK))	Mass density (kg/m^3)	Initial gas pressure (mbar)	Spesific heat-capacity (kJ/(kgK))	Standard dimensions (LxW) (mm x mm)	Thickness (mm)	Core/ Envelope	Additional information
Vaku-Isotherm GmbH Schönborner strasse 37 09669 Frankenberg/OT Sachsenburg Germany Tel:+49(0)37 206 89 14 50 Fax:+49(0)37 206 89 14 49 info@vaku-isotherm.de Web: http://www.vaku-isotherm.de	Standard		< 0.005[c]	150-220	pressure rise 1-4 mbar/year		150-3000 x 150-1250	10-50	**Core** Fumed silica, opacifiers and cellulose fibres **Envelope** Multiple metalized polymer layer	http://www.vaku-isotherm.de/vaku_isotherm.html [Accessed 04.06.2013]
	VakuVIP B2		< 0.005[c]	170-210	pressure rise 1-4 mbar/year		150-3000 x 150-1250	10-30	**Core** Fumed silica, opacifiers and cellulose fibres **Envelope** Multiple metalized polymer layer	http://www.vaku-isotherm.de/vaku_isotherm.html [Accessed 04.06.2013]
Variotec GmbH & Co. KG Weißmarterstraße 3-5 D-92318 Neumarkt/OPf. Germany Tel.: +49 9181 6946-0 Fax: +49 9181 6946-50 info@variotec.de http://www.variotec.de	QASA		0.007[a]	190-220	< 7 pressure rise ca. 1 mbar/year	1	250-1000 x 250-1000		**Core** Pyrogenic silica, opacifiers	Different covering solutions available http://variotec.de/hp3600/2-Newsletter-VIP-QASA.htm [Accessed 04.06.2013]
Suzhou V.I.P. New Material Co., Ltd. No. 136, Yanshan Road (W), Chengxiang Town, Taicang, Suzhou, Jiangsu, China Tel: 53665668/53665669 Fax: 0512-53 524 981 czn@hdfydq.com http://www.es-vip.com	Vacuum insulation panel		0.008[a]	240-280					**Core** Glass fibre	http://www.es-vip.com/English/a/chanpinjieshao/VIPzhenkongjuereban/ [Accessed 04.06.2013]

Manufacturer	Product	Illustration	Thermal conductivity[e] (W/(mK))	Mass density (kg/m^3)	Initial gas pressure (mbar)	Spesific heat-capacity (kJ/(kgK))	Standard dimensions (LxW) (mm x mm)	Thickness (mm)	Core/ Envelope	Additional information
Kingspan Insulation Ltd Pembridge Leominster Herefordshire HR6 9LA United Kingdom Tel: 01544 388 601 Fax: 01544 388 888 info@kingspaninsulation.co.uk http://www.kingspaninsulation.co.uk/	OPTIM-R		0.007[b]	180-210			300-1200 x 300-600	20-40	**Core** Microporous material	http://www.kingspaninsulation.co.uk/Products/Optim-R/Optim-R/Overview.aspx [Accessed 04.06.2013]
Nanopore Insulation Limited The Factory, Rectory Lane, Brimfield, Shropshire, SY8 4NX, United Kingdom. Tel: + 44 (0) 1584 711333 Fax: + 44 (0) 1584 711838 info@nanoporeinsulation.com http://www.nanopore.eu	Vacuum insulation panel		< 0.004[c], 0.008[b]	170			25-900 x 25-600	6-30	**Core** Silica, titania and/or carbon **Envelope** Three-layer laminate with aluminium metalization on two of the layers to enhance barrier performance.	http://nanopore.com/vip.html [Accessed 04.06.2013]

a) No specific information given, b) Aged value allowing for edge effect, c) Initial value, d) Rated value, e) Aged thermal conductivity values and lifetimes are not given for most of the VIP products, although these are very crucial properties for the VIPs

Table A3. Manufacturers of VIPS with protective coverings

Manufacturer	Product	Illustration	Thermal conductivity[e] (W/(mK))	Mass density (kg/m^3)	Initial gas pressure (mbar)	Spesific heat-capacity (kJ/(kgK))	Standard dimensions (LxW) (mm x mm)	Thickness (mm)	Core/ Envelope	Additional information
va-Q-tec AG-Würzburg, Headquarters Karl-Ferdinand-Braun Strasse 7 97080 Wuerzburg / Germany Tel.: +49 (0)931 35 942 0 Fax: +49 (0)931 35 942 10 info@va-q-tec.com http://www.va-q-tec.com/	va-Q-vip B		< 0.0043[c]	180-210	< 5 mbar Pressure rise 1 mbar/year	0.8	1000 x 600, 500 x 600	10-50	**Core** Fumed silica **Envelope** Foil and glass fibre	Approved for building applications http://www.va-q-tec.com/va-q-vip_b_en,2755.html [Accessed 04.06.2013]
	va-Q-plus B		< 0.0035[c]	170-200	< 5 mbar Pressure rise 1 mbar/year	0.8	1100 x 600, 1100 x 600, 550 x 600	5-20	**Core** 80 % fumed silica, opacifiers, organic fibres **Envelope** Foil and glass fibre	Specially designed for building applications with a shiplap for gapless joints extrapolated, depending on application up to 60 years http://www.va-q-tec.com/va-q-plus_b_en,19393.html [Accessed 04.06.2013]
Porextherm Dämmstoffe GmbH Heisinger Straße 8/10 D-87437 Kempten Germany Tel: + 49(0)831-575360 Fax: + 49(0)831-575363 info@porextherm.com http://www.porextherm.com	Vacupor XPS-B2-S		< 0.005[c], 0.007[d]	170-210	< 5 mbar, pressure rise 1.0 mbar/year (Theoretical)		150-1500 x 150-1000	10-50	**Core** Fumed silica, opacifiers, fibre filaments **Envelope** Aluminium foil and EPS	Approved for building applications by the german building and construction authorities http://www.porextherm.com/en/products/vacupor/vacupor-xps-b2-s.html [Accessed 04.06.2013]

