LBNL-6122E

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January 2013

Published in *Energy and Buildings* 58 (2013) 263-280
http://dx.doi.org/10.1016/j.enbuild.2012.10.006

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Window Spacers and Edge Seals in Insulating Glass Units: A State-of-the-Art Review and Future Perspectives

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Abstract

Insulating glass (IG) units typically consist of multiple glass panes that are sealed and held together structurally along their perimeters. This report describes a study of edge seals in IG units. First, we summarize the components, requirements, and desired properties of edge construction in IG units, based on a survey of the available literature. Second, we review commercially available window edge seals and describe their properties, to provide an easily accessible reference for research and commercial purposes. Finally, based on the literature survey and review of current commercial edge seal systems, we identify research opportunities for future edge seal improvements and solutions.

1 Introduction

Reducing energy use and carbon emissions is currently a top priority in the building and construction sectors. A key cost-effective strategy to reduce carbon dioxide (CO_2) emissions in buildings is by increasing the thermal performance of their envelopes. This goal can be achieved in many ways, for example by adding more insulation to both new and existing buildings. Because windows typically account for about 30 to 50 percent of transmission losses through building envelopes, improving fenestration product energy performance could significantly save energy. Much attention has therefore been given to reducing the thermal transmittance, or U-value, of fenestration products [1]. Optimizing the thermal performance of individual window components is essential to achieving a good overall thermal performance for the entire window product. Prior research areas have addressed components of insulating glass (IG) units, including the glass panes, types of gas fill, and window frame [2].

Previous research has also shown that improving spacers and edge seals could significantly reduce the energy lost through multi-pane windows [1]. The aim of our article is to report on a study of edge seals in IG units and make available, for research and commercial purposes, a review of available technologies. We surveyed the available literature on components, requirements, and desired properties of edge construction in IG units and carried out review of state-of-the-art, commercially available spacer products. Our market research focused on edge seals that have low thermal conductivity. We conclude by identifying possible future research opportunities for the spacer industry.

2 Components of edge seals in insulating glass units

IG units typically consist of multiple glass panes that are sealed in the edge-of-glass area. The panes are held together structurally along their perimeters by various types of edge seal systems. To improve the overall insulating value of an IG unit, the interpane space is typically filled with an inert gas, such as argon or krypton. The key function of the edge seal is to keep the glass panes separated at equal distances while providing a barrier to prevent infiltration of water vapor or exfiltration of the gas (or air) fill between the panes.

Edge seals consist of a number of components, including a spacer bar, a desiccant, and a sealant. These components are often combined and may serve more than one purpose. Figure 1 shows the edge seal geometry of an IG unit. Typically, edge seal total width (w) varies from 8 to 12 millimeters (mm). The interpane spacing

thickness (t) depends on factors such as the number of glass panes, the type of gas fill, and acoustical requirements. Commercial edge seal thicknesses of 6 to 24 mm are common.

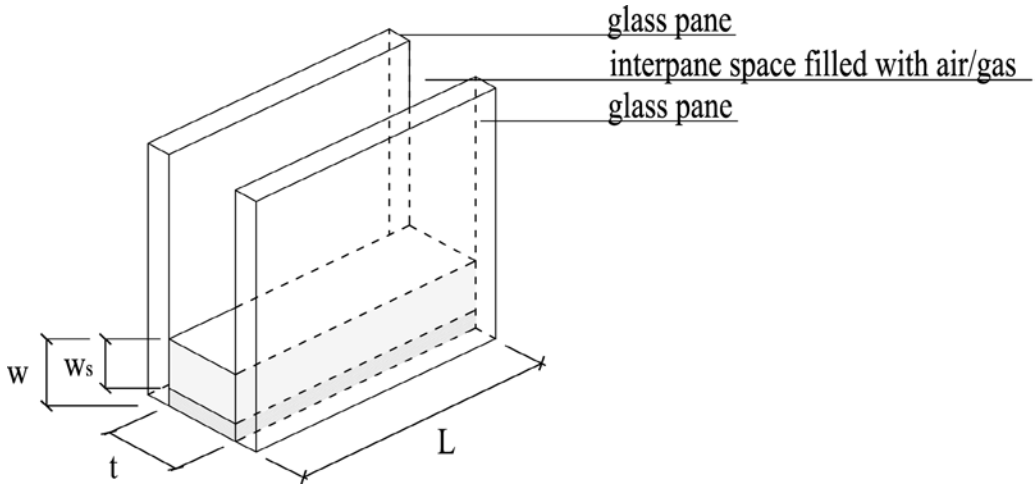


Figure 1 – Edge seal geometry of a double-pane IG unit with edge seal thickness (t), width (w), spacer bar width (w_s), and length (L).

2.1 Spacer bar

The main function of the spacer bar is to hold the glass panes at a fixed distance from each other, thus establishing the size of the interpane space. The typical profile width of spacer bars (w_s) varies between 4 mm and 8 mm. The most common spacer bar thicknesses are 12 mm and 14 mm. Hollow (metal) shaped spacer bars as well as solid (non-metal) spacer bars are commercially available. We discuss spacer bar designs and their properties in more detail below in Section 4.

2.2 Sealant

The sealant used in an edge seal structurally bonds the glass panes and spacer bar together while providing a high level of moisture vapor and gas diffusion resistance and allowing flexion to accommodate glass movement. In dual-sealed IG units (Figure 2 [right]), these functions are performed by separate primary and secondary sealants whereas single-sealed IG units (Figure 2 [left]) have only one (secondary) sealant. Today, the majority of IG units manufactured globally are dual sealed, with the market share of dual-sealed units being much larger in Europe (85-90 percent) than in North America (45-50 percent of IG units manufactured in 2003) [4].

The primary sealant in an IG unit is applied between the spacer bar and the glass panes. Its key function is to reduce water vapor and gas permeability in the edge-of-glass area. Synthetic rubbers, typically polyisobutylene (PIB), are used for this purpose. However, the strength of thermoplastic PIB decreases rapidly as temperature increases, so a PIB seal alone cannot guarantee the structural integrity of an IG unit; therefore, a secondary sealant is required, which is applied around the perimeter of the glass. The secondary sealant functions as the adhesive that unites the glass panes and spacer bar and prevents excessive movement under different environmental stresses. Polyurethane (PU), silicone (Si) and polysulphide (PS) are widely used as secondary sealants, but hot-melt butyl- or epoxy-based sealants may also be used [5],[6].

The thickness of a primary PIB sealant is typically 0.2 to 0.6 mm, and the secondary seal width is about 4 mm. A minimum 3 mm of secondary sealant is required to cover the primary sealant and protect it from contact with moisture [7]. A PIB seal's adhesion to the glass and spacer is not resistant to continuous water exposure. When butyl sealant becomes damp, it loses its ability to adhere, which can lead to premature failure of the IG unit.

