Fenestration of Today and Tomorrow: A State-of-the-Art Review and Future Research Opportunities

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Abstract

Fenestration of today is continuously being developed into the fenestration of tomorrow, hence offering a steadily increase of daylight and solar energy utilization and control, and at the same time providing a necessary climate screen with a satisfactory thermal comfort. Within this work a state-of-the-art market review of the best performing fenestration products has been carried out, along with an overview of possible future research opportunities for the fenestration industry. The focus of the market review was low thermal transmittance (U-value). The lowest centre-of-glass U_g-values found was 0.28 W/(m^{2}K) and 0.30 W/(m^{2}K), which was from a suspended coating glazing product and an aerogel glazing product, respectively. However, the majority of high performance products found were triple glazed. The lowest frame U-value was 0.61 W/(m^{2}K). Vacuum glazing, smart windows, solar cell glazing, window frames, self-cleaning glazing, low-emissivity coatings and spacers were also reviewed, thus also representing possibilities for controlling and harvesting the solar radiation energy. Currently, vacuum glazing, new spacer materials and solutions, electrochromic windows and aerogel glazing seem to have the largest potential for improving the thermal performance and daylight and solar properties in fenestration products. Aerogel glazing has the lowest potential U-values, ~ 0.1 W/(m^{2}K), but requires further work to improve the visible transmittance. Electrochromic vaccum glazing and evacuated aerogel glazing are two vacuum related solutions which have a large potential. There may also be opportunities for completely new material innovations which could revolutionize the fenestration industry.

Keywords: Fenestration; Multilayer glazing; Vacuum glazing; Smart window; Electrochromic window; Solar cell glazing; Aerogel; Low-emissivity coating; Low-e; Window frame; Phase change material; Spacer.

Contents

1. Introduction

Currently, saving energy and carbon emissions is a top priority for buildings and constructions. With up to 60% (Gustavsen et al. 2007) of the total energy loss of a building coming from its windows, fenestration products have a huge potential to provide large energy savings. Hence, windows with a low thermal transmittance, or U-value, can substantially reduce energy losses and save costs. In recent years building codes have been requiring lower U-values for new windows, e.g. the Norwegian Building Codes recently restricted the U-value for new windows to 1.2 $W/(m^2K)$ (NBC 2007), and this trend is set to continue as governments seek to save energy and reduce emissions.

This work aims to cover all main types of fenestration products, including multilayer glazing (Manz 2008), vacuum glazing (Eames 2008, Fang et al. 2009), frames (Applefield et al. 2010, Gustavsen at al. 2007), electrochromic windows (Baetens et al. 2010a, Granqvist 1995, Granqvist 2007, Granqvist et al. 2010, Jelle et al. 1993, Jelle and Hagen 1993, Jelle et al. 1999, Jelle et al. 2007, Lampert 1984, Lampert 1998, Lampert 2004), solar cell glazing (Octillion 2010), aerogels (Baetens et al. 2011, Schultz et al. 2005), low-emissivity (low-e) coatings (Chiba 2005, Reidinger et al. 2009) and spacers (Song et al. 2007). However, mechanically operated fenestration parts, e.g. blinds, shades and awnings, are not part of this study. The focus is on low U-values and solar radiation glazing factors. The first part will be a market review of the best performance state-of-the-art fenestration products available now, while the second part is a review of the research and development being performed and a look at the possible research opportunities and the potential products of the future. The definition of solar radiation glazing factors, e.g. visible solar transmittance (T_{vis}), solar transmittance (T_{sol}), ultraviolet solar transmittance (T_{uv}), solar reflectance (R_{sol}), solar factor (SF), solar material protection factor (SMPF) and solar skin protection factor (SSPF), may be found in Jelle et al. (2007) and Jelle and Gustavsen (2010a). When calculating U-values the method used must be noted as there can be up to a 3 % difference between the North American (ASHRAE) and European (ISO) methods (Blanusa et al. 2007). For further information on thermal transmittance values and their calculation see works by Gustavsen et al. (2007), Gustavsen et al. (2008) and Blanusa et al. (2007). Earlier review works on advanced glazing technology (Lampert and Ma 1992), advances in window technology (Arasteh 1994) and zero energy windows (Arasteh et al. 2006) are noted.

This work gives many tables with a lot of information, e.g. manufacturers, product names and various properties, both in the main text and in the appendixes. Some of these properties are very important and even crucial to the performance of the various products. Hence, the tables provide the readers with valuable information concerning these products. However, unfortunately it is often hard to obtain all the desired information (e.g. product properties) from all the manufacturers. In general, many property values are often not available at the manufacturers' websites or other open information channels, which is then seen as open spaces in the tables within this work. Hopefully, our addressing of this fact could act as an incentive for the manufacturers to state all the important properties of their products at their websites and other information channels, and also as an incentive and reminder for the consumers and users to demand these values from the manufacturers.

2. State-of-the-Art Review of Best Performance Fenestration Products

2.1. Glazing

Glazing can be considered as the most important part of fenestration products. This is especially true when calculating the U-value of a window as the glazing nearly always has the largest area of the constituent parts, and this greatly affects the overall U_w-value (Gustavsen et al. 2008). Presented within this section are examples of multilayer and vacuum glazing. Multilayer glazing is the most popular commercially available glazing and therefore constitutes the majority of products reviewed. The focus has been on European and North American glazing as they tend to have high solar factors as the climate is such that overall this is most beneficial for reducing heating costs in winter (Fig.1, Armstrong et al. 2008). Nevertheless, this has not restricted the review to only glazing with high solar factors, as glasses with low U-values have been included even if they have low solar factors.

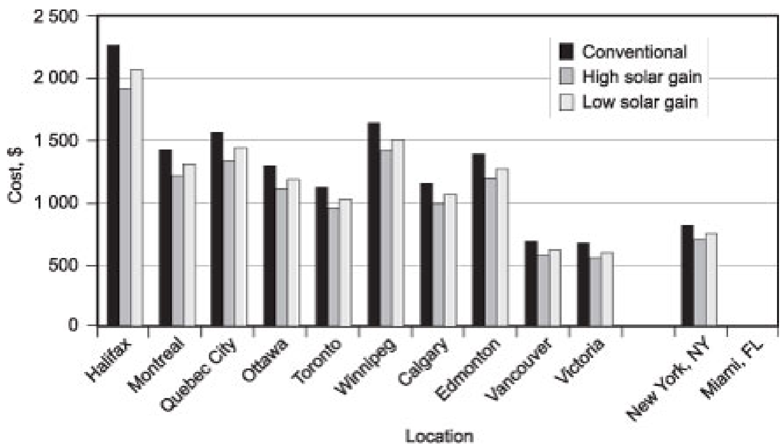


Figure 1. Annual cost of heating for North American locations (Armstrong et al. 2008).

2.1.1. Multilayer Glazing

The most common glazing that gives a low U-value is triple glazing (Appendix A). Typically this is with a gas fill of either argon or krypton, with krypton producing lower U-values with less cavity or fill thickness (and volume). This can help to reduce the weight of the window, as reduced cavity thickness means the frame can be made smaller, i.e. thinner. Table 1 presents a few examples of the best low U-value triple glazing, showing the glazing U-value (U_g), visible solar transmittance (T_{vis}) and the solar factor (SF). A full table containing several more values and products can be found in Appendix A.

Table 1. Literature data for some of the best low-e triple glazing products.

Manufacturer	Product 4:/12/4/12/:4 Kr 90%	U_g (W/(m^{2}K))	T_{vis}	T_{sol}	SF	Reference
AGC Glass UK	Top N$^+$	0.50	0.70		0.48	www.float-glass.co.uk/products/AGC_Glaverbel/Summary-tables.pdf (VII. Performance Summary Tables)
GUARDIAN Flachglas GmbH	ClimaGuard N^3	0.49	0.72	~0.37	0.54	www.passiv.de and www.eu.en.sunguardglass.com/SunguardProducts/GlassConfigurator/index.htm (calculation tool)
	ClimaGuard N	0.50	0.71	~0.45	0.53	www.guardian-europe.com and www.eu.en.sunguardglass.com/Sunguard

						Products/GlassConfigurator/index.htm (calculation tool)
INTERPANE Glas Industrie AG	iplus 3CE	0.49	0.71		0.47	www.passiv.de
	iplus 3CL	0.53	0.72		0.55	

All of the glasses in Table 1 have the configuration 4:/12/4/12/:4 Kr 90%, which shows that currently krypton is the most common gas fill for the best high performance glazing, but note that krypton is considerably more costly than argon. The best performing triple glazing with argon as the gas fill found by this report has a U_g-value of 0.64 W/(m^{2}K) but uses a cavity thickness of 18 mm, which adds an extra 12 mm to the glazing width compared to the glasses in Table 1. For further details see Appendix A.

2.1.2. Suspended Films

There are some products on the market that have a variation on the more common multilayer glass with gas fill method. These incorporate 'suspended coated films' (SCF) or only 'suspended films' in between the outer and inner panes which act as a third or fourth 'glass pane'. These films can reduce the weight of the window and may also allow a larger gas cavity thickness in the same window cavity as ordinary multilayer glazing due to the films being thinner than a glass pane. Table 2 gives examples of two suspended film products on the market today. For further details see Appendix A. It should be noted that all polymer products applied in exterior glazing units have to withstand the climate exposure during several decades. This is also applicable for polymer films placed inside a glazing unit, as the glass itself does not stop all ultraviolet and short-wave visible solar radiation which may degrade polymer materials. In addition, with respect to the durability issues, the polymer films and their fastening systems need to maintain smooth and parallel films with no wrinkles. For details on solar material protection factors it is referred to the work by Jelle et al. (2007).

Table 2. Literature data for suspended film glazing products.

Manufacturer	Product	Configuration	U_g (W/(m^{2}K))	T_{vis}	SF	Reference
Serious Materials	1125 Picture Window (SeriousGlass ™ 20)	Dual Pane, 3 Low SHG Films. Xenon fill.	0.28	0.23	0.17	www.vereco.ca/green_document/SeriousWindows_1125_Dsheet1271084115.pdf "SeriousWindows 1125 Saves more energy than any other window. Period." www.SeriousWindows.com
Visionwall Solutions Inc.	Series 204 4-Element Glazing System	6:/26/*/20/*/26/6 Air 100% *film	0.62	0.50	0.303	Visionwall Solutions Inc. – Performance Values for Series 104 & 204 4-element Glazing Systems (from Goran Jakovljević, jakovljevicg@visionwall.com)

The products in Table 2 have very competitive U-values compared to ordinary multilayer glazing products. The drawbacks of these products are the relatively low solar factor and T_{vis} values compared to the more ordinary triple glazing products. That is, when a high solar factor is desired, since often one also want to have as low solar factor as possible to avoid overheating. The Visionwall product uses only air as a fill which makes it unique within the products reviewed. Although a low U-value is achieved using two suspended films the width of the overall product is considerably greater than triple glazing windows with comparable U-values (see Appendix A). The Serious Materials product uses a xenon fill which is the only product reviewed to do so but is likely to cost considerably more than argon or krypton filled products. Note the very low centre-of-glass U_g-value of 0.28 W/(m^{2}K) from Serious Materials, in fact the lowest one found in this review amongst all the different normal glazing products.

The manufacturer Serious Materials are currently involved in a retrofit of the windows in the Empire State Building, using their SCF technology. This has enabled them to reuse all of the existing window frames and glazing, thus simply change the spacers and add in the SCF, significantly reducing costs and CO_2 emissions for the project by avoiding new material and window production and transportation (Fig.2, Serious Materials 2010).