Manufacturer	Product	Illustration	Thermal conductivity[e] (W/(mK))	Mass density (kg/m^3)	Initial gas pressure (mbar)	Spesific heat-capacity (kJ/(kgK))	Standard dimensions (LxW) (mm x mm)	Thickness (mm)	Core/ Envelope	Additional information
Vaku-Isotherm GmbH Schönborner strasse 37 09669 Frankenberg/OT Sachsenburg Germany Tel:+49(0)37 206 89 14 50 Fax:+49(0)37 206 89 14 49 info@vaku-isotherm.de Web: http://www.vaku-isotherm.de	Gum-1		< 0.005[c]	150-250	pressure rise 1-4 mbar/year		150-3000 x 150-1250	10-50	**Core** Fumed silica, opacifiers and cellulose fibres **Envelope** Multiple metalized polymer layer + 3 mm rubber granulate	http://www.vaku-isotherm.de/vaku_isotherm.html [Accessed 04.06.2013]
	SP-1		< 0.005[c]	150-220	pressure rise 1-4 mbar/year		150-3000 x 150-1250	10-50	**Core** Fumed silica, opacifiers and cellulose fibres **Envelope** Multiple metalized polymer layer and 10 mm polystyrene plates	http://www.vaku-isotherm.de/vaku_isotherm.html [Accessed 04.06.2013]
	SP-2/E		< 0.005[c]	150-220	pressure rise 1-4 mbar/year		150-3000 x 150-1250	10-50 + Polystyrol -Envelope	**Core** Fumed silica, opacifiers and cellulose fibres **Envelope** Multiple metalized polymer layer, 10 mm polystyrene plates and sides covered with EPS	http://www.vaku-isotherm.de/vaku_isotherm.html [Accessed 04.06.2013]
	Protekt-1		< 0.005[c]	150-220	pressure rise 1-4 mbar/year		150-3000 x 150-1250	10-50 + fleece envelope	**Core** Fumed silica, opacifiers and cellulose fibres **Envelope** Multiple metalized polymer layer and 1.4 mm fleece	http://www.vaku-isotherm.de/vaku_isotherm.html [Accessed 04.06.2013]
	Bauplatte		< 0.005[c]	150-220	pressure rise 1-4 mbar/year		150-3000 x 150-1250	10-50 + kunststoff - recyclingplatte	**Core** Fumed silica, opacifiers and cellulose fibres **Envelope** Multiple metalized polymer layer, 4 mm plastic plates and sides covered with EPS.	http://www.vaku-isotherm.de/vaku_isotherm.html [Accessed 04.06.2013]

Manufacturer	Product	Illustration	Thermal conductivity[e] (W/(mK))	Mass density (kg/m^3)	Initial gas pressure (mbar)	Spesific heat-capacity (kJ/(kgK))	Standard dimensions (LxW) (mm x mm)	Thickness (mm)	Core/ Envelope	Additional information
Vaku-Isotherm GmbH Schönborner strasse 37 09669 Frankenberg/OT Sachsenburg Germany Tel:+49(0)37 206 89 14 50 Fax:+49(0)37 206 89 14 49 info@vaku-isotherm.de Web: http://www.vaku-isotherm.de	Sandwich Paneel 1		< 0.005[c]	150-220	pressure rise 1-4 mbar/year		150-3000 x 150-1250	10-50 + glass envelope	**Core** Fumed silica, opacifiers and cellulose fibres **Envelope** Multiple metalized polymer layer, glassplates and sides covered with EPS.	http://www.vaku-isotherm.de/vaku_isotherm.html [Accessed 04.06.2013]
	Sandwich Paneel 2		< 0.005[c]	150-220	pressure rise 1-4 mbar/year		150-3000 x 150-1250	10-50 + glass and Al envelope	**Core** Fumed silica, opacifiers and cellulose fibres **Envelope** Multiple metalized polymer layer and glass/Al and sides covered with EPS	http://www.vaku-isotherm.de/vaku_isotherm.html [Accessed 04.06.2013]
	Sandwich Paneel 3		< 0.005[c]	150-220	pressure rise 1-4 mbar/year		150-3000 x 150-1250	10-50 + Al envelope	**Core** Fumed silica, opacifiers and cellulose fibres **Envelope** Multiple metalized polymer layer and Al/Al and sides covered with EPS	http://www.vaku-isotherm.de/vaku_isotherm.html [Accessed 04.06.2013]
Variotec GmbH & Co. KG Weißmarterstraße 3-5 D-92318 Neumarkt/OPf. Germany Tel.: +49 9181 6946-0 Fax: +49 9181 6946-50 info@variotec.de http://www.variotec.de	QASA		0.007[a]	190-220	< 7 Ca. 1 mbar/year pressure rise	1	250-1000x 250-1000		**Core** Pyrogenic silica, opacifiers **Envelope**	Different covering solutions available Can be used for building applications http://variotec.de/hp3600/2-Newsletter-VIP-QASA.htm [Accessed 04.06.2013]

a) No specific information given, b) Aged value allowing for edge effect, c) Initial value, d) Rated value, e) Aged thermal conductivity values and lifetimes are not given for most of the VIP products, although these are very crucial properties for the VIPs

Figure captions

Figure 1. Schematic of a VIP (Alam et al. [1]).

Figure 2. Thermal conductivity versus gas pressure for different core material (Tenpierik [56]).

Figure 3. VIP with a fumed silica core (va-Q-tec [60]).

Figure 4. Illustration of an Al foil and multilayer foils (Wegger et al. [65]).

Figure 5. Thermal conductivity versus time for different envelope solutions (Wegger et al. [65]).

Figure 6. Thermography of a VIP facade from the outside. The green square (auffälliges VIP) shows a broken VIP and the green lines shows poorly executed joints (Heinemann et al. [25]).

Figure 7. Illustration of a SVP (Nanopore insulation [44]).