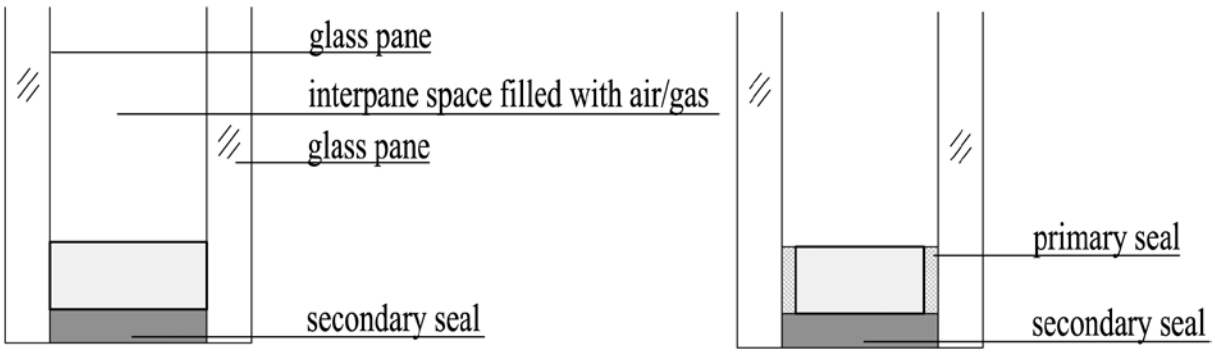


Figure 2 –Single-sealed IG unit [left] and dual-sealed IG unit [right]

2.3 Desiccant

Desiccants are used in IG units to prevent the inside glass surfaces from fogging as because of condensation of moisture vapor or organic vapors that may be in the interpane space. Moisture vapor might be trapped in the interpane space during manufacturing of the IG unit or can permeate through the edge seal while the IG unit is in use. Organics that off-gas in the interpane space can react with glass surfaces that become damp from water vapor condensation. These reactions leave a permanent opaque deposit on the inside glass surface, a phenomenon referred to as “chemical fogging” [5],[7],[8]. ISO 20492 describes chemical fogging tests and requirements for IG units [11]. Desiccants in IG units prolong the windows’ service life by adsorbing moisture and organic vapor until the desiccant is saturated. Desiccant can either be integrated in the edge seal design or used as a fill in hollow spacer bars that are perforated to allow contact between the desiccant fill and the vapor [7]. The capacity of desiccants is limited, and any water vapor infiltrating the interpane space after the desiccant is saturated can result in fog on the internal surface of the IG unit.

Commonly used desiccants in the IG industry are molecular sieves or a blend of silica gel with molecular sieves [8]. Highly porous crystals of molecular sieves with uniform pore sizes of 3, 4, 5, and 10 Angstroms (Å) exist, each having a strong affinity for a specific size of molecule. The 3-Å molecular sieve’s structure allows water vapor adsorption yet excludes most other molecules. The 4-Å molecular sieve has a slightly higher water vapor capacity but also adsorbs larger molecules including oxygen and nitrogen; it is, therefore, less commonly used in IG edge seals. Molecular sieves have a high adsorption capacity at low relative humidity (Figure 3) and are therefore particularly useful in dry environments such as the interpane glazing space. Silica gel is a highly porous granular-shaped desiccant with pore sizes ranging from 20 to 200 Å [9]. Because of this wide range of pore sizes, silica gel is capable of adsorbing compounds other than water, such as ammonia, alcohols, aromatics, diolefins, olefins, and paraffins [10]. A blend of 3-Å molecular sieve and silica gel can prevent both condensation and chemical fogging by adsorbing water vapor as well as off-gassed organics while also limiting the adsorption of argon or nitrogen gas.

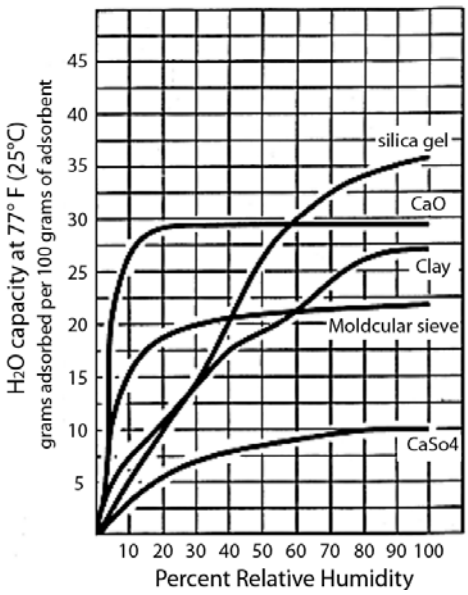


Figure 3 – Equilibrium water (H_2O) capacity of various adsorbents as function of relative humidity [10]

3 Edge seal properties and requirements

Before discussing available edge seal products and their properties, we present properties of an effective IG edge seal, which we identified through a review of the literature on edge seals. The main focus has been on thermal performance.

3.1 Structural functionality

The combined system of spacer bar and secondary sealant provides sufficient strength to hold two panes of glass at a fixed distance apart. Because the primary seal does not contribute to the structural integrity of the IG unit, it is essential that the secondary sealant adhere over the long term to the glass, glass coatings, and spacer bar materials. To ensure a long service life for the IG unit, the secondary seal must also be flexible to accommodate glass movement under variety of continuous mechanical stresses. These include pressure differences between the interpane space and the outside atmosphere that are introduced during manufacturing, transportation, and installation of the glazing unit; and stresses during the service life of the IG unit from environmental conditions such as solar radiation, temperature differences, wind loads, and barometric pressure. Pressure differences exert force on the panes and cause them to deflect**Error! Reference source not found.**. This, in turn, exerts forces (tension and compression) on the edge seal of the IG unit. ASTM C1249 [12] and ISO 20492 [13] describe structural properties, adhesion testing, and requirements for secondary sealants.

Structural demands do not restrict the shape of the spacer bar as long as it has good mechanical stability and allows tightly sealed corner connections [14]. Mechanically stable corners can be achieved by plug-type connections (i.e., with metal or plastic corner keys) or, more commonly, by bent spacer corners. The corners must be sealed properly to guarantee stability of the frame as well as water vapor and gas tightness of the corner connections. Quality assurance testing according to the German Institute for Standardization [15] showed that IG units with bent corners performed considerably better than units with plug-type or soldered corners.

3.2 Thermal performance

Spacer bars for IG units have traditionally been made of aluminum or galvanized steel. These metal spacer bars have high thermal conductivity and thus create a thermal bridge on the interior glass pane surface in the edge-of-glass area. The edge-of-glass region is described [16]as the perimeter of the glass between the edge of the frame or sash and the point where the glass surface temperature is the same as the temperature at the center of glass [16]. Initial laboratory experiments [17] showed that this region is restricted to a band approximately 63 mm (2.5 in.) wide around the perimeter of the glazing, as illustrated in Figure 4. However, later studies [18] showed that the edge-of-glass region is larger, i.e., 102 mm (4 in.). Low temperatures in the edge-of-glass region increase the potential for condensation, which, in turn, can lead to mold growth and deterioration of window frames, window seals, and wall sections, especially in cold climates [19]. New edge seal designs with improved thermal performance (and therefore higher internal glass surface temperatures in the edge-of-glass region) are less prone to condensation. The term "Warm Edge Technology" (WET) has been introduced in the literature for these products.