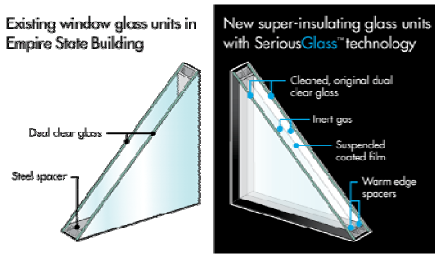


Figure 2. Before and after Empire State Building windows retrofit (Serious Materials 2010).

2.1.3. Vacuum Glazing

Vacuum glazing was first conceived in 1913 by Zoller but was not successfully produced until 1989 (Eames 2008). It consists of two sheets of glass separated by a narrow vacuum space with an array of support pillars keeping the two sheets of glass apart (Fig.3). This can be combined with another layer of low-e coated glass to produce windows with competitive U-values to low-e triple glazing. Table 3 details the best vacuum glazing product on the market today, NSG's SPACIA 21. Further technical information is contained in Appendix A.

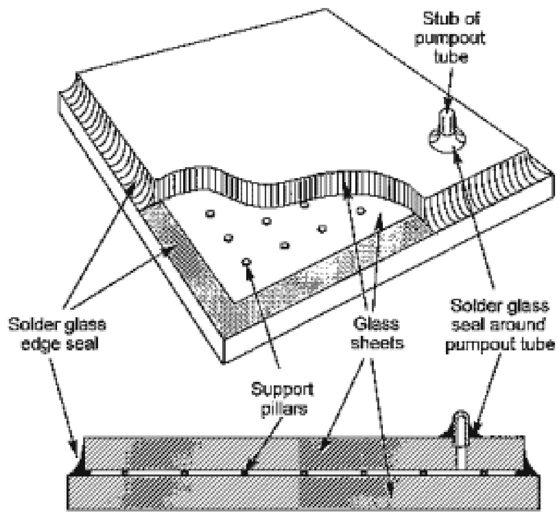


Figure 3. Schematic diagram of a vacuum glazing (NSG 2010).

Table 3. Literature data for SPACIA-21 vacuum glazing.

Manufacturer	Product	Configuration	U_g (W/(m^{2}K))	T_{vis}	T_{sol}	R_{sol}	SF	Reference
Pilkington/NSG	SPACIA-21	3:/12/3/0.2*/:3 Ar 90% *vacuum	0.70	0.533	0.228	0.401	0.32	www.nsg-spacia.co.jp/spacia21/performance.html

SPACIA-21 is what NSG call 'Hybrid' glazing, as it is a combination of vacuum glazing and low-e coated glass with an argon fill in between. One advantage vacuum glazing has over multilayer is that the width is considerably narrower. For example NSG SPACIA-21 has a total thickness of around 21 mm while an ordinary multilayer glass with the same U-value (0.70 W/(m^2K)), AGC UK's Planibel LOW-E Tri, has a total thickness of 40mm, i.e. almost a factor of two in thickness difference. This can be particularly advantageous when replacing existing windows.

2.1.4. Low-Emissivity Coatings

Low-emissivity (low-e) coatings are typically metals or metallic oxides and can be categorised into hard and soft coatings. Hard coatings such as pyrolytic deposited doped metal oxides, are on-line coatings, i.e. they are applied as part of the float line production. They are more durable than soft coatings and can be toughened. Soft coatings usually consist of dielectric-metal-dielectric layers and are most often off-line coatings, i.e. they are applied to individual glass panes after manufacturing. The best process of applying soft coatings is magnetron sputtering. Soft coatings have higher infrared reflection and are more transparent than hard coatings but require extra protective layers due to their lack of durability (Chiba et al. 2005, Del Re et al. 2004, Hammarberg and Roos 2003 and Reidinger et al. 2009). Table 4 shows some examples of hard and soft low-e coatings currently available. Various coatings may also be applied on the outer surface of the exterior glass for anti-condensation (anti-fog), anti-reflection or self-cleaning purposes. As the U-values are getting lower and lower for the highly insulating windows, these may at times depending on the climate conditions (temperature and relative humidity) experience condensation on the outer surface of the exterior glass. These issues which are not directly energy related are not treated further here, except self-cleaning glazing (ch.2.1.7 and ch.3.7).

Table 4. Hard and soft low-e coatings currently available.

Manufacturer	Product	Coating	ε	Reference
Pilkington	K Glass™	Hard	0.17	www.pilkington.com/Europe/Norway/Norwegian/products/bp/bybenefit/thermalinsulation/optitherms3/default.htm
	Opitherm™ S3	Soft	0.037	
	Opitherm™ S1	Soft	0.013	
Saint-Gobain Glass UK Ltd	Planitherm Total+	Soft	0.05	www.energy-efficient-glass.com/technical-support.asp
	Planitherm Ultra N	Soft	0.03	

2.1.5. Smart Windows

Smart windows have already been researched for some decades and today the first commercial products are emerging onto the market (Baetens et al. 2010a). The windows can change solar factor (SF) and transmittance properties to adjust to outside and indoor conditions, thus reducing energy costs related to heating and cooling. Smart windows can be divided into three different categories: (thermo-, photo- and electro-) chromic materials, liquid crystals and suspended particle devices (Baetens et al. 2010a). This review will focus solely on chromic material devices, in particular electrochromic windows (ECWs), as Baetens et al. (2010a) found that they are the most reliable and promising of the three technologies. Table 5 shows properties of the best electrochromic windows available today. A broader technical specification is provided in Appendix B.

Table 5. Data for electrochromic windows, where the cycles column refers to the guaranteed number of colouring/bleaching cycles (see e.g. Baetens et al. 2010a and the respective web addresses). (Note: These are U_g-values and not U_w as wrongly stated in Baetens et al. 2010a.)

Manufacturer	Product	Size (mm x mm)	U_g (W/(m^{2}K))	T_{vis}	T_{sol}	SF	Cycles	Reference
ChromoGenics AB		800 x 1800						www.chromogenics.com Granqvist (2011).
EControl-Glas GmbH & Co. KG	EControl® Double Glass	1200 x 2200	1.1		0.50–0.15	0.36–0.12	10-year gurantee	www.econtrol-glas.de
	EControl® Triple Glass Kr		0.5		0.45–0.14	0.30–0.10		
GESIMAT GmbH		800 x 1200		0.75–0.08	0.52–0.06		10-year guarantee	www.gesimat.de
SAGE Electrochromics, Inc.	Classic™	1080 x 1500	1.59	0.62–0.035	0.40–0.015	0.48–0.09	10^5	www.sage-ec.com
	Classic™ Triple Glass Kr		0.62	0.52–0.03	0.27–0.012	0.38–0.05		

For ECWs it is important to achieve as high T_{vis} as possible in their transparent state in order to obtain as much natural daylighting as possible. For energy regulation and to be able to shut off as much solar radiation as possible, it is important to have as low T_{vis} as possible in the coloured state. The total solar radiation regulation is given by T_{sol} or SF, where it is important to have as high and low values as possible in their transparent and coloured states, respectively.

In terms of U_g-value the EControl® Triple Glass with Kr fill (0.5 W/(m^{2}K)) from EControl-Glas matches the multilayer glazing products already reviewed, while the Classic™ Triple Glass with Kr fill (0.62 W/(m^{2}K)) from SAGE Electrochromics has a somewhat higher U_g-value. However, the main advantages smart windows have over multilayer glazing are their dynamic solar factor and transmittance properties which enable them by application of an external voltage to control the solar radiation throughput, thus saving energy.

ChromoGenics has an electrochromic foil which can be applied to existing windows which shows the retrofit possibilities for smart windows (ChromoGenics 2010). Note that ChromoGenics was founded as a spin-off of the work by Claes-Göran Granqvist and his team at the Ångström Laboratory of Uppsala University in Sweden. Therefore along with suspended films, smart windows have the potential to be widely applied to existing windows and save the cost of new glass and glazing production.

2.1.6. Solar Cell Glazing

Recent developments in technology have enabled solar energy collection from transparent glass. The technology involves spraying a coating of silicon nanoparticles on to the window which work as solar cells (Sherer 2008, Octillion 2010, Lewis et al. 2009 and Jiang 2009). Windows with the capability to produce electricity can be seen as having a lot of potential in the building industry. This highlights the alternative uses of windows as they can function as normal while also producing electricity. Table 6 shows properties of some solar cell glazing products on the market. For further details see Appendix C.

Table 6. Literature data for solar cell glazing products.

Manufacturer	Product	Configuration	U_g (W/(m^{2}K))	T_{vis}	Wp/m^2	Reference
Glaswerke Arnold GmbH & Co KG	*Voltarlux*®-ASI-T-ISO-E	Amorphous silicon thin-film ASI® tandem cell. TVG6WG/PV3 SZR 16 Float 6 N 41 Thickness: 32 mm	1.1			http://www.voltarlux.de/images/upload/File/e_Voltarlux-ASI-T-ISO-E(1).pdf
	Voltarlux®-ASI-Standard T-Standard -ISO	Amorphous silicon thin-film ASI® tandem cell. PV3/TVG6 SZR16 Argon VSG8 N41 Thickness: 35 mm	1.2	0.1		http://www.voltarlux.de/images/upload/File/e_Voltarlux-ASI-Standard.pdf
Sapa Building System		Mono-crystalline high efficient 25 mm distance		0.36	135	http://www.sapagroup.com/Companies/Sapa%20Building%20System%20AB/Pictures/brochures/Solar_BIPV_low.pdf
		Polycrystalline 50 mm distance		0.42	82	

For daylighting purposes T_{vis} should be as high as possible, whereas a high T_{vis} limits the solar radiation energy available for electricity production in the solar cell glazing. Hence, priorities have to be made by choosing a certain golden mean with respect to both daylighting and electricity generation. For solar regulation purposes where both high and low values of T_{vis} and T_{sol} (and SF) are desired, see discussion in above chapter on smart windows (ch.2.1.5).

The U_g-values of solar glazing products are not as low as the multilayer products previously reviewed, but are comparable to smart window products. The T_{vis} of these products is still very low and should for certain applications be higher, but nevertheless their main advantage is their capacity to produce electricity. A higher T_{vis} (> 0.70) will often be desirable to make these windows more acceptable to the public for use in homes with respect to daylighting, however this may have an adverse effect on the ability of the window to produce electricity.

2.1.7. Self-Cleaning Glazing

Self-cleaning glazing works by utilizing photocatalytic reactions within a thin coating on the glass and then as water falls on the glass it carries dirt off in one movement (hydrophilicity) (Pilkington 2010). Figure 4 shows this process. The coating used is either titanium or silicon dioxide (Chabas et al. 2008, Guan 2005 and Mellott et al. 2006). Note that it is organic dirt which is broken down on the coating surface, i.e. not inorganic dirt like e.g. sand. Table 7 shows properties of some self-cleaning glazing products. More information is given in Appendix D.