Figure 8. Residential and office building in Munich (BINE informationsdients [6]).

Figure 9. Termographic scan of the the VIP project from Munich (Pool [50]).

Figure 10. The Sun Ship in Freiburg (VIP-Bau [61]).

Figure 11. Single family house in Leipzig (VIP-Bau [61]).

Figure 12. Installation of VIPs with adhesives (MacLean et al. [38]).

Figure 13. A photo of translucent/transparent aerogel (Dornob [16]).

Figure 14. Technology cross-section of a GFP (Fi-Foil company [20]).

Figure 15. Conceptual model of a NIM based on hollow nanospheres (left), TEM image of actual hollow silica nanospheres (right) (Sandberg et al. [51]).

Figure16 . Serpentine edging in VIPs (Thorsell [59])

Figure 17. Illustration of a vacuum insulation material (VIM) (Baetens et al. [5]).

Fig1

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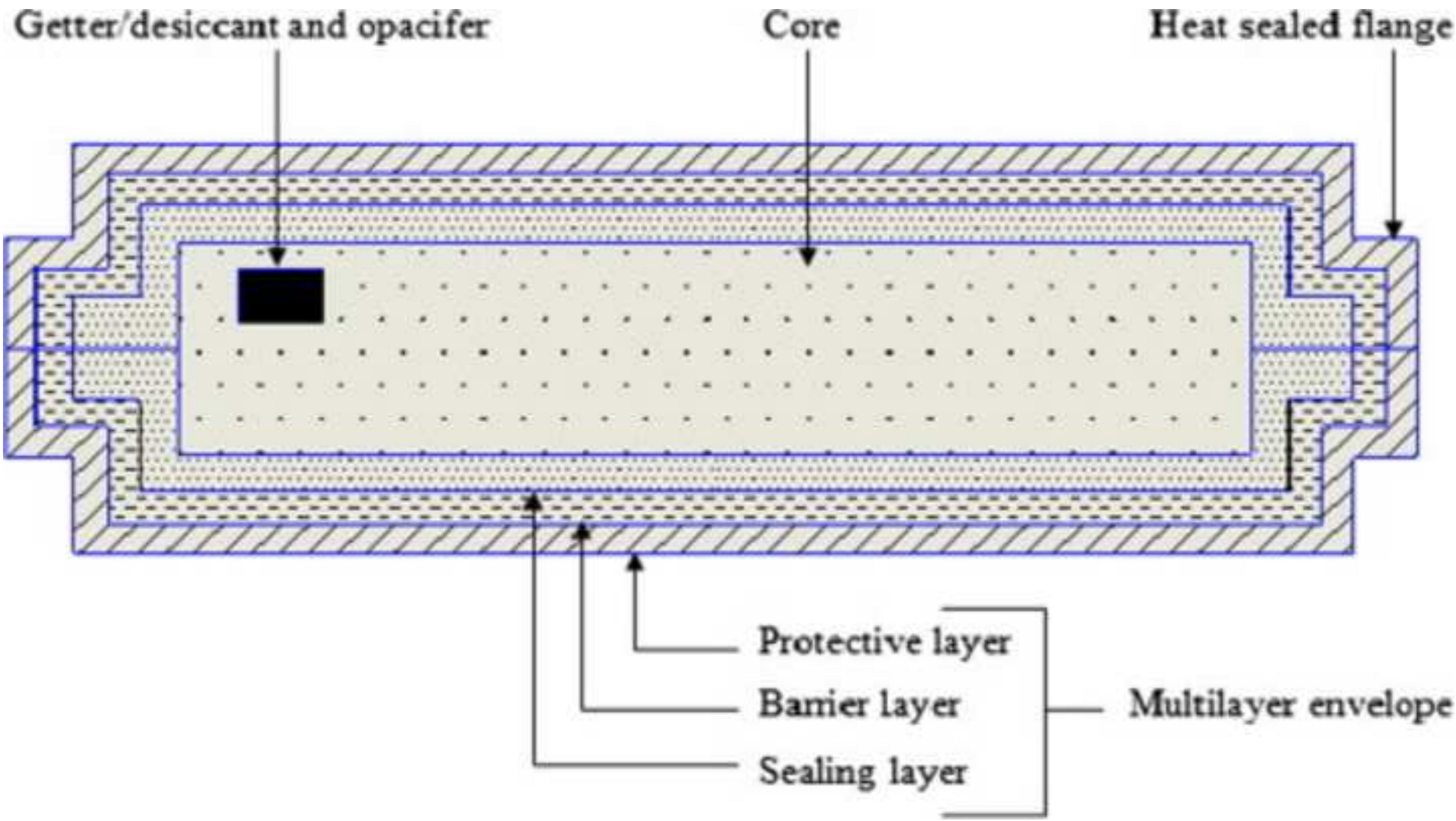