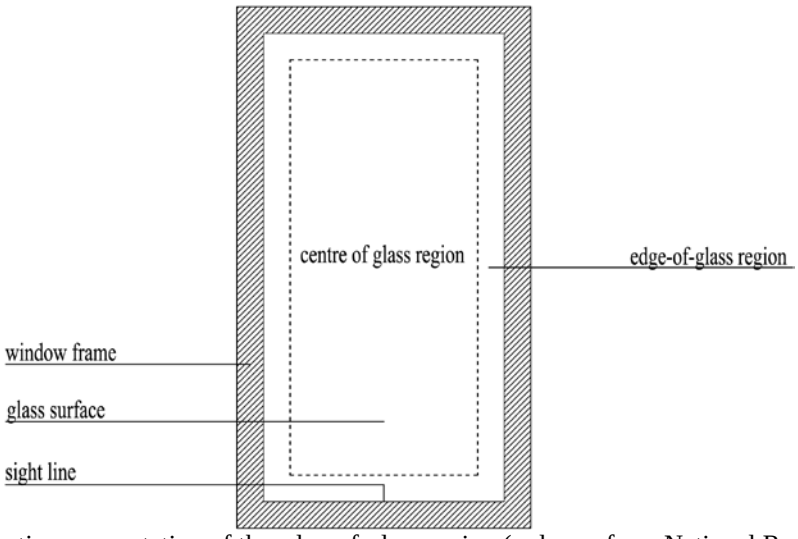


Figure 4 – Schematic representation of the edge-of-glass region (redrawn from National Research Council of Canada (NRC) [16])

In addition to their impact on condensation, the thermal properties of the edge seal also have a significant influence on the overall U-value of a fenestration product [16],[20]: insulated spacer bars and thermally improved edge seals can considerably reduce heat loss through an IG unit. For these reasons, several studies have focused on the thermal performance of the edge seal. We summarize below information from the literature on glass surface temperature and the effect of edge seals on the thermal performance of windows.

Numerical investigations [21] show that total window U-value is reduced by 6 percent when a traditional aluminum spacer is replaced with an insulating spacer in a standard double-glazed wood-frame window that does not have low-emissivity (low-e) coating on any of the glass panes. In high-performance windows (i.e., double glazed with low-e coating, or triple-glazed windows) insulating spacers can reduce total window U-value by 12 percent compared to the U-value with aluminum spacers.

The effect of spacer designs on the glass surface temperature in the edge-of-glass region was examined by Elmahdy [20] using hot-box measurements and by numerical simulations**.** Four different edge seal configurations were studied, in double-pane glazing without a frame around the edge. The spacer with the highest thermal resistance showed the warmest glass surface temperature on the warm side (and the coldest temperature on the cold side) of the glass in the edge-of-glass region. The study also found that, when the glazing/spacer configurations were inserted in a simple wooden sash, the variation in glass surface temperature was reduced as a result of the sash.

Elmahdy [22] also studied the warm-side glass surface temperature of different edge seal designs under laboratory conditions (Figure 5). In these tests, 10 spacers were mounted between two clear glass panes, with air in the glazing cavity. Testing was first performed with no frame. The results (Figure 6) demonstrated that the use of WET spacer bars leads to higher glass surface temperatures in the edge-of-glass region relative to temperatures when conventional aluminum spacers were used (IG 7 in Figure 5). Tests of glazing units (1.0 m x 1.0 m) with four different frame materials (vinyl, thermally broken aluminum, redwood, and foam-filled fiberglass) showed that some combinations of spacer bar/frame material resulted in more desirable glass surface temperatures in the edge-of-glass region. However, because of the variety of possible frame designs and edge seals, these findings should not be generalized. The overall thermal resistance (R-value, expressed in square meter kelvins per watt [m^2K/W]) of the different fenestration products was also tested. A comparison of the R-values of the spacer/frame combinations studied (Figure 7) showed that WET spacer bars improve the overall R-value of fenestration products compared to the results for windows with conventional metal spacers. Figure 7 also indicates that interaction between spacer bar design and frame material affects the overall thermal performance of a window. It is notable that the relative performance of tested frames is more important than the absolute R-values. Some combinations of spacer bars, glazing, and frame performed better than others because of a slightly larger gap thickness, details of the frame design, manufacturing tolerances, or other elements of the test unit; as a result, these findings should not be generalized.

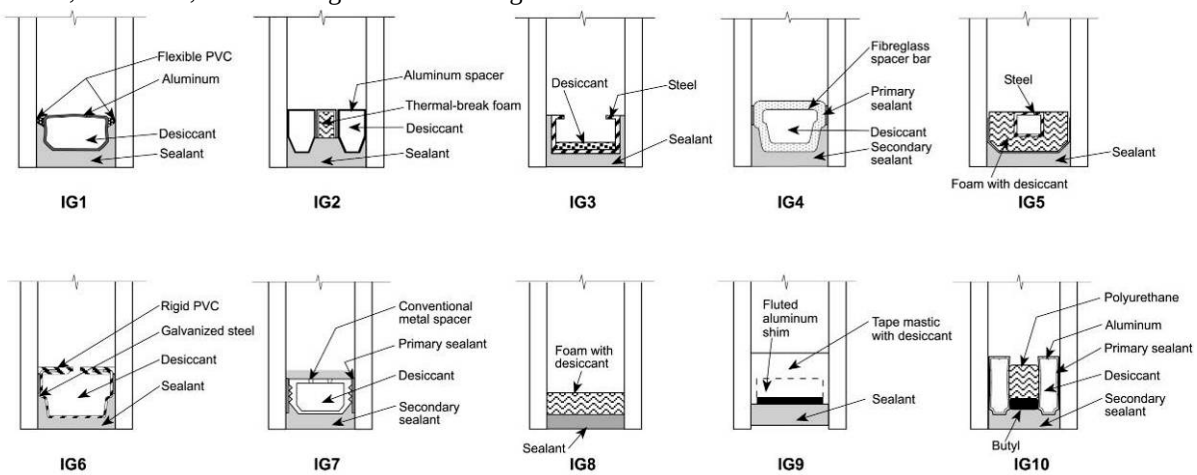


Figure 5 – Diagrams of 10 spacer systems tested by Elmahdy [16]

