PROPERTIES AND PERFORMANCE OF VACUUM INSULATED GLAZING

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INTRODUCTION

As energy codes become more stringent, maximising the energy efficiency of the glazing used in buildings becomes of greater importance. Many new solutions have been proposed to reduce heat transfer through windows. One such technology that is currently growing in prominence is vacuum insulated glazing (VIG). VIG has been manufactured successfully in Japan for over 16 years, and although used primarily in Asian markets, its use has been growing in both Europe and North America over the last five years.

VIG is different from other insulated glass technologies, providing excellent energy efficiency whilst maintaining an ultra-thin form factor—6.2 mm being the thinnest. A large range of product options are available and will be described in detail in this article, as well as a number of examples of their use. The advantages of using VIG in both retrofit of older buildings and the glazing of new construction will be detailed and new developments in the technology discussed. It will be demonstrated that VIG will be a key technology in the future, giving new options to building designers.

KEYWORDS

energy efficiency, high performance glazing, vacuum insulated glazing

GLASS PERFORMANCE BASICS

Windows play a very important role in the design of a building. It has been well documented that windows increase occupant well-being and worker productivity. The energy usage of a building is also heavily influenced by windows and the building designer must balance two important factors: aesthetics and performance. Aesthetic choices relate to glazing appearance—how it matches other materials and complements the rest of the site. Performance is defined by the HVAC needs of the building, occupant comfort, and always by energy and safety codes. The number of design and product options available to the building designer is constantly growing and developing, so understanding some of the important parameters in glazing design is very important [1, 2].

In general, the thermal performance characteristics of any glazing can be best described by two attributes: Solar Heat Gain Coefficient (SHGC) and U-Factor. The SHGC is defined

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as the ratio of solar heat gain through the glass relative to the incident solar radiation on the glazing; i.e., how much heat from the sun is transmitted into the building. SHGC is a decimal quantity from 0.0 to 1.0 with higher numbers representing a larger amount of solar gain. SHGC includes both the solar energy directly transmitted through the glazing plus the solar energy absorbed by the glazing and subsequently convected and thermally radiated inward. Whether a high or low solar gain is desired is generally dependent on whether free passive solar gains are advantageous. Typically, it is beneficial to incorporate a higher SHGC glazing when the heating costs of a simple building exceed its cooling costs. In commercial buildings, solar gain is not very welcome in interior spaces as most of these structures generate more heat than they need from lighting, computers, machinery, and people, even on cold winter days. Depending on the SHGC requirements of a building, a large number of coated and uncoated glass options exist that can be used to achieve them.

The second parameter related to the thermal performance of a glazing is U-Factor, which describes thermal conductivity or the heat flow through the glazing from the warm side to the cooler side. U-factor is the rate of heat loss per square metre, under steady state conditions, for a temperature difference of one kelvin and is expressed in W/m^2K. This means that the higher the U value, the worse the thermal performance of the building envelope. Heat loss can also be quantified in terms of thermal resistance, abbreviated to R value. This is the inverse of the U-factor. As for SHGC, there are a number glazing options that can be used to control U-factor; however, to select the correct design it is important to understand how heat is lost.

HEAT TRANSFER

Mechanisms of Heat Transfer

Heat flows from hot to cold and heat transfer takes place via three mechanisms: conduction, convection and radiation. When we consider heat loss in glass products, there are three defined stages.

1. *Heat loss to the internal glass surface.* This is heat lost from the room when the glass is at a lower temperature than the room temperature. Heat loss results from convection/conduction from the room air moving over the glass surface and exchange of long wavelength radiation between the glass and room surfaces. Radiative heat loss dominates unless the glass surface has a low emissivity coating (emissivity typically from 0.02 to 0.2).
2. *Heat loss through the glazing.* Glass has a high thermal conductivity. This is why single glazing is such a poor insulator. Heat loss can be reduced by adding an additional pane and air space, i.e., an insulated glass unit (IGU). The low thermal conductivity of air will reduce conductive loss and the second pane gives additional resistance loss by radiation. Performance can be further improved by using a lower thermal conductivity gas such as Argon or Krypton. Use of a low-e coating in the air gap will reduce the long wave radiation exchange between the panes by more than 75% and lower U-factor by approximately 25% to 40%.
3. *Heat loss from outer glass surface.* Here conduction and convection dominate due to the influence of wind. Radiation exchange depends on the temperature of the surrounding surfaces and sky.