Fig2

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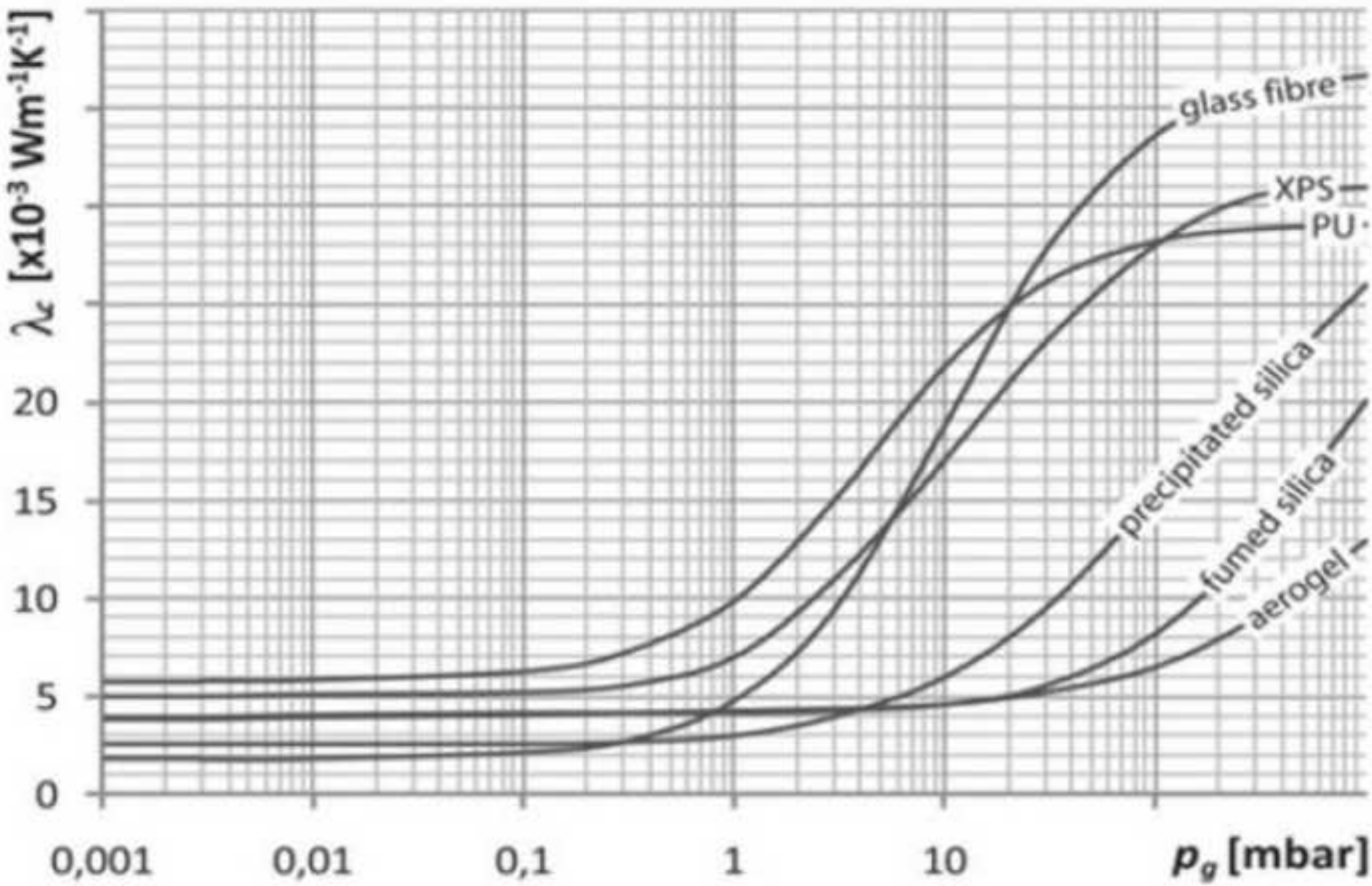

Fig3
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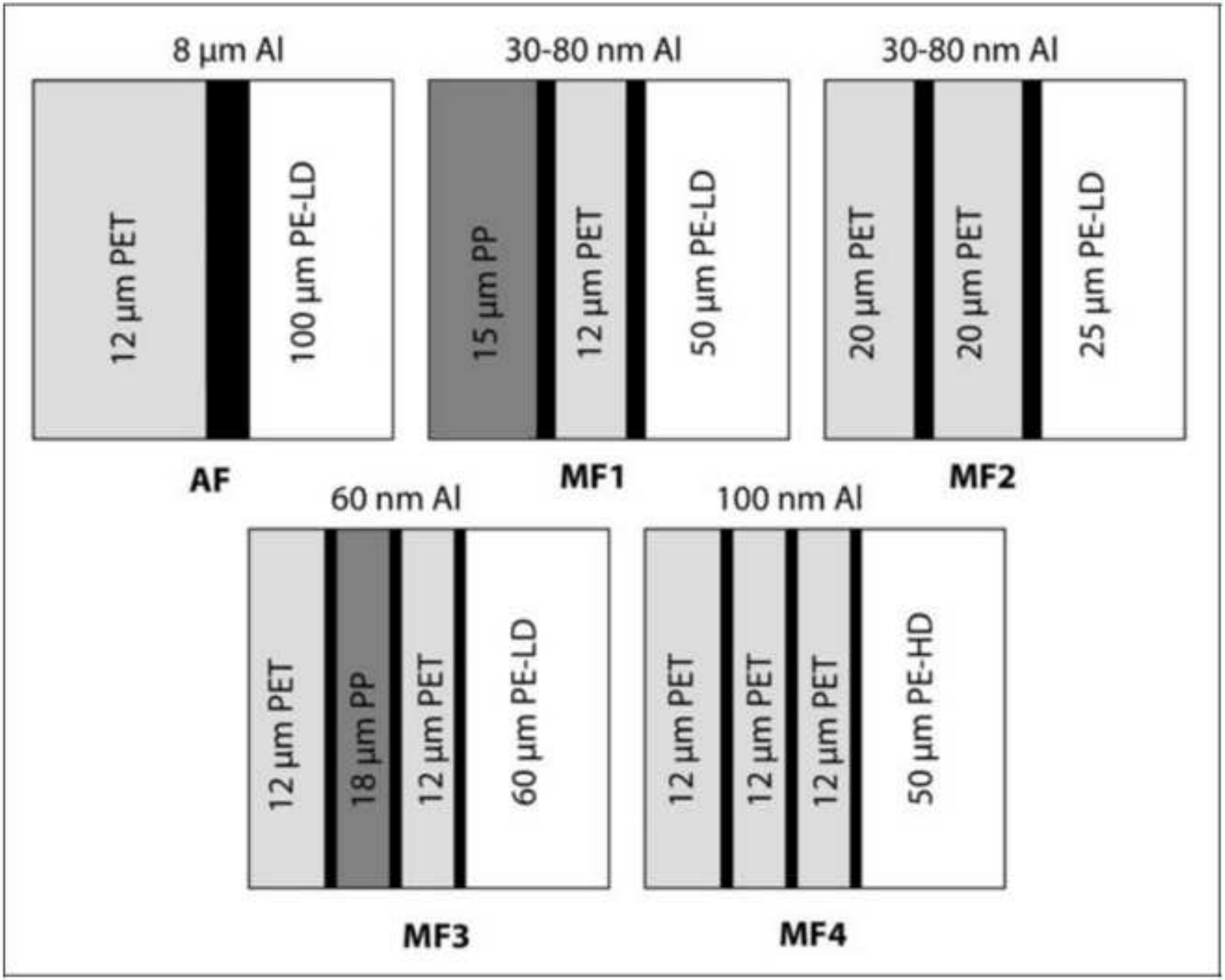