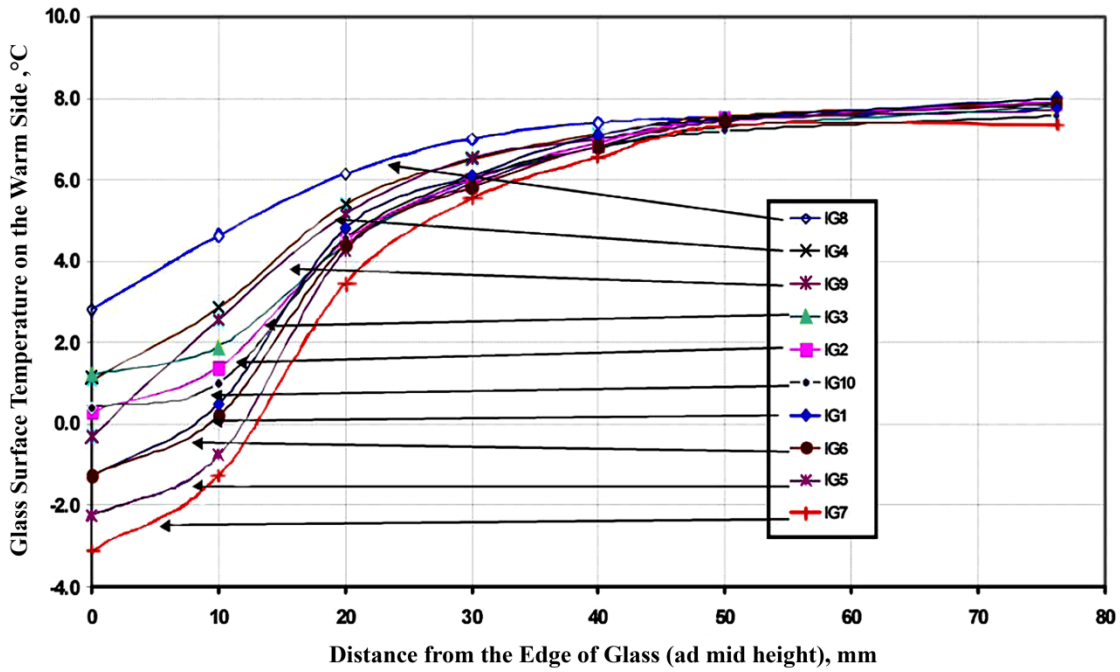


Figure 6 – Comparison of glass surface temperatures with 10 spacer systems mounted between two clear glass panes, air in the glazing cavity, and no frame around the glass edge [22]

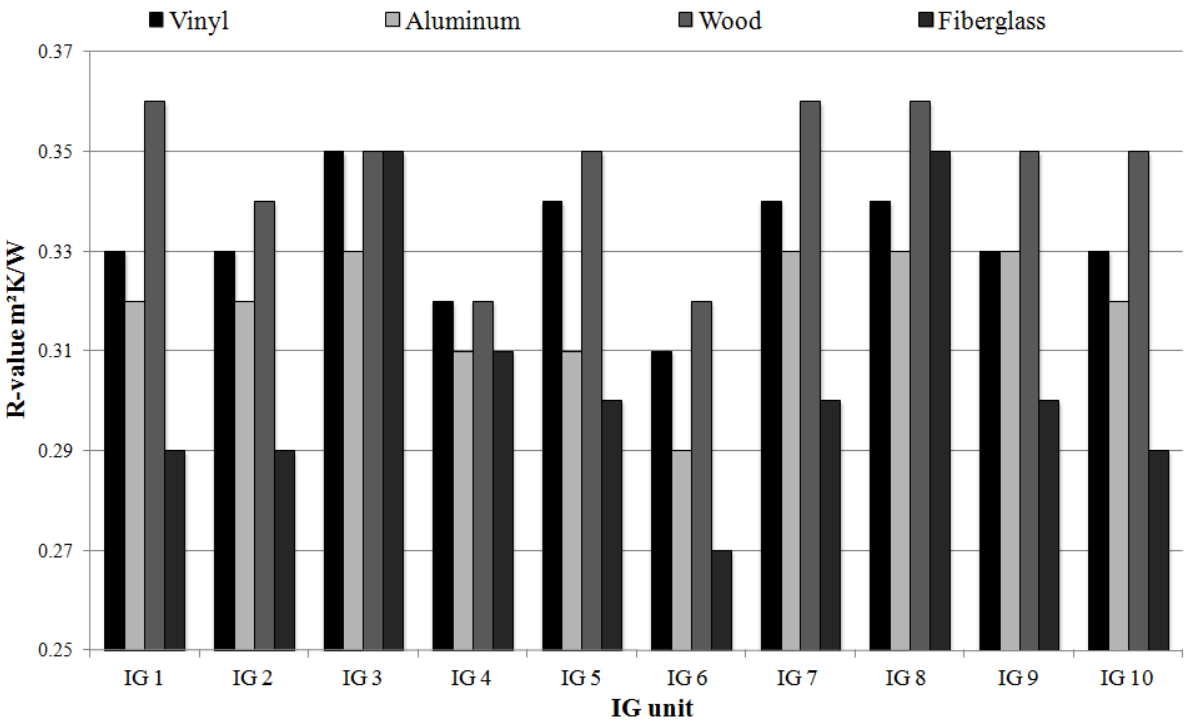


Figure 7 – Comparison of the thermal resistance of the 10 spacer systems inserted in four different frames (redrawn from [22])

Different spacer systems have also been studied using hot-box measurements and numerical simulations [23]. Gustavsen et al. studied total window U-values and glazing temperatures for double glazing with a conventional aluminum and an insulating spacer bar. Two different cavity sizes, 12 mm and 15 mm, were studied, with argon fill and a low-e coating ($\varepsilon = 0.05$) on the innermost glazing layer facing the glazing cavity. The glazing was mounted in a wooden frame. The temperature diagrams showed a significant increase in interior surface glazing temperature when an insulating spacer was used instead of an aluminum spacer. Measured and simulated results for glazing surface temperature from this study showed relatively good agreement although the numerical

simulations predicted a higher interior glazing temperature in the edge-of-glass region than was found in the experiments. Natural convection and surface coefficients used in the numerical simulations resulted in these slight deviations. The difference in U-value between test units with aluminum and insulating spacers was greater in the simulated results than in the measured results. For the simulated windows with 12-mm cavity spacing, the U-value was reduced by 7 percent when the aluminum spacer was replaced by an insulating one, but the measured reduction was only about 1 percent. Results were similar for the 15-mm cavity unit: 9 percent and 2 percent in the simulated and measured cases, respectively. The large difference was attributed to the fact that the center-of-glass U-value was found independently of the frame and spacer material and configuration in the calculations for the simulated cases.