Options to Reduce Heat Transfer

Building codes continually strive for lower U-factors to reduce heat loss from windows, and to meet these requirements, many solutions have been proposed. Some examples are below:

- Use of a gas with lower thermal conductivity than Argon, e.g., Krypton
- Low-e coating on surface #4 of a double glazed IGU, i.e., the outside surface of the internal pane of glass
- Using a second air space and third pane of glass, giving a triple glazed unit

Lower thermal conductivity gases will indeed lower U-factor; however, they are costly and have not been widely adopted. The main disadvantage of this approach is that gas will inevitably leak from the IGU over time, reducing energy efficiency. The use of a low-e coating on surface #4 of a double glazed IGU is increasing. This coating typically complements a low-e coating on surface #2 of the unit and reduces U-factor by around 20%; however, this increases the risk of condensation formation, due to the temperature of the internal pane of glass being reduced. Although this is a manageable phenomena, many manufacturers see an increased risk and choose not to adopt this technology. Triple glazed units are increasing in prominence in North America and are a recognised solution in European markets. Although a proven technology, their introduction requires redesign of fabrication facilities and increases both cost and weight of the glazing unit significantly. With these comments in mind, there is a need for a high performance glazing which reduces U-factor significantly without some of the disadvantages mentioned above. Vacuum insulated glazing (VIG) is one such technology.

VACUUM INSULATED GLAZING (VIG)

Introduction to VIG

The concept of VIG is not new. It was first described in the patent literature by Zoller in 1913 [3]; however, it was 1989 before the successful fabrication of a VIG was reported by Collins et al. at the University of Sydney [4]. In simple terms, a VIG is a double glazing unit where the air between the two panes of glass has been extracted, creating a partial vacuum. A vacuum provides excellent thermal efficiency because if the pressure is low enough, it will eliminate the conductive and convective heat exchange between the two panes of glass. In a standard double glazed unit with a low-e coating, the conduction/convection component can result in 70% of the heat lost; so eliminating this loss is significant. As will be described in more detail below, the radiative heat loss can then be reduced by use of a low-e coating inside the VIG, producing an even lower U-factor. Due to the efficiency of a vacuum in reducing heat loss, it is not necessary to have a large distance between the two panes of glass; the typical distance is 0.2 mm. This is significantly less than a conventional IGU, which will generally have an air space of around 12 mm. As a result, VIG units can have overall thickness of as little as 6.2 mm, comparable to a monolithic piece of glass but with the performance of a triple glazed insulated glass unit. Current state-of-the-art in terms of U-factor for a commercially available 6.2 mm thick VIG is 1.0 W/m^2K (Table 1).

The thin form factor of VIG is a key feature, as this gives many new opportunities to building designers and architects in projects where it is not possible to increase the thickness of the glazing beyond ~6 mm. In these situations, heat loss through monolithic glazing is

TABLE 1. Performance figures of VIG versus conventional glazing.

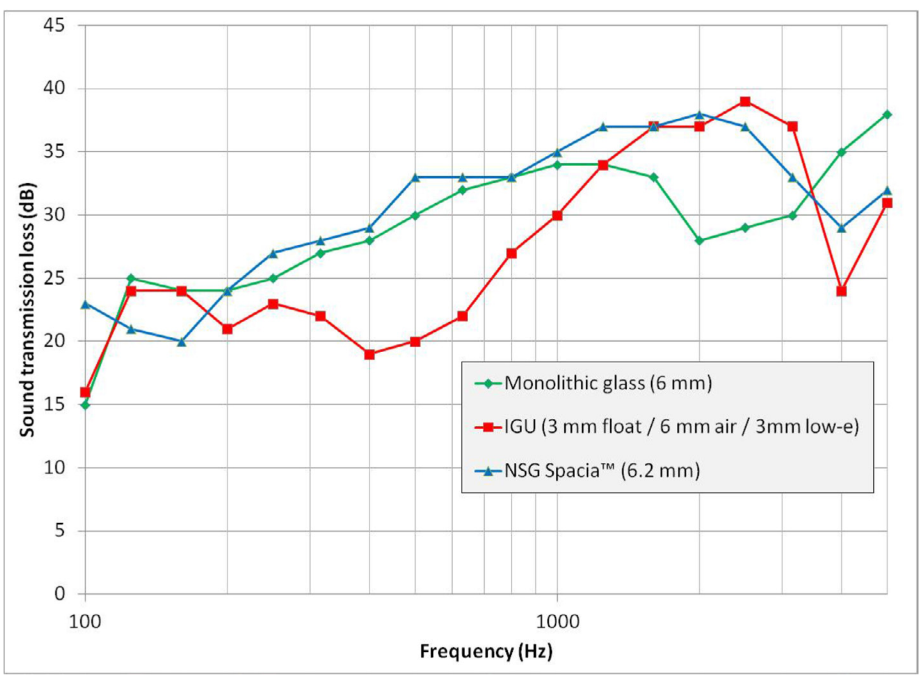
Glazing unit	Thickness (mm)	U-factor: winter (W/m2K)	U-factor: winter (Btu/hft2F)	SHGC
IGU: Low-e	24.1	1.9	0.47	0.62
IGU: Solar control low-e	24.1	1.7	0.29	0.39
NSG Spacia™	**6.2**	**1.4**	**0.25**	**0.66**
NSG Spacia™ Cool	**6.2**	**1.0**	**0.18**	**0.49**

significant and VIG can provide significant benefits to energy efficiency without compromising the aesthetics or design of the building.