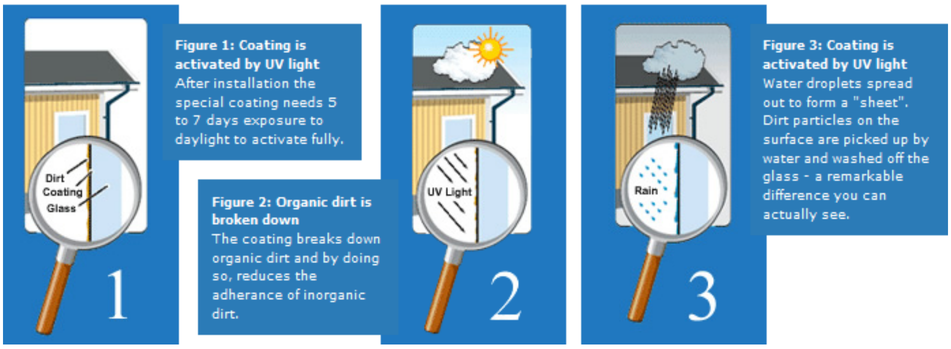


Figure 4. How self-cleaning glazing works (Pilkington 2010).

Table 7. Literature data for self-cleaning glazing products.

Manufacturer	Product	Configuration	U_g (W/(m^{2}K))	T_{vis}	SF	Reference
Pilkington Group Ltd	Pilkington Ativ™ Neutral/ Pilkingotn Optitherm™ S4	:4/16/:4 Ar 90%	1.2	0.44		http://www.pilkingtonselfcleaningglass.co.uk/pdf/literature/0819292%20Activ%20Neutral%20D%20Sheet.pdf
Saint Gobain Glass UK Ltd	SSG BIOCLEAN/ SSG PLANITHERM TOTAL+	:4/16/:4 Ar 90%	1.2	0.77	0.67	http://www.selfcleaningglass.com/performance.asp

These self-cleaning glazing products have slightly higher U-values than other products reviewed but are still compliant with the Norwegian Building Codes value (NBC 2007). By removing the need for cleaning chemicals which runoff into water sources, these products can have a positive environmental impact. Another product is Rain Racer™, which is a polymer that can be applied to windows and has a self-cleaning effect. It achieves this by providing a super hydrophobic surface on top of the glass, which carries dirt and particles off as soon as water hits it (Rain Racer 2005 and 2010). It should be noted that the term self-cleaning does not necessarily mean that one does not have to clean the window oneself any more, but rather that one may have to clean the window less than a normal window.

2.1.8. Aerogels

Aerogels, often known as solid air, are the lowest density solid known (from 1 to 150 kg/m^3) and were extensively developed by NASA for its Stardust mission (Bahaj et al 2008 and NASA 2005). The aerogel products reviewed are silica aerogels but they can be made from various materials. The technology is relatively new in fenestration and currently only one company, Cabot, seems to manufacture transparent and translucent aerogels that are used in glazing. They supply the aerogel to various partners in the USA and Europe who use it in various products. Aspen Aerogels (2008ab) is one of the main manufacturers of aerogels, but to the authors' knowledge they do not so far produce transparent or translucent aerogels. Table 8 shows properties of three aerogel products. Advanced Glazings Ltd (North America) and Okalux (Europe) offer customized products so an overall range of values is quoted. Further information is given in Appendix E.

Table 8. Literature data for aerogel glazing products*.

Manufacturer	Product	Configuration (mm)	U_g (W/(m^{2}K))	T_{vis}	SF	Reference
Advanced	Solera +	76.2 (just aerogel,	0.31	0.07 –	0.31 –	http://www.advancedglazin

Glazings Ltd.	Nanogel	glass to order)		0.32	0.07	gs.com/nanogel/
Cabot Corporation	Nanogel® Aerogel	10	1.38	0.80		"Nanogel Aerogel Daylighting – The New Standard in Eco-Daylighting Solutions" www.nanogel.com
		20	0.78	0.62		
		40	0.42	0.39		
		70	0.25	0.19		
Okalux GmbH	Okagel	From 6/30/6 to 6/60/6 (outer/inner glass, aerogel filling)	0.30 – 0.60	≤0.59	≤0.61	http://www.okalux.de/en/products/brands/okagel.html

*Aspen Aerogels (2008ab) is one of the main manufacturers of aerogels, but to the authors' knowledge they do not so far produce transparent or translucent aerogels, and is thus not included in this table.

These aerogel products are solar light diffusing as translucent aerogel granules are used. For further information on aerogel granules and their properties see works by Reim et al. (2004, 2005). The low T_{vis} (as a result of sufficient large thickness and thus low U_g), together with the high costs, are the major downsides of aerogel glazing at the moment, as the products are more suited to roofing and facades in commercial buildings and sports halls and are not yet in a position to challenge conventional residential windows where transparent (and not translucent) glazing most often will be a requirement. However the U-values are very competitive, especially with only two glass panes and no low-e coatings being used. As aerogel is a very light material this represents a dramatic reduction in weight from triple glazed windows.

2.1.9. Glazing Cavity Gas Fills

Between the extremeties vacuum and aerogels, there is normally a gas between the glass panes in a window. Naturally, the traditional and also cheapest gas has been common air. As air has a rather high thermal conductivity, i.e. about 26 mW/(mK) at room temperature and atmospheric pressure, the noble gas argon (Ar) with a thermal conductivity around 18 mW/(mK) has become in widespread use as a gas fill in today's fenestration products. The noble gases krypton (Kr) and xenon (Xe) offer considerably lower thermal conductivities, i.e. about 9.5 mW/(mK) and 5.5 mW/(mK), respectively, offering even lower U-values and thinner glazing units than with argon. However, as the costs of krypton and xenon are very high, especially xenon, these gases are not in widespread use as of today. Optimum glazing cavity thicknesses with respect to the different gases, their costs and the number of panes may be found, where also thickness restrictions or limitations of the glazing unit may play a role.

2.2. Spacers

Spacers are the components that are used to separate panes of glass and with a sealant provide a protective seal for the air or gas fill between them. Traditionally, spacers have been made of metals, in particular aluminium, which have a very high thermal conductivity. Currently, spacers are made of less conductive materials to provide a better thermal insulation in windows, as they can greatly influence on how well a window performs (Song et al. 2007). The focus of this state-of-the-art review will be non-metallic spacers. Table 9 shows data for foam and thermoplastic spacers. It should be noted that the thermal conductivity value is very important for the spacers, but unfortunately it is very hard to obtain these thermal conductivity values from the manufacturers, and in general these values are not available at the manufacturers' websites or other open information channels. Hopefully, our addressing of this fact could act as an incentive for the manufacturers to state their thermal conductivity values at their websites and other information channels, and also as an incentive and reminder for the consumers and users to demand these values from the manufacturers. For further information see Appendix F.

2.2.1. Foam Spacers

The leading foam spacer on the market today comes from Edgetech, who launched their Super Spacer in 1989. It has 'warm edge technology' (WET) which means that it has better thermal properties than traditional aluminium spacers. It is made from structural foam and is pre-desiccated to reduce condensation (Edgetech 2010).

2.2.2. Thermoplastic Spacers

Thermoplastic spacers (TPS) are usually made from polyisobutylene, also known as PIB. They also include desiccant material and have WET.

Table 9. Literature data for foam and thermoplastic spacers, comparing thermal conductivity and linear thermal transmittance.

Manufacturer	Product	Materials	Widths Available (mm)	Thermal Conuctivity (W/(mK))	Reference
ADCO North America	Ködimelt™ TPS	Thermoplastic elastomer formulated with inclusion of desiccant material			www.adcocorp.com
Bystronic Lenhardt GmbH	TPS®	1-component-polyisobutylen with included desiccant material	6 - 20		www.bystronic-glass.com
Edgetech IG Inc	Super Spacer	No-metal, pre-desiccated, structural foam spacer system. Thermal Set Spacer (TSS)			www.superspacer.co.uk
Traco HQ and Manufacturing	**NEXGEN™** —Energy Spacer™	Non-metallic airspacer			www.traco.com
Tremco illbruck Ltd	Duralite	5 components in 1: desiccated topcoat, powerful bond-line adhesive, impermeable foil moisture vapour barrier, sightline stiffener and non-metal flexible stabiliser	6 - 20		http://www.tremco-illbruck.co.uk/celumdb/documents/Duralite_Brochure_GB_7728.pdf
Viridian	ThermoTech™ Thermoplastic Spacer TPS®	Synthetic rubber	6 - 18	0.28 (at 23°C)	http://www.viridianglass.com/Products/thermotech-thermoplastic-spacer-tps/default.aspx?ProductType=Specifier

2.2.3. Metal-Based Spacers

Although as mentioned the focus of this state-of-the-art review will be on non-metallic spacers, some important metal-based or metal-containing spacers should be mentioned. These metal-based spacers include Swisspacer, Thermix, TGI and various stainless steel spacers. Stainless steel has a thermal conductivity of about 17 W/(mK) which is considerably lower than the conductivity for aluminium of about 200 W/(mK). TGI spacers are manufactured of stainless steel combined with a high quality plastic polypropylene as a strengthening and insulating material due to its low thermal conductivity. Thermix is constructed from PVC (0.21 W/(mK)) and high grade steel (26 W/(mK)). Swisspacer is a thermally-improved, or warm-edge, spacer bar manufactured from special fibreglass, composite material, and is available in two versions: (i) Swisspacer, where the composite material is covered by an ultra thin foil of aluminium, and (ii) Swisspacer V, using an extremely thin stainless steel foil for maximal possible insulation. Furthermore, for information on thermally broken aluminium spacers and other spacers that include metals see Song et al. (2007).

2.3. Frames

When determining how efficient a window is the glazing is not the only part that matters. The frame may also have a significant influence on the efficiency. Window frames can be manufactured from many different materials including wood (incorporating polyurethane (PUR)), wood with insulation filled aluminium cladding, polyvinylchloride (PVC), PVC with insulation filled aluminium cladding, aluminium and fixed wood and aluminium. A market review goes in depth on the subject and also looks at the research being done on frames (Gustavsen et al. 2007). The main focus of the market review were frames that satisfied the Passivhaus requirements (entire window U-value ≤ 0.80 W/(m^{2}K), using the ISO 10077-2 procedure, which uses an insulation panel in place of the glass) and which is also the focus for this review. Since 2007 there have been some new frames given Passivhaus certification and the ones with the lowest U-values may be seen in Table 10. A more complete table also containing the best frames from Gustavsen et al. (2007) can be found in Appendix G.

Table 10. Literature data for lowest U-value Passivhaus certified frames since the report by Gustavsen et al. (2007). The best frames from this report, including frames manufactured by Internorm International GmbH and Endl-Wagner GmbH, can be found in Appendix G.

Manufacturer	Product	U_f (W/m^{2}K)	Spacer Ψ_g (W/(mK)) U_w(W/(m^{2}K)) U_g (W/(m^{2}K)) w x h (m)	Materials	Reference
Bracia Bertrand Sp.J.	Thermoline 110	0.691/ 0.693	TGI – Wave 0.042 0.80 0.70 1.23 x 1.48	Wood, PUR (λ = 0.040 W/(mK)).	www.passiv.de
PAZEN Fenster + Technik	ENERsign	0.64/ 0.78	Thermix 0.033/0.031 0.77 0.70 1.23 x 1.48	Wood, Glass-Reinforced Plastic, Insulation Material (λ = 0.031 W/(mK)).	www.passiv.de
Stabalux GmbH	Stabalux H, System 60 PH	0.61	Thermix TX.N 0.040 0.80 0.70 1.23 x 1.48	Wood.	www.passiv.de
Stabalux GmbH	Stabalux H, System 50/60 PH	0.63	Swisspacer V 0.029 0.78 0.70	Wood.	www.passiv.de

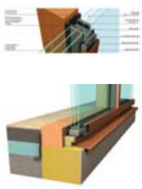
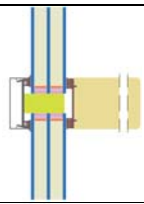
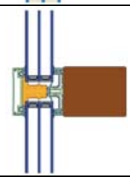
			1.23 x 1.48		

The frames chosen as the 'best' ones all have U_f values < 0.70 W/(m^2/K). The U_w values that accompany these frames could be lowered if glazing products from Chapter 2.1 were used as their U_g values are lower than the 0.70 W/(m^2/K) values given in Table 10. Experimental and numerical examination of the thermal transmittance of high performance window frames have been carried out by Gustavsen and co-workers (2010). The connection between the window frame and the building is also important to address with respect to energy efficiency issues, but is not within the scope of this work.