A spacer thermal performance study by WESTLab Canada for the Insulating Glass Manufacturers Alliance (IGMA) [24] estimated the impact of the edge construction on the total fenestration thermal performance. The study modeled an aluminum frame window system for non-residential applications and a polyvinyl chloride (PVC) window system for residential applications with varying spacer system effective thermal conductivities (k_{eff}). The spacer system thermal conductivity is defined as the thermal conductivity of a single block of homogeneous material with the same dimensions as the actual spacer system, resulting in a heat transfer equivalent to the heat transfer through the detailed edge seal [24] (see also Section 3.3.2). The study found a logarithmic relationship between the overall U-value and k_{eff} (Figure 8). Figure 8 indicates that, for spacer systems with effective thermal conductivities greater than 2.0 watts per meter per kelvin [W/(mK)], the total product U-value curve flattens out. This means that variations in k_{eff} greater than 2.0 W/(mK) will not significantly affect the total product U-value. For k_{eff} less than 2.0 W/(mK), the effect on the U-value of reducing k_{eff} is significant. Figure 11 also shows that the effective conductivity has a larger impact when the window size is small.

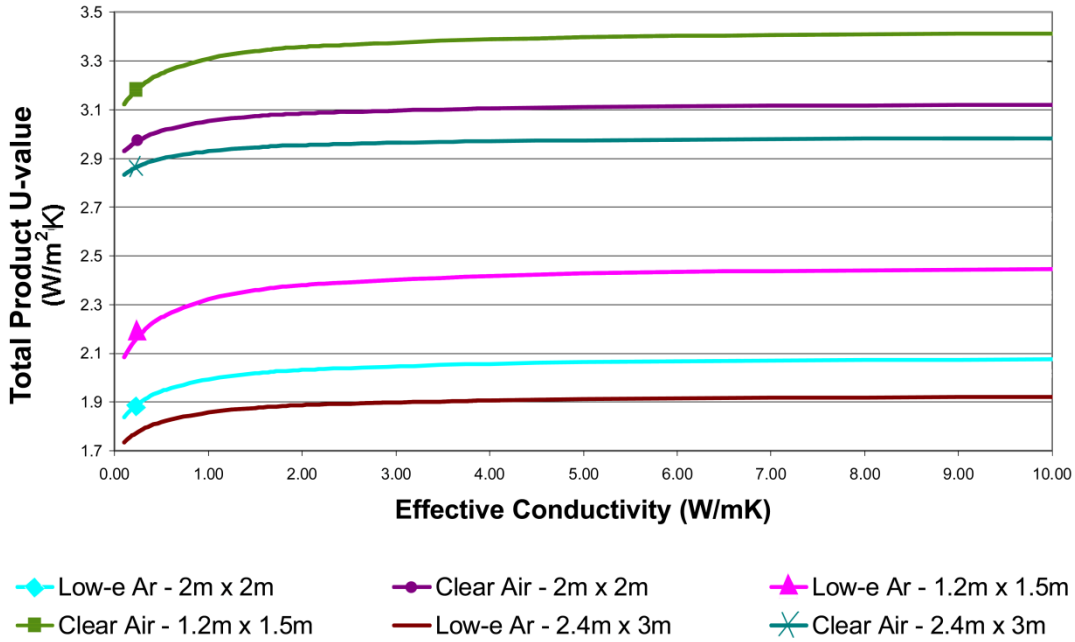


Figure 8 – Total product U-value vs. spacer effective conductivity (k_{eff}) for different sizes of non-residential thermal break aluminum frames [24]

Gustavsen et al. performed similar simulations [3] on five different window frames: thermally insulated wood, solid wood, PVC, and two thermally broken aluminum frames. The study analyzed the effects of spacer effective conductivity, k_{eff}, on the frame and edge-of-glass U-values of different frame configurations with triple glazing, argon filled cavities, and two low-e coatings ($\varepsilon = 0.037$) [i.e., a glazing U-value of 0.710 W/(m^{2}K)]. For the frames studied, the spacer was simulated as a block of homogeneous material with an effective conductivity k_{eff} that was varied between 0.02 and 10 W/(mK). Conductivities between 0.01 and 0.02 W/(mK) were also included for comparison with the conductivities of today's best insulating materials.[1]

The results of this study showed that frame and edge-of-glass U-value decreased with decreasing spacer conductivity. Changing the effective spacer conductivity from 10 to 0.25W/(mK), which is close to the effective

[1] This excludes vacuum insulation panels (VIPs), which, when pristine and not aged, typically have thermal conductivities around 4 mW/(mK).

conductivity of the best spacers available today, decreases frame U-value by more than 18 percent for the frames studied. For some frames, the decrease is as much as 36 percent. The actual percentage depends on frame thermal performance and tends to increase with decreasing frame U-value. This study shows that exceeding the performance of the best spacer technologies available today would decrease the frame U-value. For example, reducing the effective spacer conductivity from 0.25 to 0.1 W/(mK) would decrease the frame U-value by more than 6 percent. A decrease in spacer conductivity from 0.25 to 0.05 W/(mK) would decrease U-value by more than 10 percent.

3.3 Thermal conductivity of edge seals

Experiments and numerical simulations have demonstrated that edge seals have a significant effect on the U-value of a glazing unit. The complex nature of the heat flow and the interaction of the edge seal with the wide variety of window frames make it difficult to characterize this effect, so one should be careful about generalizing conclusions. However, the results of these thermal conductivity studies make clear that windows should use the best spacers available and that research should be undertaken to develop alternative and improved insulating spacer systems [3].

In practice, there is a need to define the thermal characteristics of the edge-of-glass region of IG units. Different methods have been proposed: 1) linear thermal conductivity (k_{lin},), 2) effective thermal conductivity (k_{eff},) and 3) equivalent thermal conductivity of a two-box model (λ_{eq}). Each method is summarized below.

3.3.1 Linear thermal conductance

The thermal performance of edge seals has been characterized by linear conductance (k_{lin}) (W/(mK)) [19],[26],[27], which is defined as the rate of heat transfer through a unit length of edge seal exposed to a unit temperature difference (Eq.1). Figure 9 illustrates the edge seal geometry related to this definition. The heat loss through the seal is given by:

$$Q = q \cdot A = L \cdot k_{lin} \cdot (T_1 - T_2) \tag{1}$$

where
- Q = heat loss through the seal (W),
- q = heat flux = heat loss through the seal per unit area (W/m^2),
- L = length of the seal (m),
- k_{lin} = linear thermal conductance (W/[mK]),
- A = L·w, area of the seal in contact with glass (m^2),
- w = width of the seal in contact with glass (m),
- $T_1 - T_2$ = temperature difference applied across the seal (K).