The reduced thermal conductivity of VIG also provides increased condensation resistance. Condensation can be a major issue in buildings, both from an aesthetic standpoint and due to the damage it can cause to window frames and other building materials. For a 6.2 mm VIG with a U-factor of 1.4 W/m^{2}K, installed in a room with internal conditions of 20 °C and 60% relative humidity, no internal condensation will form at external temperatures down to –21 °C. Identical tests using a conventional 12 mm IGU with low-e resulted in condensation forming at temperatures around 0 °C.

A further advantage in the use of a VIG can be seen in its sound reduction performance relative to a conventional IGU. Due to the use of a vacuum between the panes, the attenuation of noise is improved over almost all frequency ranges relative to an IGU, but particularly in the mid-frequency range where noise from traffic and public transport is prevalent. As can be seen in Figure 1, the sound reduction performance of VIG can be regarded as that of a single pane with the same thickness as the VIG unit.

FIGURE 1. Sound transmission loss of NSG Spacia™ compared with conventional glazing.



Design of a VIG Unit

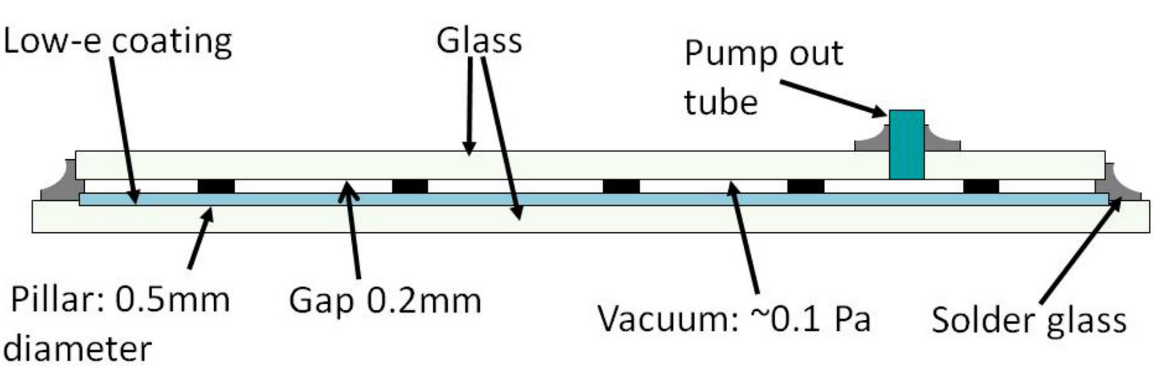
Building on the work by Collins et al., Nippon Sheet Glass (NSG) launched the world's first commercially available VIG in October 1997, NSG Spacia™ (Figure 2). Aside from the range of VIG products manufactured by NSG, the only other companies with a commercial VIG product are Beijing Synergy Vacuum Glazing and Qingdao Hengda, both of China. For all the companies the design principles of the VIGs are similar and are described below.

FIGURE 2. NSG Spacia™.

In its most simple design, a VIG consists of two sheets of glass that are hermetically sealed around the edge and separated by a narrow evacuated space. The pressure in the evacuated cavity is typically on the order of 0.1 Pa and the hermetic seal is provided by a low melting point solder glass with a coefficient of thermal expansion that matches that of soda lime glass [5]. In order for the VIG to replace single paned glazing, thickness is minimised using two sheets of 3 mm glass; however, if greater strength is required—for example against wind load—then a thicker unit can be designed. This can be achieved either by increasing the thickness of the external pane or the thickness of both panes. In order to reduce radiative heat loss, a low-e coating is used on one of the internal surfaces of the VIG, typically surface #2. To maintain separation of the glass panes under atmospheric pressure, a pillar array is used that maintains a distance of approximately 0.2 mm between the two panes of glass. The final unique design feature of a VIG unit is the small glass pump out tube, through which the internal volume of the unit is evacuated. This pump out tube is melted and closed near the end of the manufacturing process in order to ensure a hermetic seal and is then covered by a protection cap. A schematic diagram of a VIG unit is shown in Figure 3.

One of the key challenges to be overcome in the production of a durable vacuum glazing unit is in the design of the pillar array that separates the glass panes. There are a number of variables here that must be considered, such as the size and shape of the support pillars, the type of material used, and the spacing and pattern of the array. All of these parameters are critical, as the pillar array influences both the strength of the unit and its thermal insulation

FIGURE 3. Schematic diagram of a VIG unit.



properties. The significant compressive stress acting on the pillars due to atmospheric pressure means the choice of a material with suitable compressive strength is critical. Furthermore, as heat will flow through the pillars, their thermal conductivity should be minimised as much as possible. Balancing pillar diameter and spacing is also important to ensure that conical indentation fracture will not occur in the glass sheet. In the case of the NSG Spacia™ product, pillar diameter is 0.5 mm and the separation between pillars is 20 mm. Finally, the material used should not degrade in vacuum.