2.4. Glass Facade Systems

Glass facade systems use different types of frames compared to ordinary or residential windows. Examples of these frames are shown in Table 11. The Visionwall product reviewed in Chapter 2.1.2 is a glass facade system glazing product. Further information may be found in Gustavsen et al. (2007) and in Appendix G.

Table 11. Examples of frames for glass facade systems. Further information on these frames can be found in Appendix G.

Manufacturer	**Product**	**Illustration 1**	**Illustration 2**	**U_f (W/m^{2}K)**	**Reference**
Endl-Wagner GmbH	ON TOP PLUS			0.65	www.passiv.de
RAICO Bautechnik GmbH	RAICO THERM+ 76H-I Isobloc P			0.69	www.passiv.de

2.5. Phase Change Material Window Products

Phase change materials (PCM) change phase from solid state to liquid when heated, thus absorbing energy in the endothermic process. When the ambient temperature drops again, the liquid PCMs will turn into solid state materials again while giving off the earlier absorbed heat in the exothermic process. Hence, PCMs are interesting for the thermal building envelope and may thus also be interesting for fenestration products as these are part of the thermal and solar building envelope. The phase change cycle may stabilize the indoor building temperature and decrease the heating and cooling loads. A suitable phase change temperature range, depending on climatic conditions and desired comfort temperatures, as well as the ability to absorb and release large amounts of heat energy, are crucial properties when selecting a specific PCM for building applications.

Various paraffins are typically examples of PCMs, but a low thermal conductivity (Farid et al. 2004) and a large volume change during phase transition (Hasnain 1998) limit their building application. An overview of the main PCMs has been given by Demirbas (2006), whereas other reviews on PCMs may be found in works by Baetens et al. (2010c), Farid et al. (2004), Hasnain (1998) and Khudhair and Farid (2004), where corresponding melting enthalpies and melting temperatures are depicted for various groups of PCMs by Dieckmann (2006). Ismail and Henriquez (2001) have numerically and experimentally studied thermally effective windows with moving PCM curtains, which included spectrometric measurements in the solar radiation wavelength region.

As an example, Fig.5 shows an actual building where PCM integrated windows are in use, with the GlassX®crystal system from the manufacturer GlassX (2011). Furthermore, Fig.5 also depicts a principal drawing of this GlassX®crystal PCM window system. The insulating glass construction is reported to have an U-value less than 0.5 W/(m^2K), where a prismatic glass implemented in the space between the panes (left in drawing, Fig.5) reflects the solar radiation when the angle of incidence is larger than 40º (summer and sun high in the sky) and admits (transmits) the solar radiation when the angle of incidence is smaller than 35º (winter and sun low in the sky). The central element of the GlassX®crystal system is the PCM heat storage (and release) module (right in drawing, Fig.5) that receives and stores the solar energy and releases it again below a certain temperature. The PCM unit is made up of a salt hydrate hermetically sealed in polycarbonate containers painted grey to improve the absorption efficiency (GlassX 2011).

Figure 5. (Left) Building with the GlassX®crystal translucent wall element incorporating PCMs. (Right) Principal drawing of the GlassX®crystal PCM window system, see further details in the text (GlassX 2011).

2.6. Integrated Production

Currently, there is only one technology which enables fully integrated window production. Integrated window production means that the entire window is produced in one fluid sequence or production line, not at different factories or by different manufacturers. The advantage of this is that a more consistent quality should be obtained, transportation costs of different materials to different sites would be reduced and orders should be completed more quickly as production is located at one place. Sashlite™ allows the window to be produced as a whole, with the glass being placed onto the sash rather than a separate insulating glass unit being fitted to the sash. This has significantly simplified production and improved efficiency, claimed by the manufacturer (Sashlite 2010). The technology is also capable of producing triple glazed windows, which have been shown to be the majority of high performance glazing products today. Bystronic Glass has adopted the Sashlite™ technology and used it in their 'sashline' production line. For more information see Bystronic Glass (2010). Figure 6 shows the finished Sashlite™ product.

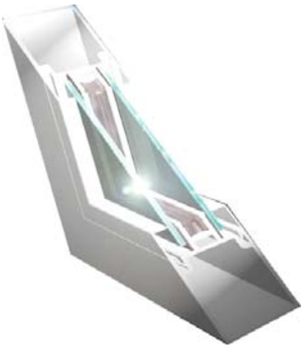


Figure 6. Image of a window produced using the Sashlite™ production method (Sashlite 2010).

3. Future Research Opportunities

This section aims to outline the research currently being doing into improving fenestration products and creating new innovations. Conclusions will also be drawn on what are regarded as the best solutions for the future of the industry.

3.1. Multilayer Glazing

With multilayer glazing generally the lower the U-value the lower the visible solar transmittance (T_{vis}), which is due to there being several glass layers and several coating layers in triple glazed products. For example AGC Glass UK's Top N+ product can be double or triple glazed. The double glazed product with argon fill has a U_g value of 1.1 W/(m^{2}K) and a T_{vis} of 0.78 (AGC Glass UK 2010), compared with the triple glazed product with krypton fill which has a U_g value of 0.50 W/(m^{2}K) and a T_{vis} of 0.70 (AGC Glass UK 2010). Achieving the double glazing level of T_{vis} could be part of the next step in improving triple glazing performance.

3.2. Air Sandwich

Sekisui in Japan (Sekisui 2007, 2010) currently have a product available called the 'air sandwich' as depicted in Fig.7. It consists of a number (which can be chosen) of thin plastic films with plastic spacers with air 'sandwiched' between for insulation. In Fig.7 the U-value as a function of the number of air layers for three given fixed widths (i.e. 4, 10 and 100 mm) is shown as the three coloured lines each with a optimum point for the lowest U-value, whereas T_{vis} (note that T_{vis} increases downwards on the y-axis) is shown as the black graph increasing with a decreasing number of layers.

Sekisui (2007) gives an example of an air sandwich with 5 air layers and a total width of only 4 mm with an U-value of 3.4 W/(m^{2}K) and a T_{vis} of 0.60. Another example from Sekisui (2007) is 7 air layers and a total width of 12 mm with an U-value of 1.8 W/(m^{2}K) and a T_{vis} of 0.55. The product available is designed to be fixed to the interior of windows to provide greater insulation. It was not deemed suitable to mention in the market review as it is still being developed and the thermal performance of the product is currently not at the level of the other products treated here. However, with further improvement this or similar products may have the potential to become a viable alternative to glass. Nevertheless, the long-term durability of the plastic film system has to be proven, e.g. with respect to both polymer degradation by solar radiation and the ability to maintain all plastic films smooth and parallel with no wrinkles.

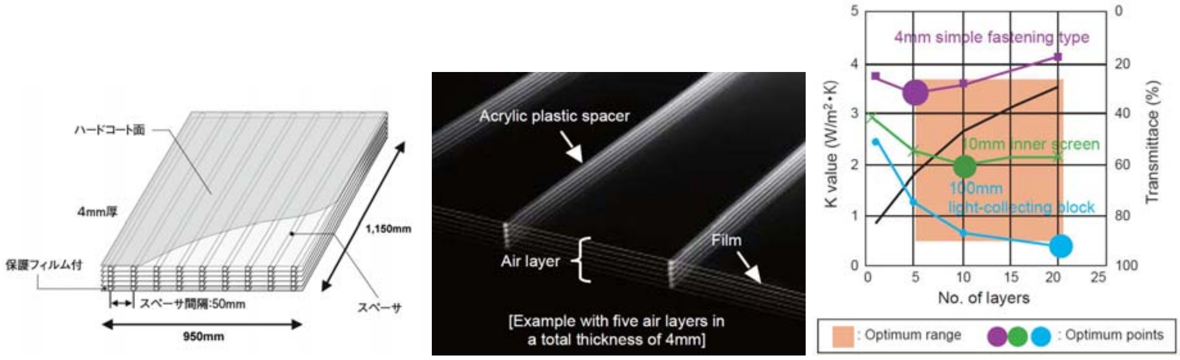


Figure 7. Sekisui air sandwich with principal drawings and U-value and T_{vis} performance with respect to number of air layers divided by thin plastic films. The U-value is depicted for three given fixed widths (i.e. 4, 10 and 100 mm), see further details in the text.(Sekisui 2007, 2010).

3.3. Vacuum Glazing

Vacuum glazing can be seen as having great potential in the fenestration industry. Currently it can produce comparable U-values to ordinary multilayer glazing but with considerably less width and weight. By using a low-temperature sealing process Eames (2008) reports that one may produce vacuum glazing with a U-value in theory down to 0.5 W/(m^{2}K) with a glazing that is only 8 mm wide, i.e. a major improvement compared to current multilayer (and much thicker) products with the same U-value. Furthermore, Griffiths et al. (1998) predict a U_g-value of 0.36 W/(m^{2}K) and T_{vis} of 0.72 for a system with two 6 mm glass panes separated by 0.2 mm diameter pillars 40 mm apart. The use of low-e coatings can improve current vacuum glazing products as shown in Fig.8, also depicting the U-value dependence of various emittance values for one or two low-e coatings in use (Fang et al. 2007).

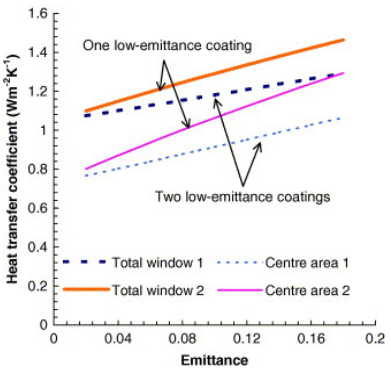


Figure 8. Predicted overall heat transfer coefficients of vacuum glazing window 1 with two low-e coatings and window 2 with one low-e coating (Fang et al. 2007).

Figure 8 shows the potential for a vacuum glazing window to have a U-value of ~ 0.80 W/(m^{2}K) with one low-e coating with an emittance of around 0.02. This U-value would be considerably lower than any double glazed window available today and the vacuum window would weigh less and have less width. It is apparent that vacuum glazing has huge retrofit potential. Edge seals and thermal expansion challenges are major concerns or development points for vacuum glazing.

3.3.1. Triple Vacuum Glazing

Currently a form of 'triple' vacuum glazing can be found in NSG's SPACIA 21 product (see Chapter 2.1.3) but this is more of a hybrid between vacuum and ordinary multilayer products. Triple vacuum glazing, i.e. three glass panes with a vacuum between, has been investigated by Manz et al. (2006). The work predicts that a triple vacuum glazing system could have a U_g-value of less than 0.2 W/(m^2K) using four low-e coatings with an emittance of 0.03, with a total thickness of only 16 mm. This is a far better U-value than currently available triple glazing products, again with less weight and width.