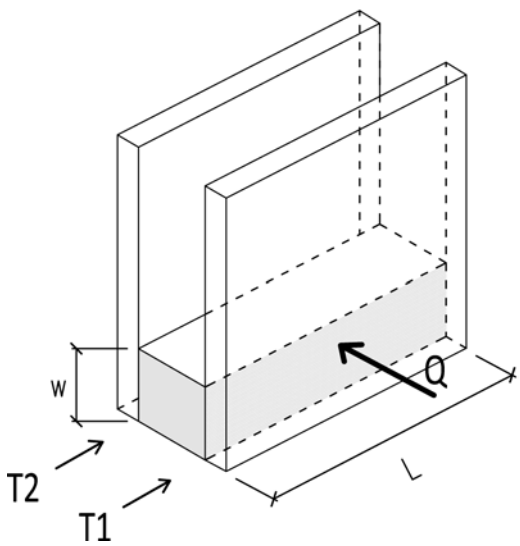


Figure 9 – Edge seal geometry related to the definition of k_{lin}

In two-dimensional window simulations, the edge seal can be replaced with a single block of a fictitious, homogeneous material. The conductivity of this material is then specified such that it allows the same amount of heat transfer as an edge seal of known geometry (i.e., thickness, t, and width, w) and known k_{lin}. Using a measured k_{lin}, we can calculate this fictitious conductivity k_{fict} (W/(mK)) as

$$k_{lin} = k_{eff} \frac{t}{w} \quad (2)$$

It is important to note that the homogeneous block must retain the same dimensions as the seal it replaces. This model has been validated by an investigation of nine different single- and double-sealed edge seal designs for industrial applications. Detailed two-dimensional numerical simulation models were developed [28] and compared to the linear conductance of the edge seal, measured in a guarded hot-plate experiment [26]. The measured k_{lin} showed good agreement with the simulation model.

No desiccant was assumed in this method, which is advantageous for modeling efforts because it eliminates the need to determine the thermal conductivities of heterogeneous materials, i.e. desiccant-doped sealants or desiccant-filled cavities. This approach allows a comparison of edge seal designs, eliminating edge-glass, sash, and frame effects. Although the boundary conditions necessary to model the edge seal effects differ somewhat from actual window conditions, the authors believe that this does not detract from the utility of this method for designing and developing efficient edge seals.

The method suffers from the disadvantage that the linear conductance represents the thermal performance of the entire edge seal and therefore does not provide insight about the contributions of individual edge seal components. When measured data are used to validate simulations models, it is possible for the models to estimate the effect of small details of the spacer bar/sealant combinations. Possible design improvements could be explored by means of simulations, but fabrication and testing are recommended to confirm a design's actual performance.

3.3.2 Effective thermal conductivity

The thermal performance of edge seals has been characterized using effective conductivity k_{eff} (W/(mk)) [25], which allows us to account for the performance of individual components of the edge seal. This model is based on the assumption that the performance of the frame components and IG unit, including spacer variations, can be modeled separately and then put together using interpolating curves. The effective thermal conductivity is defined as the thermal conductivity of a single block of homogeneous material with the same dimensions as the actual spacer system (i.e., total width, w, and thickness, t), resulting in heat transfer equivalent to that of the detailed edge seal [24]. The k_{eff} of the edge seal is calculated as follows:

1) Develop a detailed model of the edge seal in THERM software [29] and determine the heat flow or overall thermal resistance (R_{tot}) through the spacer, applying the boundary conditions shown in Figure 10.

2) Calculate the effective conductivity k_{eff} from the total resistance (Eq. 3):

$$R_{tot} = \frac{1}{U} = \frac{1}{h_0} + \frac{t}{k_{eff}} + \frac{1}{h_i}, \quad (3)$$

where
- R_{tot} = overall thermal resistance of a given edge seal (W/(m^{2}K)),
- U = overall thermal transmittance (m^{2}K/W)
- t = spacer thickness (m),
- h_0 = outside heat transfer coefficient, h_0 = 30.0 W/(m^{2}K),
- h_i = inside heat transfer coefficient, h_i = 8.0 W/(m^{2}K).

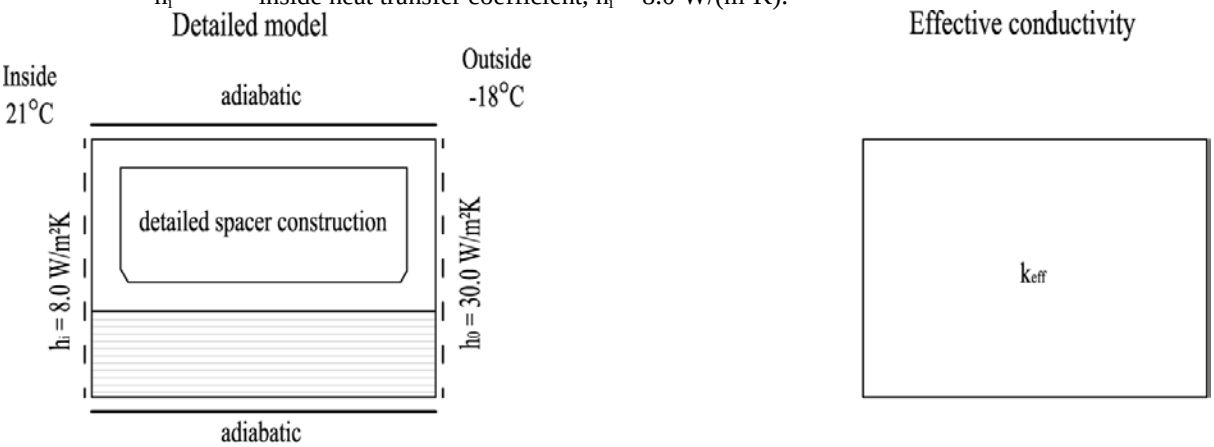


Figure 10 – Model geometry and boundary conditions of edge construction; Actual edge construction with boundary conditions used in THERM [29] to calculate the thermal resistance [left] and homogeneous block with keff representing the actual edge seal [right].

The effective conductivity has been used in calculations for different edge seal configurations to estimate the impact of the edge construction on the overall product U-value [25]. This is illustrated by the logarithmic relationship shown in Figure 8. The effective conductivity has also been used in a thermal performance study [24] comparing different spacer systems, as well as for examining the impact of several spacer system variables on total fenestration system thermal performance. The results of the comparison are discussed in Section 4.1.2.

3.3.3 Equivalent thermal conductivity of a two-box model

A simplified model consisting of two boxes and an equivalent thermal conductivity, λ_{eq} [W/(mK)], has also been developed [30],[31]. In this approach, the detailed edge seal is modeled as two boxes such that it results in the same heat flow as the actual edge construction. One 3-mm box with a thermal conductivity of 0.4 W/(mK) replaces the PS sealant, and one 6-mm box with the equivalent thermal conductivity λ_{eq} replaces the spacer profile.

The calculation procedure for λ_{eq} is summarized in two steps:
1) Calculate the heat flow through the actual edge construction using a two-dimensional simulation program (e.g., THERM [29]) with the boundary conditions shown in Figure 11).
2) Fit the thermal conductivity λ_{eq} of the spacer box until the same heat flow is achieved as in the detailed model. Unlike in the calculation of k_{eff}, the effect of the glass panes is accounted for in step 1 of this method: a heat-transfer coefficient of 200 W/(m^{2}K) on both sides of the spacer represents the heat transfer through the glass panes.