One of the main differentiators between vacuum glazing and a standard insulating glass unit is in the design of the seal between the two panes of glass. In a standard insulated glass unit, two sealant materials are typically used—one organic and one inorganic. Although these seals are reliable, some leakage into and out of the unit is inevitable over time. In the case of a unit which uses a low thermal conductivity gas such as Argon, this leakage will lead to a reduction in the energy efficiency of the unit. Moisture ingress on the other hand will lead to visible condensation, a condition that is typically described as a seal failure. In a VIG unit, a hermetic seal is essential to maintaining the vacuum and energy efficiency of the unit, so such failures cannot be tolerated. Use of a glass seal in a VIG ensures that—providing the seal is manufactured correctly—ingress due to moisture is eliminated (glass has a moisture vapour transport rate of $< 10e^{-6}$ g/m^2/day). Matching the thermal expansion coefficient of the soda lime glass with the glass seal is important to ensure that thermal mismatches do not occur that could cause seal failure. A specially designed glass solder that meets the above requirements is used. This type of solder glass has been used in the electric industries for many years with products like vacuum tubes, CRT displays, and plasma display panels. Although flexible edge seals based on metal have been proposed, no units of this type are currently being manufactured commercially. The pump out tube is also sealed using glass.

A further unique consideration is outgassing from the internal surface of the glass, which can raise the pressure inside the unit and reduce thermal efficiency. Accelerated aging of vacuum units has been carried out by both NSG and Lenzen et al., and based on the above work, the likely pressure increase after 25 years at 30 °C was studied and found to be 0.04 Pa [6]. The result of such a pressure increase in a VIG with a starting U-factor of 1.40 W/m^{2}K would be a degradation of 0.01 W/m^{2}K, giving a U-factor of 1.41 W/m^{2}K, a very small increase. The level of diffusion-related degradation is heavily influenced by the manufacturing conditions, so optimising these conditions is important in negating the effects of outgassing.

From the above information it can be seen that, providing the VIG is manufactured correctly, there are very few mechanisms for the unit to fail in standard operation. Various durability tests have been developed and passed successfully, giving confidence in the durability of the construction. Furthermore, long-term degradation of any of the key components of the unit is unlikely, as they are all based on glass.

Manufacture of VIG

As would be expected from the above, manufacture of a VIG is very different from that of a conventional IGU. An automated manufacturing process is used; where glass sheets are first cut to size and machined before washing. As described below, various glass types can be used, with at least one pane being coated glass (pyrolytic or sputtered). The pillar array is then positioned onto the surface of the lower glass sheet and inspected, before the top sheet is positioned. It is critical that the inner surfaces of both glass sheets are not touched following washing. This may cause cosmetic issues, but more importantly, may lead to instability of the vacuum. Once the glass is pared, the glass solder material is deposited around the edge of the two sheets of glass and the pump out tube positioned. A high temperature process is then used to melt the solder, which seals the unit via capillary action between the glass sheets and fixes the pump out tube. Once the hermetic seal has been established, the unit is evacuated using a pumping system, reducing the pressure to the order of 0.1 Pa. Following this, the tip of the glass tube is melted and closed with the protection cap then being applied to the pump out tube.

VIG PRODUCT OPTIONS AND PERFORMANCE

Standard VIG units

The basic design of a VIG has been described; however, building designers typically have to balance many parameters to select the optimum glazing option. As a result, a range of VIG product types are available. For all of the options that will be described below, one consistent design feature is that the side of the VIG unit incorporating the pump out tube is always intended to face into the building interior.

Beginning with the 6.2 mm unit that was described above, its performance can be optimised using different low-e coatings, typically on surface #2. In situations where passive solar gain is useful, low-e coatings offering a higher SHGC are typically used. These could be either pyrolytic or sputtered coatings. NSG Spacia™ uses a pyrolytic coating resulting in a VIG with a U-factor of 1.4 W/m^{2}K and SHGC of 0.66. As described above, for many situations a lower SHGC value is desirable and can be achieved through the use of an optimised single silver coating, a double silver coating, or even triple silver coatings. NSG Spacia™ Cool offers this functionality, giving a reduced SHGC of 0.49 with a U-factor of 1.0 W/m^{2}K in a 6.2 mm thickness. Performance figures of all of the products discussed are shown in Table 2 [7].

Although in many situations, the thin form factor of a VIG unit is important, there are occasions where a thicker unit is necessary in order to accommodate higher wind loads. For such a project, a thicker unit would typically be used and both the outer pane and inner pane thicknesses can be increased to e.g. 5 mm. Regarding wind load; since the two panes are pressed against each other due to the force of atmospheric pressure, the VIG unit's wind load resistance can be regarded as approximately 80% of a single pane of the equivalent thickness. This has been confirmed through product testing. For all of the 6.2 mm units listed above,

TABLE 2. Detailed specifications of selected VIG designs.