3.3.2. Electrochromic Vacuum Glazing

In recent years bringing electrochromic and vacuum glazing together has been researched. Papaefthimiou et al. (2006) evaluated electrochromic vacuum glazing (ECVG) prototypes with T_{vis} (in the bleached state) of 0.63 and U-values of 0.86 W/(m^2K), showing the potential of ECVG. This research was taken further with larger prototypes using up to two low-e coatings with emittances down to 0.02 being tested under ASTM winter conditions for thermal performance (Fang et al. 2010). Figure 9 shows the layout of an ECVG. This technology may have great potential in the fenestration industry.

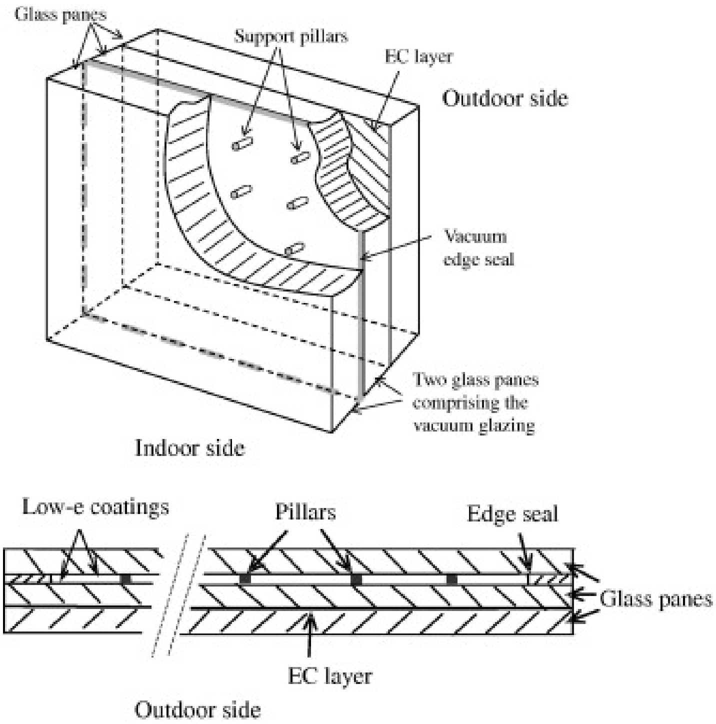


Figure 9. Schematic diagram of an ECVG. Up to two low-e coatings can be applied in the vacuum gap (Fang et al. 2010).

3.4. Low-Emissivity Coatings

Research is being continued into different new low-e coatings and improving existing ones. The emissivity can be lowered compared to the coatings reviewed in ch.2.1.4, where an emissivity as low as 0.013 was found for Opitherm™ S1 from Pilkington. Work is also being carried out to improve the visible transmittance of low-e coated glazing by applying antireflection coatings (Hammarberg and Roos 2003). However, low-e coatings have also some drawbacks when applied in high performance glazing products as they do reduce visible transmittance and reflect solar energy (which is undesirable in heating demand orientated climates). Windows using aerogels and no low-e coatings can already produce better thermal insulation that triple glazed low-e windows, although visible transmittance is also an issue for aerogels. Aerogel and vacuum glazing solutions may be able to produce better overall visible and solar performance in the future than low-e coated windows. Another issue is the ageing of low-emissivity surfaces, i.e. for how long can the surface maintain a low emissivity before it increases substantially.

3.5. Smart Windows

Electrochromic and suspended-particle windows have been seen as the most promising technologies, with electrochromic windows (ECWs) already commercially available and performing well (see ch.2.1.5). Gasochromic windows also have the potential to compete with the aforementioned types of smart windows but do have some limitations. Liquid crystal windows are another type of smart window, although they have long term UV stability issues. Photochromic and thermochromic windows are also smart windows, but can not be controlled like ECWs as they change according to ambient solar radiation and temperature, respectively (Baetens et al. 2010a). Improvement to the solar and visible transmittance of ECWs has been studied with the use of antireflection coatings with positive results (Jonsson and Roos 2010), showing that they have a large potential in the fenestration industry. As today's commercial and almost all research ECWs are solar radiation absorbing ECWs, research carried out on reflecting ECWs may pay off as these have a large potential in solar energy control. Reflecting ECWs avoid any heating problems which absorbing ECWs may be subjected to. Furthermore, reflecting ECWs may in principle control more of the solar energy as these windows block off the solar radiation by reflecting it back towards the outside, while absorbing ECWs reemits the absorbed solar radiation in all directions both towards the outside and towards the inside, the latter process hence decreasing the overall solar energy regulation for absorbing ECWs. For further information about smart windows it is referred to the recent state-of-the-art review by Baetens et al. (2010a).

3.6. Solar Cell Glazing

Solar cell glazing products incorporating both the transparent or translucent properties of glass and solar energy harvesting properties of solar cells may have many application areas. These products may then be utilized in fenestration with respect to daylight, solar heat gain, solar shading, solar energy gain by converting solar radiation into electricity, miscellaneous architectural expressions, etc. Nevertheless, various optimizing schemes of the key properties in these fenestration types have to be chosen and carried out, e.g. the solar radiation utilized in a solar cell and converted into electricity cannot be exploited as daylight in the buildings. One might also envision incorporating solar cells or photovoltaics with electrochromic materials in completely new fenestration products, where the photovoltaic and electrochromic material or materials cover the whole glazing area. However, normal windows still need a transparent (in some cases translucent) state, and when in this state such windows cannot produce electricity from the visible part of the solar spectrum as the visible light is transmitted through the window. The solar cell materials themselves are continuously being developed, including thin-film technologies, sandwich cells, dye sensitized solar cells (DSSC) and various other polymer cells. Future solar cell materials may also be envisioned as thin laminate or paint layers, hence also enabling application by paint brush or spray.

3.7. Self-Cleaning Glazing

Self-cleaning glazing has great potential to grow into a more common product in the fenestration industry as it reduces maintenance for the user. It is already being combined with anti-reflection coatings to produce multifunctional coatings (Prado et al. 2010). It could also be added to high performance triple glazing, vacuum glazing and aerogel products as the film is on the outer glass pane, thus not interfering with low-emissivity coatings. Research put into the ability to also break down and remove inorganic dirt (e.g. sand) would increase the cleanability or self-cleaning effect of the future self-cleaning windows.

3.8. Aerogels

Aerogel glazing has very high potential in the fenestration industry, with current products already achieving U-values as low as 0.30 W/(m^2K) (see ch.2.1.8). It may be possible to lower the U-value of aerogel glazing even further, with potential values of ~ 0.1 W/(m^2K), which is lower than a modern wall (Bahaj et al. 2008). As mentioned in ch.2.1.8, the main focus for improving aerogel glazing should be on improving the T_{vis} values and to obtain transparent aerogel instead of translucent aerogel, so that it can compete with residential glazing products. Potentially, entire glass panes could be manufactured solely of aerogel (Young 2010), but this is unlikely to become a reality soon. Note also the recent state-of-the-art review on aerogel insulation for building applications by Baetens et al. (2011).

3.8.1. Monolithic Silica Aerogel

The aerogel glazing on the market today uses aerogel granules packed between glass panes, which leads to a rather poor T_{vis} performance of current aerogel glazing, at least with respect to transparent properties. That is, these aerogel glazing products are translucent and not transparent. Figure 10 shows a picture of aerogel granules in an Okalux product.

Figure 10. Aerogel granules in glazing (Okalux 2010).

Monolithic silica aerogels can help to improve the T_{vis} and transparent performance of aerogel glazing if they are produced as one complete tile, although there are still issues with preventing cracking when drying the aerogel (Duer and Svendsen 1998, Rigacci et al. 1998 and 2004, Schultz and Jensen 2008). Currently, the maximum size of a crack-free monolithic aerogel tile is 0.58 m x 0.58 m, limited by the size of the autoclave (Schultz and Jensen 2008), where the thickness could be varied freely (in the actual projects it was 15 mm).

3.8.2. Evacuated Aerogel Glazing

Evacuated aerogel glazing can be produced using monolithic silica aerogel. Schultz and Jensen (2008) report to lower the thermal conductivity from 0.017 W/(mK) at atmospheric pressure to approximately 0.010 W/(mK) by evacuating the aerogel to a rough vacuum in the range 10-50 hPa. The glazing protypes had a measured U_g-value of 0.66 W/(m^2K) and a total solar energy transmittance of 76-80 % (Schultz and Jensen 2008). Furthermore, Schultz and Jensen (2008) claim through calculations that an aerogel glazing with 20 mm glass distance can reach an U_g-value below 0.5 W/(m^2K) combined with a total solar energy transmittance (solar factor) above 75 %.

Figure 11 shows the position of aerogel glazing on an energy balance graph as a combined function of U-value and solar factor (SF, g-value) for the heating season in a Danish climate (Schultz and Jensen 2008). This shows the limited benefit of triple glazing (which may actually be an area for further research and development) as the solar factor is reduced by the extra glass panes. It is clear from Fig.11 that aerogel glazing has high potential as it can combine low U-values with high solar factors.

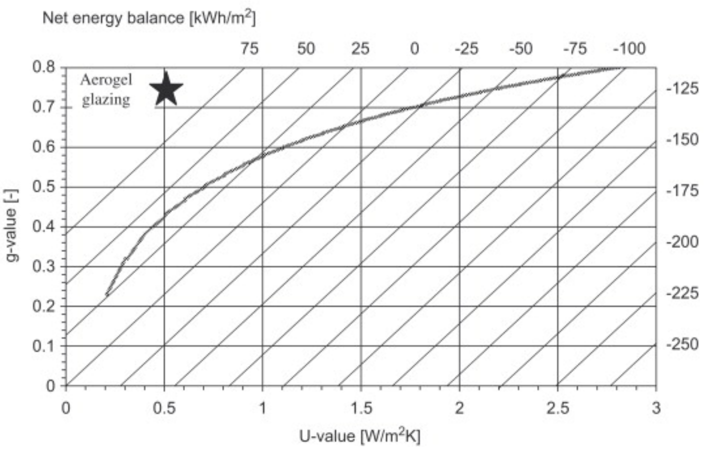


Figure 11. Energy balance (kWh/m^2) for window glazing as a function of U-value and solar factor (g-value). The curve represents the typical relationship for window glazing systems and the star shows the position of aerogel glazing (Schultz and Jensen 2008).

3.9. Glazing Cavity Gas Fills

Currently, argon is the most common gas fill for new double or triple glazing units being produced today, although krypton is also used to some extent as it produces lower U-values, though to a substantially higher cost. And as mentioned earlier, another gas that is not so widely used is xenon, which has the best thermal properties compared to those of air, argon and krypton. However, again, xenon is by far the most expensive of these gases, which has hindered its use (Manz 2008). Making gas fills more efficient may be done by evacuating the glazing cavity. Gas fill durability (sealant durability) is critical and more research is needed to improve the gas retention performance. It may be noted that Prausnitz and Arasteh (2009) at Lawrence Berkeley National Laboratory (LBNL) propose in a yet unpublished work to manufacture krypton at a possible lower cost process by separating krypton from air by absorption with an ionic liquid. The proposed process results in a krypton rich gas with some xenon residuals (about one order of magnitude less xenon in air than krypton) which may be further separated if desirable. With respect to gas conduction and idea generation, it is referred to the recent investigations by Baetens et al. (2010bcd), Baetens et al. (2011), Jelle et al. (2010b) and Jelle (2011), treating vacuum insulation panels (VIP), phase change materials (PCM), gas-filled panels (GFP), aerogels and the possible future thermal building insulation materials and solutions, e.g. nano insulation materials (NIM) with open or closed nano pore structures.