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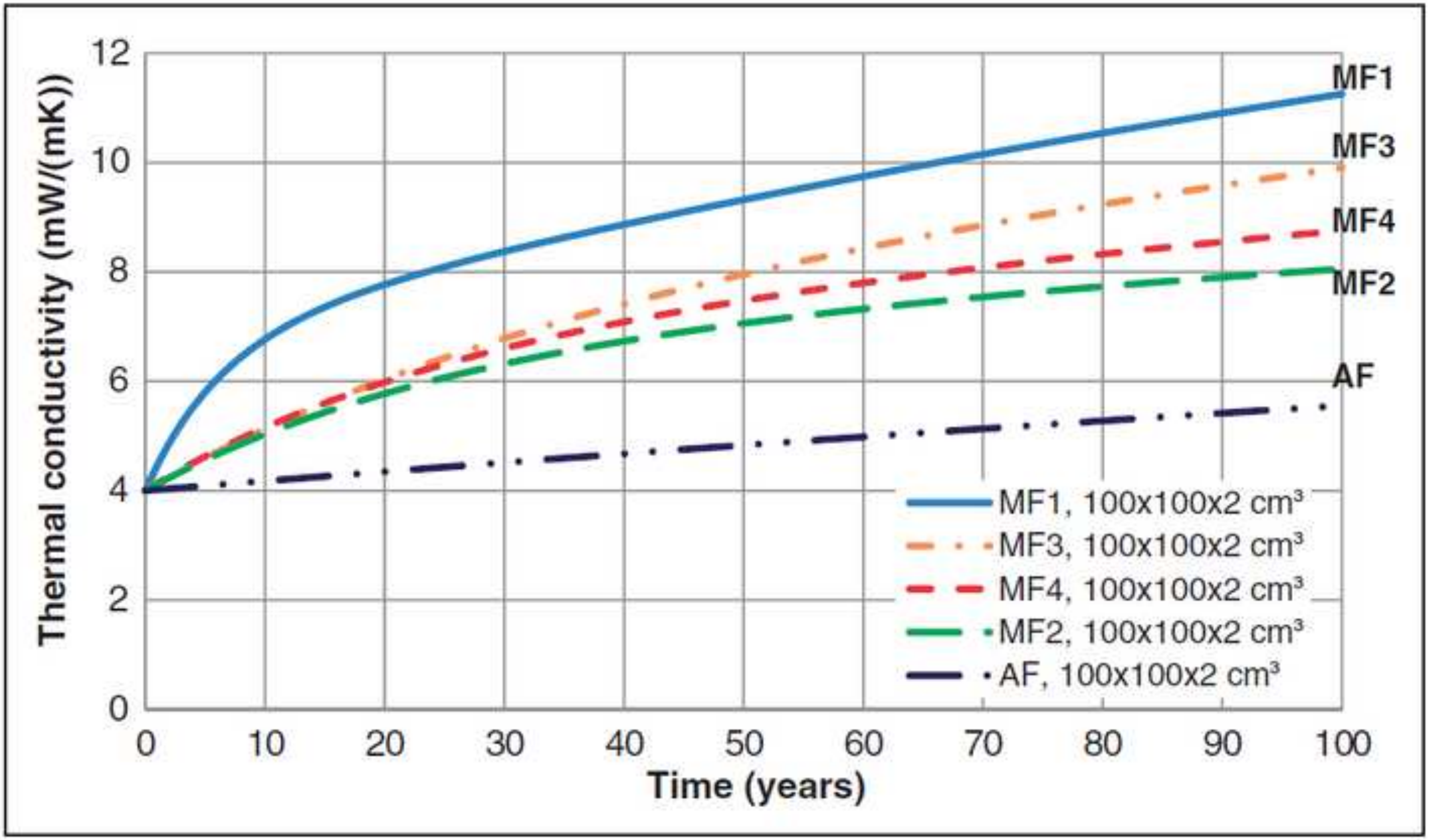