Glazing unit	Thickness (mm)	Tvis (%)	Rvis (%)	Tsol (%)	Rsol (%)	U-factor: winter		SHGC
						W/m2K	Btu/hft2F	
NSG Spacia™	6.2	76	16	61	15	1.4	0.25	0.66
NSG Spacia™ Cool	6.2	70	23	46	36	1.0	0.18	0.49
NSG Spacia™ Cool	10.2	68	23	43	33	1.0	0.18	0.48
NSG Spacia™ Shizuka	9.2	73	15	56	13	1.4	0.25	0.61
NSG Spacia™ Cool Shizuka	9.2	68	22	42	29	1.0	0.18	0.46
NSG Spacia™ 21	18.2	66	19	42	26	0.9	0.16	0.51
NSG Spacia™ 21 Solar Control	18.2	58	19	29	40	0.8	0.15	0.34
NSG Spacia™ 21 Solar Control	21.2	58	19	29	40	0.7	0.14	0.34

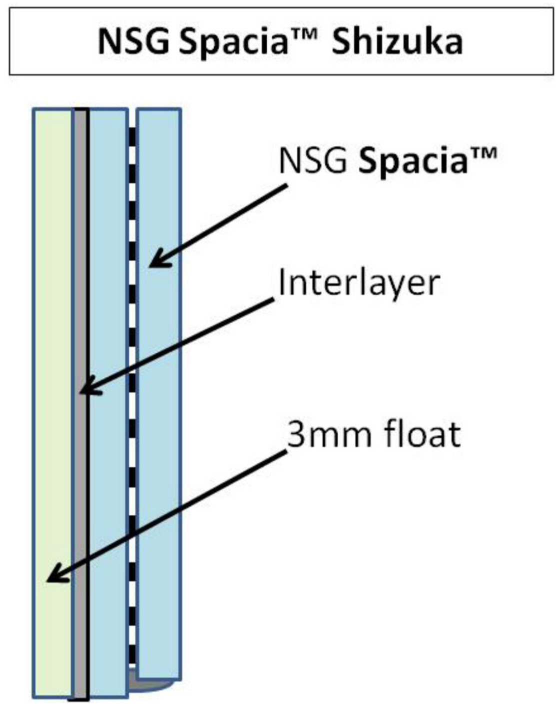
the maximum available size currently is 1,350 × 2,400 mm. When the thickness of the unit is increased to 10 mm through the use of two 5 mm panes, this size can be increased to 3,000 × 2,000 mm.

VIG Units for Safety Glazing

One disadvantage in current VIG designs is that tempered glass panes cannot be used. Work is ongoing by a number of companies to address this issue; however, currently no such option exists. There are a number of reasons for this. One key issue is that tempering of glass will always introduce some level of distortion, which can cause issues regarding pillar placement in finished units. Nonetheless, in certain situations, safety glazing is essential to the building designer; and so, a number of options are available to address this.

The first is the use of an additional glass pane laminated to the exterior pane of the VIG unit. This pane is typically between 2.5 mm to 5 mm thick. Use of such a laminate construction provides additional safety performance in addition to improved sound reduction and almost 100% absorption of UV. This is provided by NSG Spacia™ Shizuka which is shown in Figure 4. If further burglar or vandal protection is required, an additional polycarbonate sheet can be laminated between the exterior pane and the VIG unit. Additionally, use of a safety film on standard 6.2 mm units has been demonstrated to provide a classification of 2 (B) 2 on the pendulum body impact resistance test conforming to EN 12600; enabling their use in many applications. For all of these constructions there is no significant effect on the optical or thermal properties of the VIG unit.

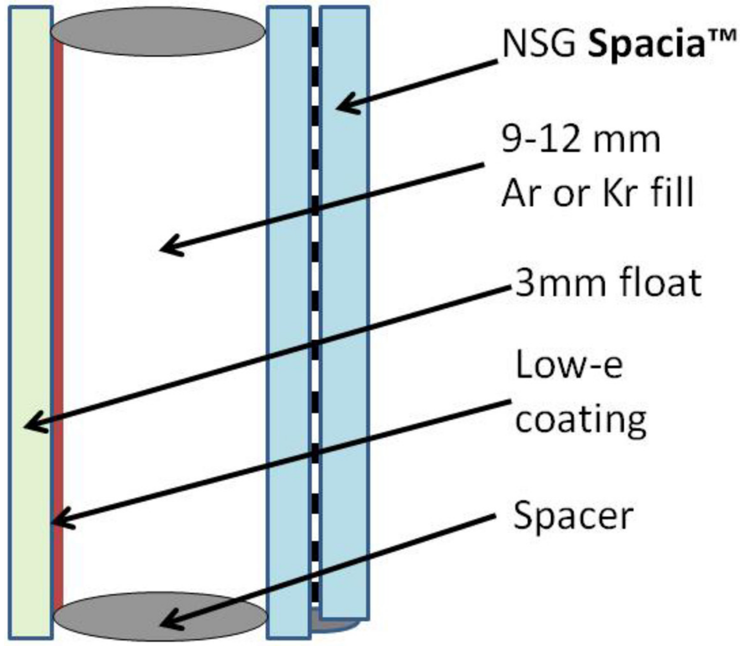
FIGURE 4. Schematic diagram of laminated NSG Spacia™.