3.10. Spacers

A study on the effect of spacers on the thermal performance of windows found that spacers made from foam, fibreglass, and tape mastic (all with desiccant) were the best performing (Elmahdy 2003). The non-metallic spacers can be seen as the future in terms of thermal performance. Again, as mentioned earlier, it is essential to obtain a glazing system with adequate spacers and sealants which ensure a satisfactory gas fill durability.

3.11. Frames

Research is continuing to be done into window frames, with materials being an area particularly focused on. Composite material frames such as the injection moulded, rice husk filled, high-density polyethylene frame studied by Rahman et al. (2008) have the potential to be the future of frames. Other materials such as the glass fibre reinforced polyester (GFRP) frame researched by Applefield et al. (2010) have potential but currently do not have U-values as low as frames containing wood. The review by Gustavsen et al. (2007) goes in addition into considerable detail on the research being carried out on window frames. The key elements for improving the thermal performance of window frames are addressed in an investigation by Gustavsen et al. (2011).

3.12. Phase Change Materials in Windows

Phase change materials (PCM) with their ability to store and release energy are likely to be applied more in buildings in the coming years, also in or in combination with various fenestration products. The research and development will be performed on various aspects of the PCMs, e.g. both material research and different combinations and solutions within the buildings. Efficient means of absorbing as much energy as possible both from solar radiation and ambient thermal (infrared) radiation (in principle both outdoor and indoor), and at the same time being able to efficiently release this energy again when needed to the indoor living space, will be crucial issues to address for the future PCM systems in windows and buildings.

3.13. Future Fenestration Materials and Solutions

Although extensive research is being done on improving and adapting the current types of fenestration products available there is still room for completely new innovations. For example if a material could be developed that was similar to aerogels but was stronger and had greater visible transmittance then this could completely replace glass and revolutionise the fenestration industry. Other possibilities include an innovation that could merge the window frame and glazing into one single component, creating a transparent frame enabling maximum visible and solar transmittance. This could also being accomplished by developing a material that was strong enough to replace frames while still being transparent. Spacers would also need to be transparent in this system but if there is a sufficiently insulating material used for the glazing only one pane needs to be used. Future fenestration products might be units which incorporate several more functions than the products of today, e.g. the normal window properties together with electrochromics, photovoltaics, phase change materials and possible others. That is, multi-functional fenestration products or multi-functional windows may emerge, which might be seen as part of a multi-functional building envelope, addressing all the needs of the users with respect to daylight, energy efficiency, energy production and occupant comfort.

4. Conclusions

This work shows that there are many high performance fenestration products on the market today. With regard to glazing the majority are triple glazed multilayer products, but the vacuum glazing and aerogel solutions are growing and produce competitive U-values. Aerogels in particular have a large potential. They are already in use for translucent applications, and if their clarity could be improved for transparent applications, together with large production cost reductions, the aerogels could become part of the future of the fenestration industry. The lowest centre-of-glass U_g-values found was 0.28 W/(m^{2}K) and 0.30 W/(m^{2}K), which was from a suspended coating glazing product and an aerogel glazing product, respectively. With regards to frames, the lowest frame U-value is currently 0.61 W/(m^{2}K). Hence, it is clear that frame U-values are still some way off their glazing counterparts and decreasing frame U-values should therefore be seen as a priority for the industry. Non-metallic spacers have helped to improve the thermal efficiency of windows, but further thermal improvements are still needed for the spacer system. Technologies like electrochromic windows and suspended coated film products may also have great potential in the fenestration industry. Integrated production techniques, e.g. manufacturing the window as a whole, and other to-be-developed novel solutions have the potential to revolutionize the way windows are produced. In short, the fenestration market has a wide selection of high performance products available and is continuing to improve its product and production efficiency. With all these developing products, attention should be given to their robustness and long-term durability.

In terms of research and future products, vacuum glazing, aerogels, electrochromic windows and solar cell glazing have a large potential in terms of becoming part of the future glazing solutions, thus besides having a high thermal resistance also being able to control and harvest the solar radiation. Currently, aerogels have the lowest U-values, and potentially, therefore a joint aerogel and vacuum glazing solution could become the optimum product. Material research is being carried out into frames with composite and plastic materials showing the highest potential. New innovative fenestration products, and, given time, aerogel glazing could provide alternatives to glass for both translucent and transparent applications. Completely new materials or other fenestration solutions could revolutionize the industry and change the way windows are being produced.

Acknowledgements

This work has partly been funded by the Research Council of Norway, Lian Trevarefabrikk and Lawrence Berkeley National Laboratory (LBNL) through the NTNU and SINTEF research project ”*Improved Window Technologies for Energy Efficient Buildings*” (EffWin), and the Assistant Secretary for Energy Efficiency and Renewable Energy, Office of Building Technology, Building Technologies Program of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.

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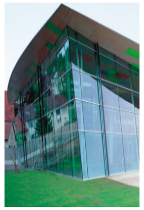
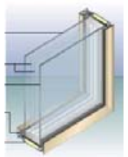
Appendix A - Multilayer, Suspended Film and Vacuum Glazing Products

Table A. Literature data for triple glazed windows, suspended film windows and vacuum glazed windows.

Manufacturer	Product	Illustration	Configuration	U_g (W/(m^{2}K))	T_{vis}	T_{sol}	T_{uv}	R_{sol}	SF	Reference/Information
AGC Glass UK 6 Allerton Road CV23 0PA Rugby United Kingdom Tel: +44 1788 53 53 53 Fax: +44 1788 56 08 53 sales.uk@eu.agc-group.com www.agc-flatglass.com	Planibel LOW-E Tri On Clearvision		4:/14/4/14/:4 Ar 90%	0.70	0.74		0.09		0.63	www.yourglass.com and www.yourglass.com/agc-flatglass-europe/Toolbox/Configurator/result.html
	Top N+		4:/12/4/12/:4 Kr 90%	0.50	0.70		0.10		0.48	www.float-glass.co.uk/products/AGC_Glaverbel/Summary-tables.pdf (VII. Performance Summary Tables)
arcon Flachglas - Veredelung GmbH & Co. KG Gewerbegebiet "Am Amselberg" Schorba 4, D-07751 Bucha Deutschland Tel. +49 3641 / 2845-0 Fax. +49 3641 / 2845-45 info@arcon-glas.de www.arcon-glas.de	N solar		4:/18/4/18/:4 Ar 90%	0.64	0.73	0.53	0.17	0.24	0.61	Go to www.passiv.de for more low u-value arcon products
			4:/12/4/12/:4 Kr 90%	0.60	0.73	0.53	0.17	0.24	0.61	
Glas-Dreisbusch GmbH & Co. KG Österreicher Straße 12, D-63773 Goldbach Deutschland Tel. +49 6021 / 50 02-0 Fax. +49 6021 / 50 02-20 td@glas-dreisbusch.de www.glas-dresibusch.de	GDG iplus 3CE		4:/12/4/12/:4 Kr 90%	0.50	0.71				0.47	www.glas-dreisbusch.de/service/GDG-IPLUS.pdf
GUARDIAN Flachglas GmbH Guardian Str. 1, D-06766 Thalheim Deutschland Tel. +49 3494 / 3615-00 Fax. +49 3494 / 3615-01 technik_flachglas@guardian.com	ClimaGuard N^3		4:/12/4/12/:4 Kr 90%	0.49	0.72	~0.37	~0.16	~0.42	0.54	www.passiv.de and www.eu.en.sunguardglass.com/SunguardProducts/GlassConfigurator/index.htm (calculation tool)
	ClimaGuard Premium		4:/12/4/12/:4 Kr 90%	0.49	0.71	~0.42	~0.20	~0.32	0.49	

Manufacturer	Product	Illustration	Configuration	U_g (W/(m^{2}K))	T_{vis}	T_{sol}	T_{uv}	R_{sol}	SF	Reference/Information
www.guardian-europe.com	ClimaGuard N		4:/12/4/12/:4 Kr 90%	0.50	0.71	~0.45	~0.19	~0.30	0.53	www.guardian-europe.com and www.eu.en.sunguardglass.com/SunguardProducts/GlassConfigurator/index.htm (calculation tool)
Ludwig Häußler GmbH, Fenster- und Türenfabrik Draisstraße 48, D-67346 Speyer Deutschland Tel. +49 6232 / 3144-0 Fax. +49 6232 / 3144-37 info@haeussler-fenster.de www.haeussler-fenster.de	Energate 1042+		4/16/6/16/4	0.50						www.haussler-fenster.de
	Energate 1202+		4/16/6/16/4	0.50						
INTERPANE Glas Industrie AG Sohnreystraße 21, D-37697 Lauenförde# Deutschland Tel. +49 5273 / 809-0 Fax +49 5273 / 809-238 info@ag.interpane.com www.interpane.com	iplus 3CE		4:/12/4/12/:4 Kr 90%	0.49	0.71		0.14		0.47	www.passiv.de and www.interpane.com
	iplus 3CL		4:/12/4/12/:4 Kr 90%	0.53	0.72		0.10		0.55	
Pilkington Group Limited Alexandra Business Park, Prescot Road, St Helens, Merseyside WA10 3TT Tel: +44 (0)1744 28882 Fax: +44 (0)1744 692660 pilkington@respond.uk.com www.pilkington.com	energiKare™ Triple		/12//12/ Kr 90%	0.70	0.67				0.68	www.pilkington.com
	Optitherm S3		4/18/:4/18/:4 Ar 90%	0.50	0.71	0.42	0.13		0.52	www.pilkington.com/resources/energisparing2.pdf
	Suncool Brilliant 66/33		6:/12/4/12/:4 Kr 90%	0.50	0.58	0.27	0.06	0.33	0.33	Pilkington Glassfakta 2007
	NSG Spacia-21		3:/12/3/0.2*/:3 Ar 90% *vacuum	0.70	0.533	0.228	0.028	0.401	0.32	www.nsg-spacia.co.jp/spacia21/performance.html

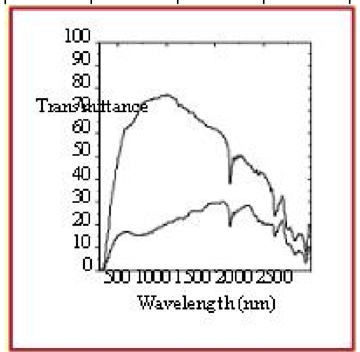
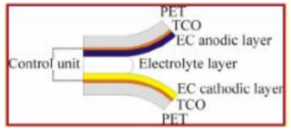
Manufacturer	Product	Illustration	Configuration	U_g (W/(m^{2}K))	T_{vis}	T_{sol}	T_{uv}	R_{sol}	SF	Reference/Information
Reflex d.o.o. Podgrad 4, 9250 Gornja Radgona Slovenija Tel: +386 (02) 564 / 35-00 Fax: +386 (02) 564 / 35-20 info@reflex.si www.reflex.si	RX WARM 0,6 C		4:/10/4/10/:4 Kr 90%	0.56	0.71				0.47	www.passiv.de
	RX WARM 0,5 C		4:/12/4/12/:4 Kr 90%	0.49	0.71				0.47	
Serious Materials 1250 Elko Drive, Sunnydale CA 94089, USA Tel: +1.800.797.8159 Fax: +1.408.716.2443 Info@SeriousWindows.com www.SeriousWindows.com	1125 Picture Window (Serious Glass™ 20)		Dual Pane, 3 Low SHG Films. Xenon fill.	0.28	0.23				0.17	www.vereco.ca/green_document/SeriousWindows_1125_Dsheet1271084115.pdf "SeriousWindows 1125 Saves more energy than any other window. Period." www.SeriousWindows.com Values calculated to NFRC 100 standard. Uses 3 suspended films instead of inner glass.
UNIGLAS GmbH & Co. KG Robert-Bosch-Straße 10, D-56410 Montabaur, DE Tel. +49 2602 / 94929-0 Fax: +49 2602 / 94929-29 info@uniglas.de www.uniglas.de	Top Premium E		4:/16/4/16/:4 Ar 90%	0.58					0.50	www.passiv.de
Visionwall Solutions Inc. 17915-118 Avenue Edmonton, Alberta, Canada T5S 1L6 Tel: +1 780-451-4000 Fax: +1 780-451-4745 visionwall@visionwall.com www.visionwall.com	Series 204 4-Element Glazing System	 	6:/26/*/20/*/26/6 Air 100% *film	0.62	0.50	0.22		0.33	0.303	Visionwall Solutions Inc. – Performance Values for Series 104 & 204 4-element Glazing Systems (from Goran Jakovljević, jakovljevicg@visionwall.com). Values calculated using LBNL WINDOW 5.2 AND THERM 5.2 software, to AAMA 1503 standard. Uses two suspended films instead of inner glass.