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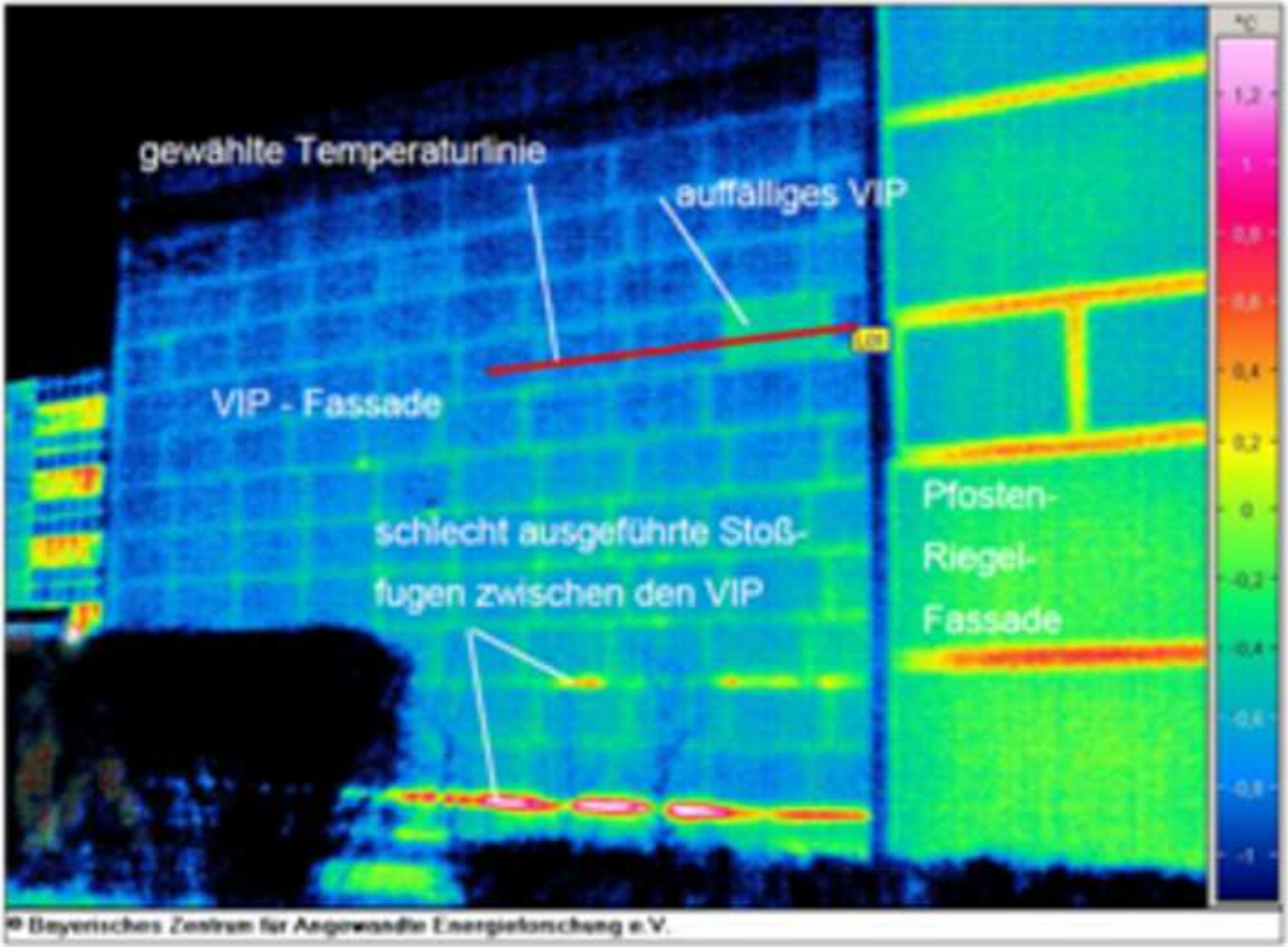

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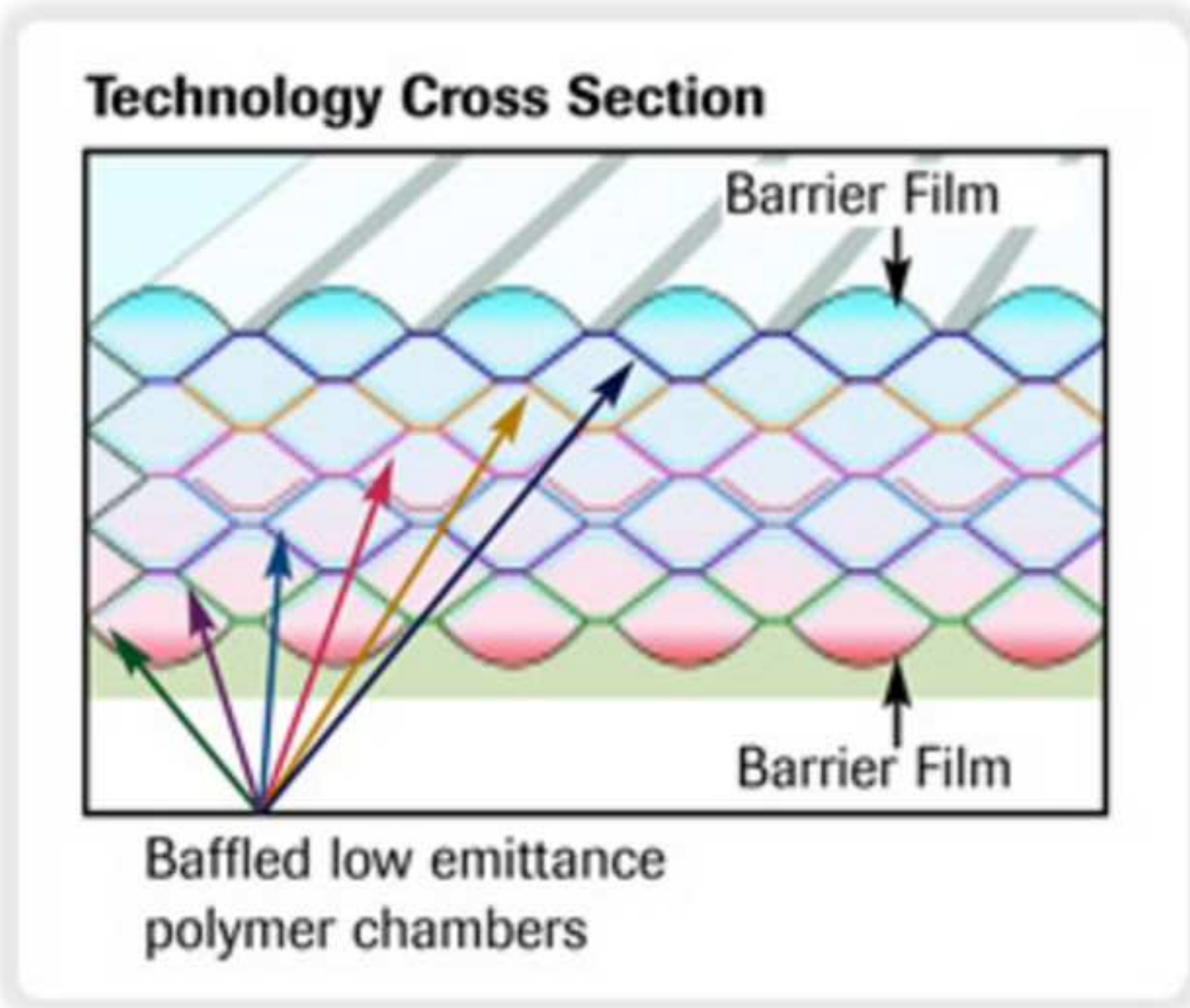