Hybrid VIG Units

An additional VIG design is the so-called hybrid VIG unit. This is a key technology to reduce U-factor and SHGC further. This type of unit combines the construction of a standard double glazed IGU, i.e., two panes of glass separated by a gas-filled space, with a VIG unit. In this design, the inner pane of glass is replaced by a VIG unit as illustrated in Figure 5. The result is a unit with excellent thermal and solar performance. Further advantages of the hybrid VIG are greater strength, the ability to use a tempered pane of glass as the exterior pane, and improved sound attenuation properties. NSG offers a product called Spacia™ 21, launched in 2002, which incorporates a 3 mm or 4 mm outer pane of glass in combination with a 6.2 mm VIG unit as the inner glazing. In this case the separation between the outer pane and VIG can be varied from 9 mm to 12 mm and the gas fill is typically Argon, with Krypton being used to improve U-factor further. A low-e coating can also be used on the exterior pane (surface #2)

FIGURE 5. Schematic diagram of NSG Spacia™ 21 hybrid VIG.



to provide added functionality. Key performance figures for Spacia™ 21 Clear are U-factor and SHGC of 0.9 W/m^2K and 0.51 respectively, whilst Spacia™ 21 Solar Control gives a further improvement to 0.7 W/m^2K and 0.34 (Table 2). In both situations, the total thickness of the unit is 18.2 mm and the maximum size is currently 1,350 × 2,400 mm.

New Developments in VIG

The information above provides the current state-of-the-art in vacuum glazing; however, ways to improve performance are always being explored. In addition to the two companies mentioned so far, a number of other companies are developing VIG technology; with many new designs being proposed. Hybrid VIG has been discussed but the use of more than one VIG unit, giving double or triple VIGs is also possible and is described by companies such as Qingdao Hengda Glass. It is not clear if these units are available commercially, but low U-factors could be achieved by these units. A variety of companies are also developing VIG utilising flexible edge seals to replace the soldered glass seals currently in use. These could give improved flexibility to the VIG unit, giving advantages related to thermal growth and contraction of the panes in extreme temperatures; however, although prototypes of such units have been made, none are currently being manufactured. One imagines it will be a challenge to ensure long term vacuum stability, as very few materials have the exceptionally low moisture vapour transport rate of glass. As described above, maintaining the vacuum of the unit is essential throughout its lifetime and VIG products made with glass solder have demonstrated this capability in a variety of climate zones.

Use of tempered glass in the VIG unit would also give many advantages and this is a key development area in the industry. The elevated temperatures used during VIG manufacture do provide challenges in the use of tempered glass however. Also as described above, the inherent distortion in a tempered pane of glass adds to the difficulty. Further improvements to the U-factor of the units by new pillar array designs and new pillar materials are also in development. The risk attached to this approach is that use of more energy efficient pillar arrays typically increases the probability of glass breakage due to stress concentration on the pillars. So there are many hurdles to overcome in improving VIG design; however, many of the potential benefits are certainly worth obtaining and will be important in increasing the adoption of vacuum glazing.

A large amount of VIG designs are already in existence, with many new developments still to come, giving building professionals a large array of options. As VIG has been produced commercially for approximately 15 years, it has been used in many different project types and some of these are described below.

PROJECTS USING VIG

Retrofit of Existing Buildings

Due to its ultrathin form factor, VIG is a perfect candidate for the retrofit of historic buildings. Typically these buildings are over 100 years old, with many having their original window frames and glazing; which is typically 6 mm and was produced by the sheet glass process. When it becomes time to update and renovate the buildings, maximising the energy efficiency is a major consideration; however, typically an architect in such projects is unwilling to compromise on the aesthetics and keeping the original look of the building is considered more critical. Use of VIG allows the designer to maximise energy efficiency without significantly altering building aesthetics.

Example 1: Massachusetts Institute of Technology, MA

One example of this approach is currently taking place at the Massachusetts Institute of Technology (MIT), a private research university in Cambridge, Massachusetts. It is almost 100 years since MIT moved the central campus to its current location, which was designed by William Welles Bosworth. A renovation of these buildings is currently taking place and one of the main challenges is maximising the sustainability of the buildings whilst maintaining their architectural integrity. Selecting the correct glazing option was clearly of critical importance and so a three-year pilot project was undertaken to assess the best replacement windows [8]. Replacing the existing windows provides an opportunity for large energy savings as these are all single paned and occupy a large area of the building. Typical two-story windows are approximately 2,400 mm wide and 8,200 mm tall, with the largest measuring around 11,000 mm.

The three-year test was carried out at a test site on the campus and considered four restoration and replacement glazing options

- Single paned glass
- Argon filled insulating glass
- Double window utilising an interior storm window
- VIG

Before the test began, the argon filled insulating glass option was rejected as a possibility. This was because it was impossible for this type of unit to fit within the available depth of the wall and so the appearance of the building would have had to be altered. A second issue with the use of an argon filled unit was that although the energy efficiency of these units is well recognised; it is impossible to guarantee the integrity of the argon fill over a long period of time.