Unless otherwise mentioned, values in this table have been calculated according to the EN ISO standards.

Appendix B - Electrochromic Window Products

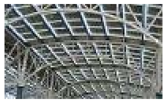
Table B. Literature data for electrochromic windows (see the state-of-the-art review by Baetens et al. (2010a) for more products).

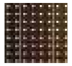
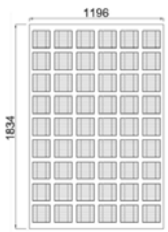
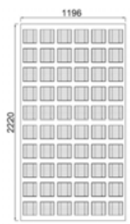
Manufacturer	Illustration	Product	U_g (W/(m^{2}K))	T_{vis}	T_{sol}	T_{uv}	SF	Durability	Max size	Electrical demand	Further Information
SAGE Electrochromics, Inc., One Sage Way, Faribault, MN 55021, USA Tel.: +1 877 724 3321; fax: +1 507 333 0145 sales@sage-ec.com www.sage-ec.com		Classic ™	1.59	0.62–0.035	0.40–0.015	0.056 – 0.008	0.48–0.09	100 000 cycles, 30 years, −30 to 60°C	Up to 108×150 cm^2	5 VDC	www.sage-ec.com Electrochromic windows for building applications. Switching time of 3–5 min. 10 years warranty. *Only* commercially available smart windows for exterior applications which passed ASTM E-2141-06. T_{uv} = 0.0 % PVB laminate. WO_3-based. U_g: Summer values given.
			1.59	0.62–0.035	0.40–0.015	0.004 – 0.001	0.48–0.09				
	(double glass)	See Green ™	1.59	0.48–0.028	0.19–0.01	0.04–0.006	0.44–0.09				
	(double glass)	Cool View Blue ™	1.59	0.40–0.023	0.30–0.01	0.000 – 0.000	0.46–0.09				
	(double glass)	Clear-as-Day ™	1.59	0.35–0.019	0.31–0.01	0.000 – 0.000	0.46–0.09				
	(triple glass)	Classic™ Triple Glass Ar	1.25	0.55–0.031	0.32–0.013	0.045 – 0.006	0.43–0.07				90 % Ar
	(triple glass)	Classic™ Triple Glass Kr	1.02	0.55–0.031	0.32–0.013	0.045 – 0.006	0.43–0.07				95 % Kr
	(triple glass)	Classic™ Triple Glass Ar*	0.85	0.52–0.03	0.27–0.012	0.036 – 0.005	0.38–0.06				90 % Ar *Additional low-e coating
	(triple glass)	Classic™ Triple Glass Kr*	0.62	0.52–0.03	0.27–0.012	0.036 – 0.005	0.38–0.05				95 % Kr *Additional low-e coating
EControl-Glas GmbH & Co. KG, Glaserstr.1, 93437 Furth im Wald, GERMANY Tel.: +49 9973 858 330; fax: +49 9973 858 331 info@econtrol-glas.de www.econtrol-glas.de		EControl® Double Glass	1.1		0.50–0.15	0.05–0.005	0.36–0.12		120×220 cm^2	5 VDC <0.5 Wh/m^2	www.econtrol-glas.de Electrochromic windows for building applications. According to DIN EN ISO 12543-4 for exterior insulating glass. WO_3-based.
		EControl® Triple Glass	0.5		0.45–0.14	0.02–0.003	0.30–0.10				

Manufacturer	Illustration	Product	U_g (W/(m^{2}K))	T_{vis}	T_{sol}	T_{uv}	SF	Durability	Max size	Electrical demand	Further Information
GESIMAT GmbH, Koepenicker Str. 325, 12555 Berlin, GERMANY Tel.: +49 30 473 89 251; fax: +49 30 473 89 252 info@gesimat.de www.gesimat.de				0.75–0.08	0.52–0.06				120×80 cm^2	0.5/2.2 V DC, 0.04 Wh/m^2	www.gesimat.de Electrochromic window based on EC and active counter-EC. WO_3+active CE.
ChromoGenics AB, Märstagatan 4, SE-75323, Uppsala, SWEDEN Tel.: +46 18 430 04 30 info@chromogenics.com www.chromogenics.com									0.8×1.8m^2		www.chromogenics.com Granqvist (2011). Two polyethylene terephthalate (PET) foils around WO_3 and NiO joined by a patented adhesive polymer electrolyte with transparent conductors of ITO (In_2O_3:Sn). 

Appendix C - Solar Cell Glazing Products

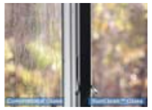
Table C. Literature data for solar cell glazing products.

Manufacturer	Product	Illustration	Configuration	U_g (W/(m^{2}K))	T_{vis}	Wp/m^2	U_{oc} (V)	I_{sc} (A)	FF	SF	Reference/Information
Abakus Solar AG Büro Gelsenkirchen Leithestr. 39 45886 Gelsenkirchen Tel.: +49 209 730 801-0 Fax: +49 209 730 801-99 info@abakus-solar.de www.abacus-solar.com	Peak In P210-60		60 poly-crystalline cells, each 156x156 mm		0.25		36.17 to 36.90	7.57 to 7.85			www.abakus-solar.com/fileadmin/user_upload/Datenblaetter_Module/a2peak/PeakIn_P210_60_Factsheet_2010_english.pdf
Glaswerke Arnold GmbH & Co KG Department SolAr Neuseser Straße 1 D-91732 Merkendorf Tel.: +49 (0) 9826 656 0 Fax: +49 (0) 9826 656 400 solar@glaswerke-arnold.de www.voltarlux.de	*Voltarlux®*-ASI-T-ISO-E		Amorphous silicon thin-film ASI® tandem cell. TVG6WG/PV3 SZR 16 Float 6 N 41 Thickness: 32 mm	1.1			49 - 93	0.9 – 0.49		0.23	www.voltarlux.de/images/upload/File/e_Voltarlux-ASI-T-ISO-E(1).pdf
	Voltarlux®-ASI-Standard T-Standard ISO		Amorphous silicon thin-film ASI® tandem cell. PV3/TVG6 SZR16 Argon VSG8 N41 Thickness: 35 mm	1.2	0.1		49 - 93	1.02 – 0.54		0.1	www.voltarlux.de/images/upload/File/e_Voltarlux-ASI-Standard.pdf
PV Glaze 26 The Downs Delamere Park Cuddington Cheshire CW8 2XD U.K. Tel: +44 (0)1606 301847 info@pvglaze.com www.pvglaze.com	EA1 Panel		SunFab™ amorphous technology Single 2600 x 2200 mm panel		0 to 0.9	59 to 6	196	2.8			www.pvglaze.com/PVGD_Brochure.pdf
	PA1 Panel		SunFab™ tandem cell technology Single 2600 x 2200 mm panel		0 to 0.9	78 to 9	289	2.46			

Manufacturer	Product	Illustration	Configuration	U_g (W/(m^{2}K))	T_{vis}	Wp/m^2	U_{oc} (V)	I_{sc} (A)	FF	SF	Reference/Information
Sapa Building System Industrielaan 17 8810 Lichtervelde BELGIUM Tel: +32 51 729 666 Fax: +32 51 729 647 info@sapagroup.com www.sapagroup.com			Mono-crystalline semi-transparent 5 mm distance		0.22	122					Other combinations are available www.sapagroup.com/Companies/Sapa%20Building%20System%20AB/Pictures/brochures/Solar_BIPV_low.pdf
			Mono-crystalline high efficient 25 mm distance		0.36	135					
			Polycrystalline 50 mm distance		0.42	82					
Schueco UK Limited Whitehall Avenue Kingston, Milton Keynes MK10 0AL Tel: +44 (0) 1908 28 21 11 Fax: +44 (0) 1908 28 21 24 mkinfobox@schuco.com www.schueco.com	Schüco Prosol TF		Thin film technology		0 / 0.2	60-70 / 50-55					www.schueco.com/web/uk/architects/products/facades/aluminium/fassadenmodul_prosol_tf/warmfassade
VIDURSOLAR Poligono industrial Bufalvent C/ Edison, num 8-14 08243 MANRESA Barcelona Spain T: + 34 93 874 86 50 F: + 34 93 873 64 76 vidursolar@vidursolar.es www.vidursolar.es	Model FV VS36 C54 P180		Extra-clear tempered glass, 5mm, polished edge Clear tempered glass, 5mm, polished edge Poly-crystalline 156x156 mm Thickness: 11.5 mm +/- 0.2 mm		0.36		32.4	7.63			www.vidur.es/img/solar/predefinidos/FV_VS36_C54_P180/FV_VS36_C54_P180_en.pdf
	Model FV VS41 C60 P200		Extra-clear tempered glass, 5mm, polished edge Clear tempered glass, 5mm, polished edge Poly-crystalline 156x156 mm Thickness: 11.5 mm +/- 0.2 mm		0.41		35.7	7.63			www.vidur.es/img/solar/predefinidos/FV_VS41_C60_P200/FV_VS41_C60_P200_en.pdf

Appendix D - Self-Cleaning Glazing Products

Table D. Literature data for self-cleaning glazing products.

Manufacturer	Product	Illustration	Configuration	U_g (W/(m^{2}K))	T_{vis}	T_{sol}	T_{uv}	R_{sol}	SF	Reference/Information
PPG Residential Glass PPG Industries, Headquarters, One PPG Place Pittsburgh, PA 15272 USA Herman.Marini@allfacilities.com james.bellante@allfacilities.com www.ppg.com	SunClean™ Self-Cleaning Windows									www.ppg.com/corporate/ideascapes/resglass/homeowners/product/sunclean/Pages/SunCleanHowItWorks.aspx
Pilkington Group Limited Alexandra Business Park, Prescot Road, St Helens, Merseyside WA10 3TT Tel: +44 (0)1744 28882 Fax: +44 (0)1744 692660 pilkington@respond.uk.com www.pilkington.com	Pilkington Ativ™ Neutral/ Pilkingotn Optitherm™ S4		:4/16/:4 Ar 90%	1.2	0.44	0.39		0.27		www.pilkingtonselfcleaningglass.co.uk/pdf/literature/0819292%20Activ%20Neutral%20D%20Sheet.pdf
Rain Racer Developments P.O. Box 73 Waterlooville Hampshire PO7 8SY England Tel: +44 023 9224 0824 support@rainracer.com www.rainracer.com	Rain Racer™ (product is a polymer that is applied to the window)	 								www.rainracer.com/pb2/houseg.htm
Saint Gobain Glass UK Ltd Weeland Road, Eggborough, East Riding of Yorkshire, DN14 0FD Tel: +44 1977 666100 Fax: +44 1977 666200 glassinfo.uk@saint-gobain-glass.com www.saint-gobain-glass.com	SSG BIOCLEAN/ SSG PLANITHERM TOTAL+		:4/16/:4 Ar 90%	1.2	0.77				0.67	www.selfcleaningglass.com/performance.asp

Appendix E - Aerogel Glazing Products

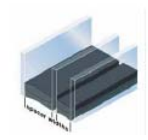
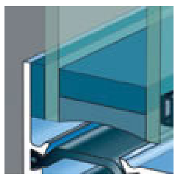
Table E. Literature data for aerogel glazing products*.