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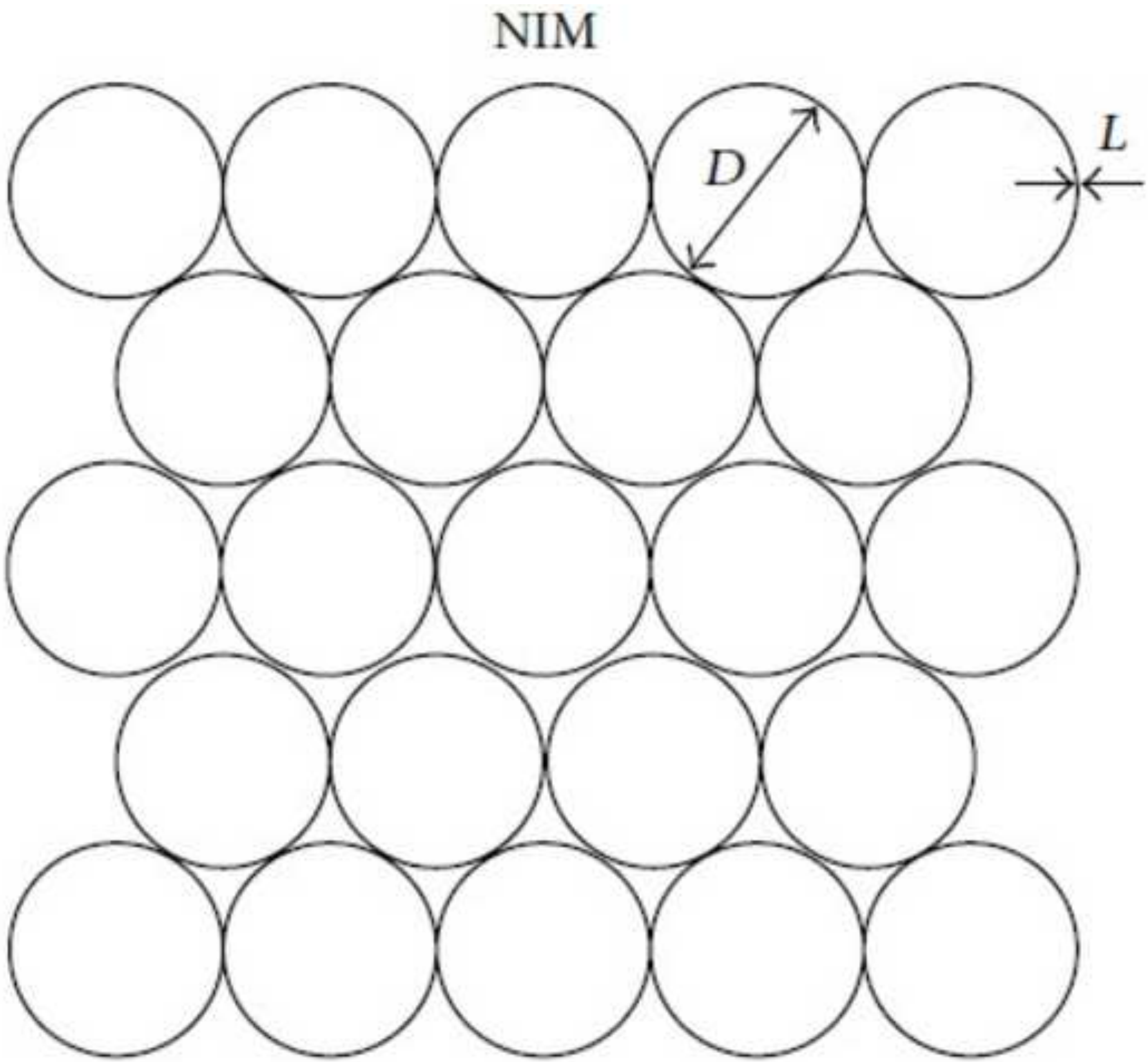