Lifetime of the windows was a critical consideration; and so for these two reasons, this type of unit was ruled out.

In 2010 the three remaining options were installed in the test site and the temperature and humidity inside the wall were monitored using an array of 60 sensors. The three-year study has now been completed and from the results it has been concluded that windows using VIG provide the greatest energy efficiency at an affordable price over the long term. The VIG product selected was demonstrated to be four times as efficient as the existing glass. Another key advantage of VIG is that the original look of the building has not been compromised.

Example 2: Hermitage Museum, Amsterdam

A similar high-profile project was the use of VIG in the Hermitage Museum in Amsterdam, the Dutch location of the famous St. Petersburg museum. The Hermitage Amsterdam opened in 2009 and is housed in a building on the Amstel River that was constructed in the 1680s. As this is a listed building, keeping the historic look was a requirement of the redesign. The window frames used on the external facade were to be maintained and these contained glass of around 4 mm thickness. There were few options available that met the requirements of approximately maintaining this thickness whilst improving the energy efficiency of the building. Also important was condensation control, as this had historically been an issue in the building and it was critical that no condensation occur at temperatures below 7 °C. VIG provided an excellent method to meet all of the above criteria, with the NSG Spacia™ product with a U-factor of 1.4 W/m^2K being selected for the project. The U-factor was a substantial improvement over other coated glass options that were considered and around 1,000 units were installed successfully in the restored window frames (Figure 6). The success of this project has resulted in a number of other installations in the Netherlands; such as the restoration of the Prince William V art gallery in The Hague and a number of properties in Arnhem, Enschede, and Franeker. In all of these cases the 6.2 mm NSG Spacia™ product was installed in original frames, which were typically more than 100 years old. Again, the original look of the building was maintained whilst greater energy efficiency and improved sound reduction were achieved.

FIGURE 6. VIG retrofit of Hermitage Museum, Amsterdam.

Example 3: Archibald Place, Edinburgh

The above examples have shown how VIG can replace existing windows to improve energy efficiency in commercial buildings; however, of equal importance is improving the energy efficiency of residential homes. Studies have been undertaken in the UK to demonstrate how VIG can be used to improve the sustainability of listed homes whilst maintaining their appearance. A research and demonstration project was carried out at the request of The City of Edinburgh Council to select, install, and monitor a range of slim profile glazing systems to assess their ability to reduce energy consumption, fuel bills, and CO_2 emissions [9]. These window systems were installed into the windows of listed buildings in central Edinburgh, a conservation area and part of the UNESCO World Heritage site. As this was a conservation area, the historic appearance of the buildings had to be maintained and the aim of the project was to inform future policy changes in relation to windows in listed buildings.

Double glazing is not currently permitted in the majority of listed buildings, however slim profile glazing systems allow the retention of the existing window frame or use of new frames with the same look and dimensions. For this study, six different glazing systems were selected: five different types of slim profile double glazed units and one VIG product, NSG Spacia™. The slim profile double glazed units incorporated low emissivity coatings and low thermal conductivity gases such as Argon, Krypton, and Xenon, and were produced by a number of different manufacturers. Cavities varied from 3–8 mm, so although these were slim profile systems, their overall thickness was still significantly greater than the original glazing. The VIG units used were 6.2 mm in thickness and installed in a Category B listed Georgian tenement (Figure 7).

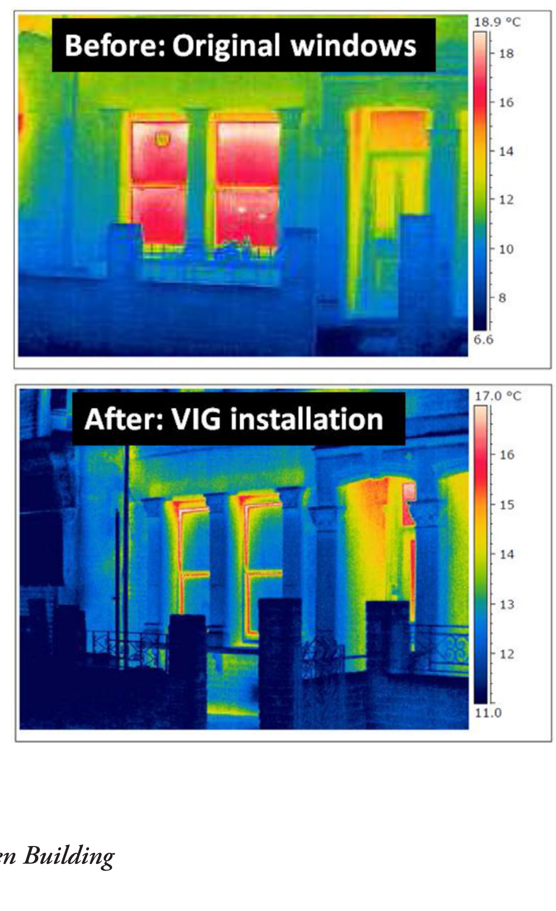
FIGURE 7. VIG retrofit of Archibald Place, Edinburgh.