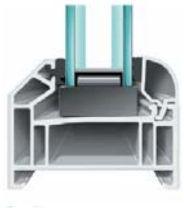
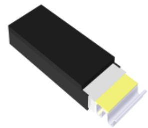
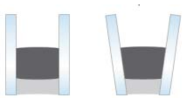
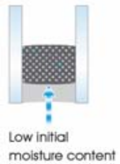
Manufacturer	Product	Illustration	Configuration (mm)	U_g (W/(m^{2}K))	T_{vis}	T_{sol}	T_{uv}	R_{sol}	SF	Reference/Information
Advanced Glazings Ltd. 870 King's Road, PO Box 1460, Station A Sydney, NS, Canada B1P 6R7 Tel: +1 902.794.2899 info@advancedglazings.com www.advancedglazings.com	Solera + Nanogel		76.2	0.31	0.07 - 0.32				0.31 – 0.07	http://sydney.advancedglazings.com/downloads/Real_Daylighting_Solutions_Brochure.pdf. Values calculated using VISION4 from Advanced Glazings Systems Laboratory at the University of Waterloo, to ASHRAE standards.
Cabot Corporation Cabot Aerogel Interleuvenlaan, 15 i B-3001 Leuven Belgium Tel: +32 16 39 25 78 Fax: +32 16 39 25 79 eu_nanogel_sales@cabot-corp.com www.nanogel.com	Nanogel® Aerogel		10	1.38	0.80	0.80				"Nanogel Aerogel Daylighting – The New Standard in Eco-Daylighting Solutions" www.nanogel.com
			16	1.00	0.70	0.70				
			20	0.78	0.62	0.62				
			25	0.64	0.55	0.55				
			32	0.51	0.47	0.47				
			40	0.42	0.39	0.39				
			50	0.34	0.31	0.31				
			70	0.25	0.19	0.19				
Okalux GmbH 97828 Marktheidenfeld, Germany Tel.: +49 (0) 9391 900-0 Fax: +49 (0) 9391 900-100 info@okalux.de www.okalux.com	Okagel		From 6/30/6 to 6/60/6 (outer/inner glass, aerogel filling)	0.30 – 0.60	≤0.59				≤0.61	www.okalux.de/en/products/brands/okagel.html

*Aspen Aerogels (2008ab) is one of the main manufacturers of aerogels, but to the authors' knowledge they do not so far produce transparent or translucent aerogels, and is thus not included in this table.

Appendix F - Non-Metallic Spacer Products

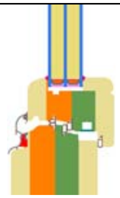
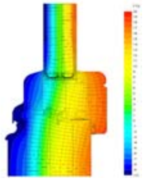
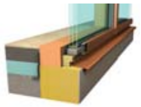
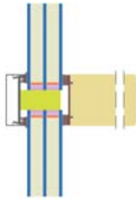
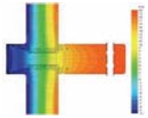
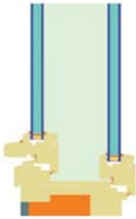
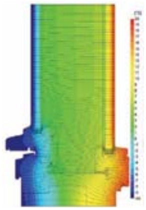
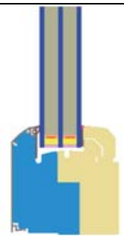
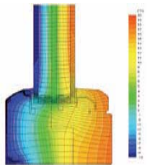
Table F. Literature data for non-metallic spacers.

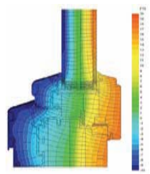
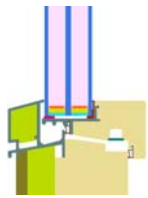
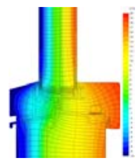
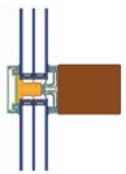
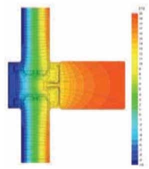
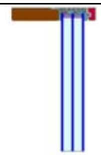
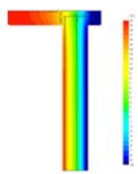
Manufacturer	Product	Illustration 1	Illustration 2	Materials	Widths Available (mm)	Thermal Conductivity (W/(mK))	Reference
ADCO North America 4401 Page Avenue P.O. Box 457 Michigan Center, MI 49254 USA Tel: +1 517-764-0334 Fax: +1 517-764-6697 construction@adcocorp.com www.adcocorp.com	Ködimelt™ TPS			Thermoplastic elastomer formulated with inclusion of desiccant material			www.adcocorp.com
Bystronic Lenhardt GmbH Abt. Vertrieb Karl-Lenhardt-Str. 1-9 75242 Neuhausen-Hamberg Deutschland Tel: +49 (0)7234 601 0 Fax: +49 (0)7234 17 19 lenhardt@bystronic-glass.com www.bystronic-glass.com	TPS®			1-component-polyisobutylen with included desiccant material	6 - 20		www.bystronic-glass.com
Edgetech IG Inc Stonebridge House Rowley Drive Stonebridge Trading Estate Coventry CV3 4FG Tel: +44 (0) 8700 566 844 Fax: +44 (0) 2476 639 727 Email: ukenquiries@edgetechig.com www.superspacer.co.uk	Super Spacer			No-metal, pre-desiccated, structural foam spacer system. Thermal Set Spacer (TSS)			www.superspacer.co.uk
Traco HQ and Manufacturing 71 Progress Avenue Cranberry Township, PA 16066 USA Tel: +1 800-837-7002 Fax: +1 724-776-7014 www.traco.com	**N**EX**G**EN™ —Energy Spacer™			Non-metallic airspacer			www.traco.com

Manufacturer	Product	Illustration 1	Illustration 2	Materials	Widths Available (mm)	Thermal Conductivity (W/(mK))	Reference
Tremco illbruck Ltd Coupland Road, Hindley Green, Wigan, WN2 4HT United Kingdom Tel: +44 1942 251 400 Fax: +44 1942 251 410 info@tremco-illbruck.co.uk www.tremco-illbruck.com	Duralite			5 components in 1: desiccated topcoat, powerful bond-line adhesive, impermeable foil moisture vapour barrier, sightline stiffener and non-metal flexible stabiliser	6 - 20		www.tremco-illbruck.co.uk/celumdb/documents/Duralite_Brochure_GB_7728.pdf
Viridian 95 Greens Road **Dandenong** VIC 3175 Australia Tel: +61 1800 810 403 www.viridianglass.com	ThermoTech™ Thermoplastic Spacer TPS®			Synthetic rubber	6 - 18	0.28 (at 23ºC)	www.viridianglass.com/Products/thermotech-thermoplastic-spacer-tps/default.aspx?ProductType=Specifier

Appendix G - Window Frame Products

Table G. Literature data for Passivhaus certified window frames.

Manufacturer	Product	Illustration 1	Illustration 2 (mm x mm)	Illustration 3	U_f ($W/(m^2K)$)	Spacer Ψ_g (W/(mK)) U_w($W/(m^2K)$) U_g ($W/(m^2K)$) w x h (m)	Materials	Reference
Bracia Bertrand Sp.J. ul. Wejherowska 12 PL- 84-242 Luzino Tel.: +58 678 07 78 Fax: +58 678 07 79 info@bertrand.pl www.bertrand.pl	Thermoline 110		 154 / 138		0.691/ 0.693	TGI – Wave 0.042 0.80 0.70 1.23 x 1.48	Wood, PUR (λ = 0.040 W/(mK)).	www.passiv.de
Endl-Wagner GmbH Hötzlarn 17, A-4770 Andorf Tel. +43 (0) 7766 41117 Fax. +43 (0) 7766 / 41117-50 office@endl.at www.endl.at	ON TOP PLUS	 	 64 ; 32		0.65	Swisspacer V 0.033 0.79 0.70 1.32 x 1.48	Wood, Aluminium.	www.passiv.de
Ing.-Büro A. Naumann & H. Stahr Sommerfelderstr. 11, D-04299 Leipzig Tel. + 49 341 / 86319-70 Fax. +49 341 / 86319-99 info@naumannstahr.info www.naumannstahr.info	Passivhaus Kastenfenster		 163 / 160		0.62/ 0.71	2 x Thermix 0.022 0.68 0.62 1.23 x 1.48	Wood.	www.passiv.de
Internorm International GmbH Ganglgutstr. 131, A-4050 Traun Tel. +43 (0) 7229 / 770-3188 Fax. +43 (0) 72 29 / 71293 www.internorm.com	'edition' als Fixverglasung		 96		0.63	Thermix 0.043 0.79 0.70 1.23 x 1.48	Aluminium, PUR, Wood.	www.passiv.de

Manufacturer	Product	Illustration 1	Illustration 2 (mm x mm)	Illustration 3	U_f (W/(m^{2}K))	Spacer Ψ_g (W/(mK)) U_w(W/(m^{2}K)) U_g (W/(m^{2}K)) w x h (m)	Materials	Reference
NIVEAU Fenster Westerburg GmbH Langenhahner Straße, D-56457 Westerburg Tel. +49 26 63 / 29 01-0 Fax. +49 26 63 / 22 33 kontakt@niveau.de www.niveau.de	KombiRoyal Plus PH		 124		0.68	Thermix 0.040 0.79 0.70 1.23 x 1.48	Wood, PUR, Aluminium, Polystyrene, Polyamide.	www.passiv.de
PAZEN Fenster + Technik Zum Kirchborn 12, D-54492 Zeltingen-Rachtig Tel: +49 6532 953426 info@eurotec-pazen.de www.pazen-technik.de	ENERsign		 100		0.64/ 0.78	Thermix 0.033/0.031 0.77 0.70 1.23 x 1.48	Wood, Glass-Reinforced Plastic, Insulation Material (λ = 0.031 W/(mK)).	www.passiv.de
RAICO Bautechnik GmbH Gewerbegebiet Nord 2, D-87772 Pfaffenhausen Tel. +49 8265 / 911-0 Fax. +49 8265 / 911-100 info@raico.de www.raico.de	RAICO THERM+ 76H-I Isobloc P		 76		0.69	Thermix 0.038 0.80 0.7 1.23 x 1.48	Wood, Aluminium.	www.passive.de
Stabalux GmbH Siemens Straße 10 , D - 53121 Bonn Tel 0228 / 909043-10 Fax. 0228 / 909043-11 info@stabalux.com www.stabalux.com	Stabalux H, System 60 PH				0.61	Thermix TX.N 0.040 0.80 0.70 1.23 x 1.48	Wood.	www.passiv.de
	Stabalux H, System 50/60 PH		 60		0.63	Swisspacer V 0.029 0.78 0.70 1.23 x 1.48	Wood.	