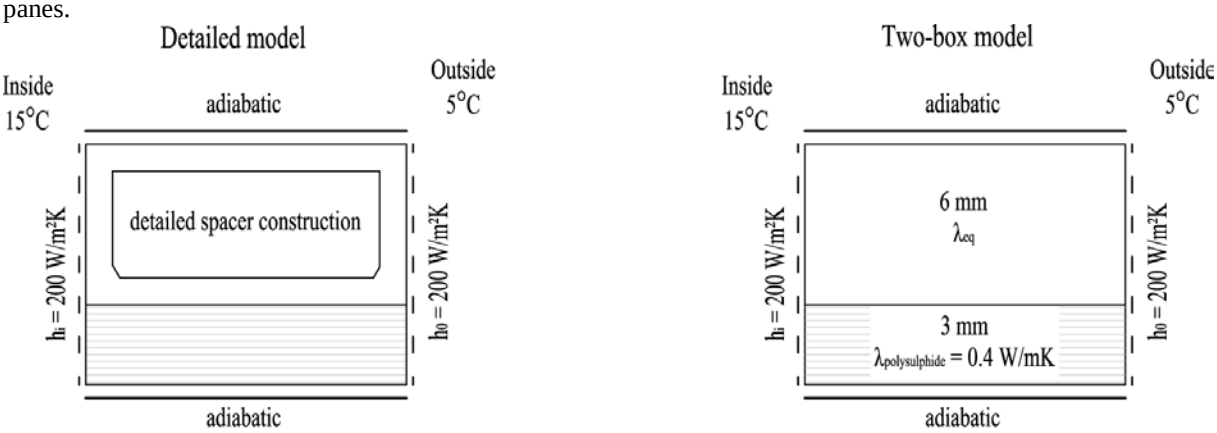


Figure 11 – Model geometry and boundary conditions of the edge construction; actual edge construction [left] and two-box model consisting of a 3-mm PS sealant and a 6-mm box representing the spacer profile [right]. (Figure redrawn from Win Dat [32]).

The equivalent thermal conductivity has been used in calculations of the linear thermal transmittance, Ψ (W/(mK)), where the two-box model replaces the actual edge construction with a spacer profile. This method was validated for three different edge constructions and three different frames: an aluminum spacer, a stainless steel spacer, and a plastic spacer with aluminum foil; and a wooden frame with aluminum cladding, a PVC frame, and a frame made of wood, aluminum, and PVC were used, respectively. In general, there was good consistency between the Ψ-values calculated with the two-box model and the detailed edge construction. The two-box model results in slightly higher Ψ-values and is thus a conservative method. However, the differences between the measured and calculated values are less than 3.1 percent; therefore, the method is considered reliable.

Equivalent thermal conductivity offers us a means to compare the thermal performance of the spacer profiles. However, a disadvantage of this method is that the spacer profile conductivity is estimated with an applied secondary PS sealant with a thickness of 3 mm and a conductivity of 0.4 W/(mK). Edge seal configurations with a secondary sealant, for example of polyurethane (conductivity of 0.25 W/(mK) [33]), that are represented by a two-box model will have significantly higher λ_{eq} than the conductivity of the actual spacer bar. The impact of the secondary sealant on the thermal performance of the fenestration product is not easily understood using λ_{eq}. Moreover, the method uses a fixed height of 6 mm for the spacer box, which is a typical height of spacer bars. Therefore, λ_{eq} is only valid for edge construction with those dimensions. For higher spacer profiles, a standard spacer box of 10 mm was suggested and investigated separately.

3.4 Moisture vapor and gas transmission

IG unit failure most commonly results from water vapor condensation between the glass panes [5]. Because of the vapor gradient between the dry interpane space and the environment, water vapor diffusion is a natural phenomenon that occurs in every IG unit. When moisture permeates through the edge seal after the unit's desiccant is saturated, condensation may occur. The edge seal must have high moisture vapor transmission resistance to minimize water vapor permeation and thus prolong the unit's service life [5],[7]. Moisture vapor flow penetrating the edge seal can be characterized by the moisture vapor transmission rate (MVTR), θ, or by the average moisture penetration index, I_{av}. Test methods for both values are described in standards ISO 20492 [13] and EN 1279 [34], respectively.

To maintain their thermal advantage, gas-filled glazing units must retain the gas within the interpane space. The differential between the partial pressure of the gas within the IG unit and that of the surrounding air causes gas to diffuse through the seal. Therefore, the seal must have low gas permeability to prevent the fill from being replaced by air [7]. Current standards [35],[36] allow a gas leakage rate L_i (i.e., the volume of gas '*i*' leaking from a gas-filled unit) of less than 1 percent per year. [2]

The primary sealant (or secondary sealant in single-seal systems) and the spacer bar together provide for a protective seal that meets the requirements for low gas and water vapor permeability. Metal is typically used as the vapor and gas barrier on the spacer bar, either in the form of a metal spacer bar profile or a foil integrated in the spacer design. In dual-sealed IG units, the secondary sealant does not contribute significantly to the diffusion resistance of the edge seal. This is because the water vapor permeability of PIB is far lower than that of the secondary seal, regardless of whether the secondary sealant is silicone, polysulfide, or polyurethane. The moisture diffusing through the primary seal is linearly dependent on the thickness and inversely dependent on the width of the primary seal. That is, the wider and thinner the primary seal, the lower its moisture diffusion. Therefore, maintaining the effective cross-section of the primary seal (as established after manufacture of the IG unit) is important for the unit's durability. A good secondary seal must reduce the mechanical stress on the primary seal, thus reducing the primary seal's chance of failure.

3.5 Life-expectancy of insulating glass units

Failure of IG units is typically visible through chemical fogging, deterioration in aesthetics, increase in U-value, or loss of the secondary seal adhesion to the glass. Failure of secondary seal adhesion refers to both primary failure within a few years of installation and failure as a result of the unit's deterioration because of a continuously wet or overheated secondary sealant.

For an IG unit to have a long service life, the primary sealant must maintain its low gas and vapor permeability, and the secondary sealant must maintain good adhesion when exposed to a variety of environmental factors. Among these factors are large temperature differences; thermal cycling; high humidity; solar radiation; atmospheric pressure fluctuation; wind loads; working loads; and all relevant loads during manufacturing, transportation, installation, and maintenance. Studies show that the simultaneous action of water, elevated temperatures, and sunlight constitutes the greatest stress on the edge seal of an IG unit.

Extensive studies have been performed of edge seal life expectancy and performance under various influences, and test methods and requirements are described in various standards. This specific topic is therefore not covered in detail in this article. Interested readers are referred to specialized literature, e.g. Wolf [1],[6], [14], Garvin [5], Spetz [7] and numerous standards (e.g., ISO [11],[13],[15],[34],[42],[43],[44],[44] and ASTM [46],[47]).