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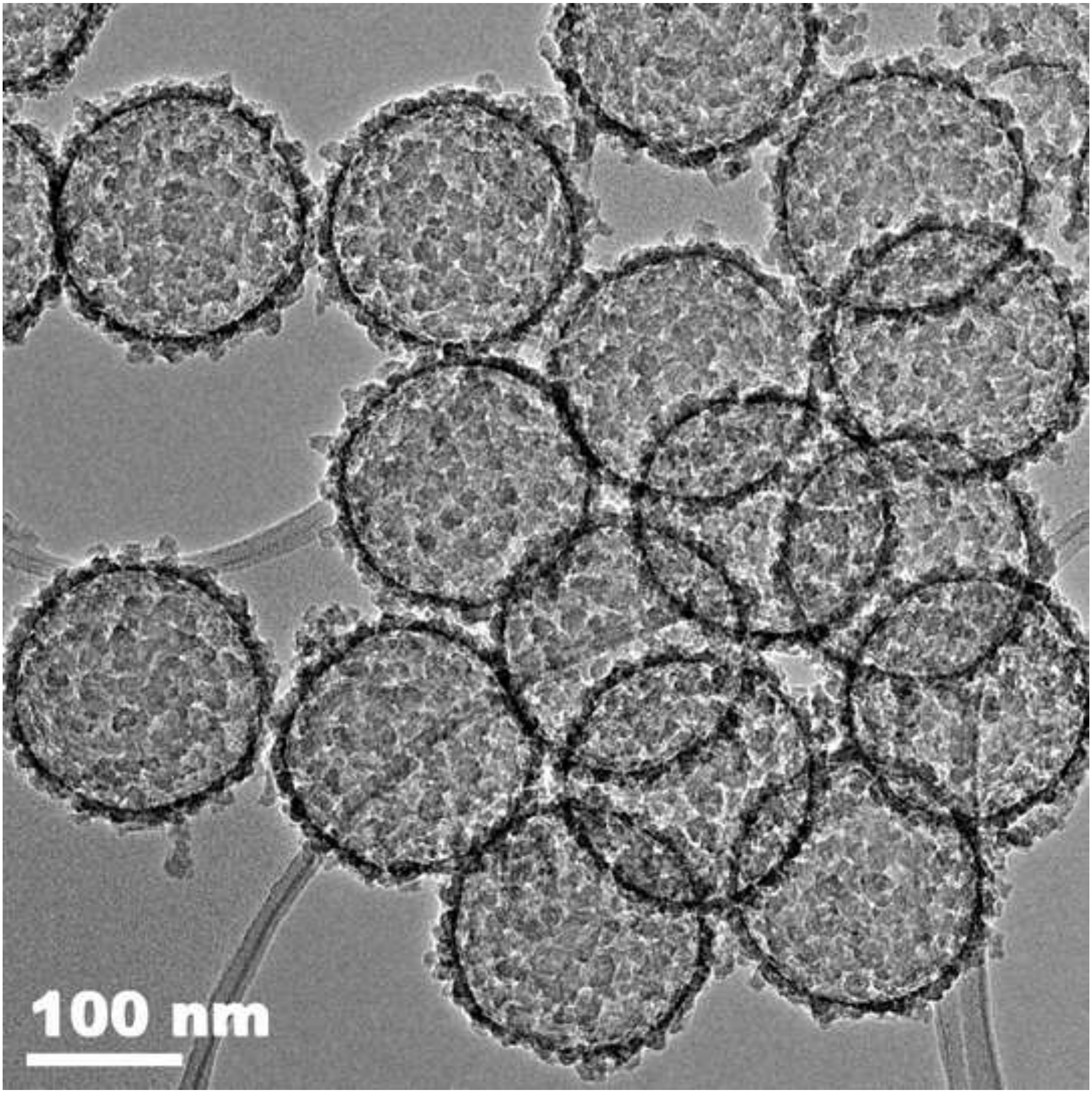

Fig16
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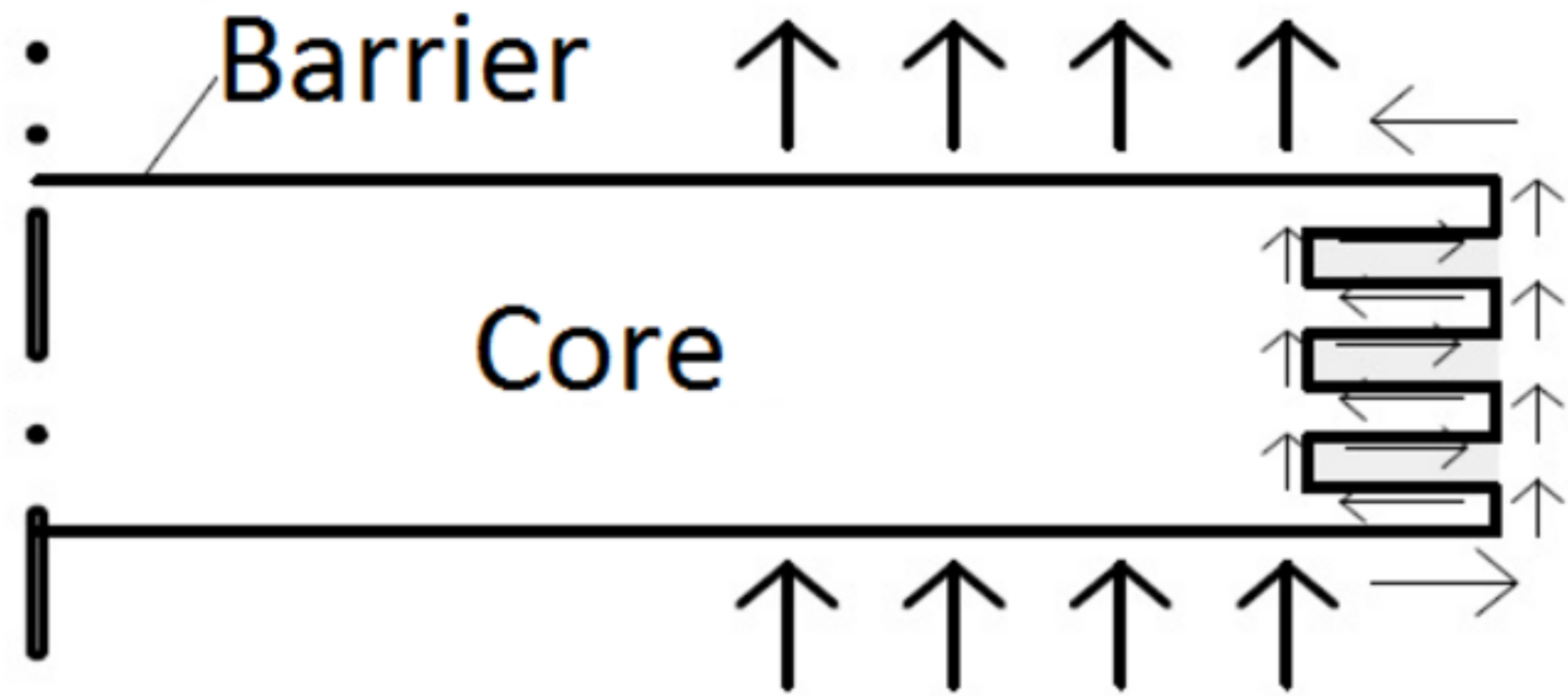

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