The results of the test program showed that of all of the units tested, the VIG units achieved the lowest U-factor by a significant margin. U-factor was 1.4 W/m^2K, as opposed to 5.5 W/m^2K for the original glazing. Although the slim profile double glazed units gave a significant improvement over existing windows, they were not optimised for thermal performance, which was sacrificed in order to produce slimmer units. Embodied energy of the products was also calculated and despite the significant transportation involved for an NSG Spacia™ unit (Japan to the United Kingdom); it had the lowest embodied energy of the options considered. Home owners were also surveyed and all respondents were satisfied that the replacement glazing looked exactly the same as the original single-glazed windows. In addition, they confirmed that their homes were more comfortable due to the improved energy efficiency of the glazing and that the appearance of condensation on the windows was significantly reduced. This is of key importance in historic wooden frames, as condensation can cause a great deal of damage. Calculations performed showed that moving to the NSG Spacia™ unit could save over $500 per year on heating costs and around 32 tonnes of CO_2 over the lifetime of the window in a typical 3 bed semi-detached property.

Example 4: Social Housing, London

Similar results were reported in social housing refurbishments in London, in both Camden and Islington. The refurbishment aims to cut household bills by 50% and reduce carbon emissions by 70% through the application of sustainable products and techniques. Here, NSG Spacia™ was demonstrated to provide similar energy efficiency performance to standard replacement low-e double glazing but in a much thinner profile. The use of thermal imaging highlighted the reduction in heat loss achieved by installing the VIG product (Figure 8). NSG Spacia™ was specified as the appropriate glazing option to replace single glazing, allowing architects and specifiers to refurbish buildings in line with current building regulations whilst maintaining or replicating the original frames.

FIGURE 8. Thermal imaging comparing original glazing and VIG installation.



Example 5: Retrofits, Japan

There are a huge number of similar examples in the Japanese residential market, where NSG Spacia™ has been used successfully for 16 years. Many existing residences use windows with single panes, offering many opportunities for VIG where the large intrinsic thickness of a standard double glazed unit is an obstacle to their use. One example is shown in Figure 9, where 1200 m^2 of NSG Spacia™ was used in the renovation of an apartment building. The key concerns of the building owner were prevention of condensation in winter and improving energy while keeping the existing alumina sash. Many hundreds of thousands of metres squared of NSG Spacia™ and NSG Spacia™ Cool have

FIGURE 9. VIG retrofit of Apartment building, Kyoto.

been used in similar renovation projects in Japan in apartments, government buildings, University campuses, and commercial buildings.

VIG use in new buildings

Due to their excellent energy efficiency, the range of VIG options available allows building designers to use them in designs for new buildings. The range of products allows VIG to meet most legislatory requirements whilst giving additional flexibility in building design. Currently the Asian market is leading the way in the use of VIG for new buildings, with few examples outside of these markets.

There are many examples of this type that can be viewed on the websites of NSG, Qingdao Hengda, and Beijing Synergy [7, 10, 11]. One well-known restaurant chain in Japan has used NSG Spacia™ in a number of new builds, with the number of new restaurants using the technology planned to reach 1000. The reasons for this are the company's commitment to sustainability, the importance of improving energy efficiency, and to reduce the effect of condensation on the windows of the restaurant. Another large company has recently used NSG Spacia™ 21 with a krypton filled cavity in their coffee shops, as the extremely low U-factor of such a unit has significantly improved the energy efficiency of the building whilst helping to achieve a LEED rating. As one can imagine, in restaurants and other similar environments condensation can be a major issue. The NSG Spacia™ 21 hybrid unit has excellent condensation resistance. For example, the solar control version prevents condensation forming for outside temperatures of as low as –23 °C, even when the interior conditions are 20 °C with relative humidity of 80%.

Both the NSG Spacia™ and NSG Spacia™ 21 ranges have been used in new apartment buildings and in hotels. The major advantages in such cases are their improved energy efficiencies and their excellent acoustic performance. For residential applications in Japan, the NSG Spacia™ 21 product has been adopted in the LCCM (Life Cycle Carbon Minus) Demonstration House [12]. This was a detailed investigation being carried out by the Building Research Institute in Japan as to the energy consumption and thermal environment under simulated living conditions. The government is planning to use the house as the standard in new residential housing by 2020. A study comparing the NSG Spacia™ 21 product with a 12 mm IGU with argon and low-e showed a 20% or more reduction in air conditioning costs for the hybrid VIG product. Given the importance of energy security in Japan, advanced technologies that can reduce air conditioning load will be critical in the future.

CONCLUSIONS

Vacuum insulated glazing is a proven technology that has been used successfully in a number of markets for well over a decade. The range of VIG products available to architects and building designers opens up many opportunities for their use, from retrofit of historic buildings to new construction. As building codes change and become more stringent, VIG gives additional options to meet these challenges and new developments in the industry can only lead to their wider adoption. A number of projects have been described, giving examples of the use of the NSG Spacia™ VIG technology, which has a 16-year track record in architectural glazing.

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