3.6 Challenges related to new technologies

Edge seals and spacers have been and are being developed to meet the requirements described in the subsections above. New technologies bring into focus different elements that should be considered for edge seals of the future. New designs and technologies can create new challenges. For example, the use of glass coatings and glass films along with new materials could introduce new problems with off-gassing chemicals in the interpane space of the IG unit. Another challenge could be high temperatures that have the potential to cause the combination of spacer, exposed desiccant, and adhesives to loosen and droop into the window's visible area.

[2] The measured L_i for most IG units is higher than the actual L_i after 10 years of natural aging. The 1 percent limit should therefore not be used for calculating the gas concentration during the lifetime of the unit [35].

4 Current State-of-the-art Edge Seal Components

Improving edge seal thermal performance will significantly reduce the negative influence of the edge seal on the overall window U-value. The subsections below review current best-available technologies for spacer bars and sealants.

4.1 Spacer bar technologies

The high thermal conductivity of traditional metal spacer bars in multi-pane IG units creates a significant risk of condensation and a high heat flow through the edge-of-glass region. In place of traditional aluminum and galvanized steel spacer bars, stainless steel spacer bars have been implemented, and several studies have documented the resulting reduction in heat transmission (see Section 3.2). Other new spacer bar designs have also reached the market. The current focus on WET implies an effort to further improve the thermal performance of spacer bars. We present below a comprehensive overview of the performance of commercially available edge seals. We group spacer systems according to their design and geometry in relation to their thermal performance. In addition to the market research we performed for this survey, we use data from a study of spacer thermal performance commissioned by IGMA [24].

4.1.1 Identification and categorization of spacer systems

Table 1 shows our proposed categorization of spacer systems. We identify two main categories: 1) **metal spacers** and 2) **non-metal spacers**. Single-sealed and double-sealed spacer systems are distinguished in the first category. We subdivide the metal spacers category according to the type of metal: aluminum, galvanized steel, or stainless steel. In addition to the three metal subcategories, we identify one category of thermally improved metal spacers, which includes U-shaped steel profiles, hybrid spacers, and thermally broken aluminum. Hybrid spacers are constructed of a stainless steel spacer bar profile combined with a highly insulating plastic top that breaks the thermal bridge at the top edge of the spacer bar. Thermally broken aluminum provides a thermal barrier in the middle of the aluminum spacer to create a warm-edge effect.

Replacing metal spacer bars with spacer bars made from non-metallic, low-conductivity materials greatly reduces heat loss through the edge-of-glass region. The second category of spacers, the “non-metal” spacers, is therefore considered to represent a promising future direction for improving the thermal performance of edge seals. Although the main structural component of these spacers is non-metallic, a metallized foil is often incorporated to ensure that the seal has low water vapor and gas permeability. The non-metal spacer category is further divided into three subgroups – composite, structural foam, and thermoplastic. Composite spacers are constructed from several components such as highly insulating composite plastics or a flexible stabilizer, a moisture barrier membrane, a desiccated top coating, and a stiffening layer. Structural foams, such as silicone foam or ethylene-propylene-diene-monomer (EPDM), are also used for spacer bars. The foam is desiccated to reduce condensation and a (multi-layer) moisture barrier is incorporated. Thermoplastic spacers (TPSs) are made from PIB with integrated desiccant. In contrast to other types of spacers, a TPS is extruded directly between the glass panes, creating a homogeneous and continuous edge seal. Because the moisture resistance of the desiccated PIB is sufficient to guarantee the edge seal tightness, no metallized foil is required in TPSs. The grouping of spacer systems in the IGMA study [24] is similar to that shown in Table 1.

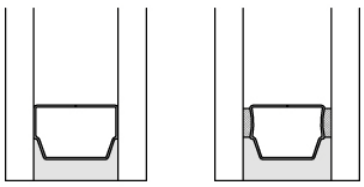
Table 1 – Categorization and schematic representation of spacer systems

Metal spacers

ALUMINUM

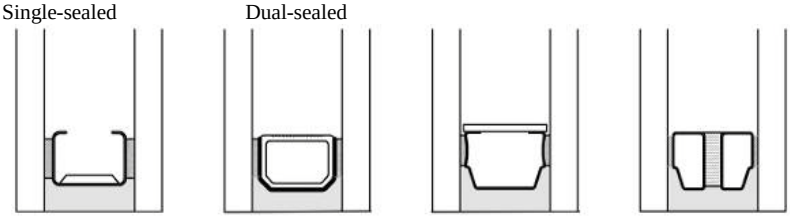
GALVANIZED STEEL

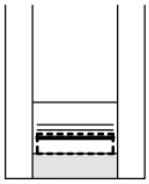
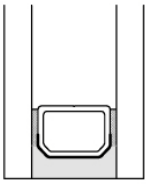
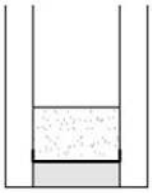
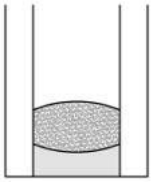
STAINLESS STEEL



Single-sealed Dual-sealed

IMPROVED METAL



	U-shaped	Hybrid spacer	Thermally broken aluminum
NON-METAL spacers with metallized film			
COMPOSITE			
FOAM			
THERMOPLASTIC (TPS)			

4.1.2 Spacer thermal performance study

The effective thermal conductivity (k_{eff}) for different spacers was determined with THERM software in the IGMA study [24]. Several variables that affect the thermal performance of a complete fenestration product were held constant the first phase of the simulations, as follows: a spacer thickness of 12.7 mm (0.5 in.), a primary PIB seal of 0.25 mm (0.010 in.) on both sides of any dual-seal spacers, a PS secondary seal, and a total edge seal width of 11.11 mm (7/16 in.). Figure 12 shows the effective conductivities of the different spacer systems. The effective conductivities were then used in THERM to model the total fenestration product thermal performance for different frames. U-value plots can be found in [24]. From this study, the following conclusions were drawn:

1) For aluminum and galvanized steel spacers, the spacer system thermal conductivity is considerably higher than for stainless steel and non-metal spacers.
2) Single-sealed spacers have higher thermal conductivities than dual-sealed spacers.
3) Effective conductivities greater than 2.0 W/(mK) do not significantly affect the total product U-value, regardless of whether the spacer is single sealed or dual sealed. For these effective conductivities, the U-value is high.
4) Aluminum and galvanized steel spacers have effective conductivities greater than 2.0 W/(mK); thus, for large variations in k_{eff}, the variation in total product U-value is very small. Aluminium and galvanized steel spacers can therefore be grouped, which reduces the number of spacer systems that must be considered and results in minimal error when determining total product U-value.
5) Design variations in stainless steel and non-metal spacer systems affect total product performance because their effective conductivities are less than 2.0 W/(mK). Therefore, grouping of these spacer systems is not appropriate because we must account for details of these system designs to accurately determine product U-value.

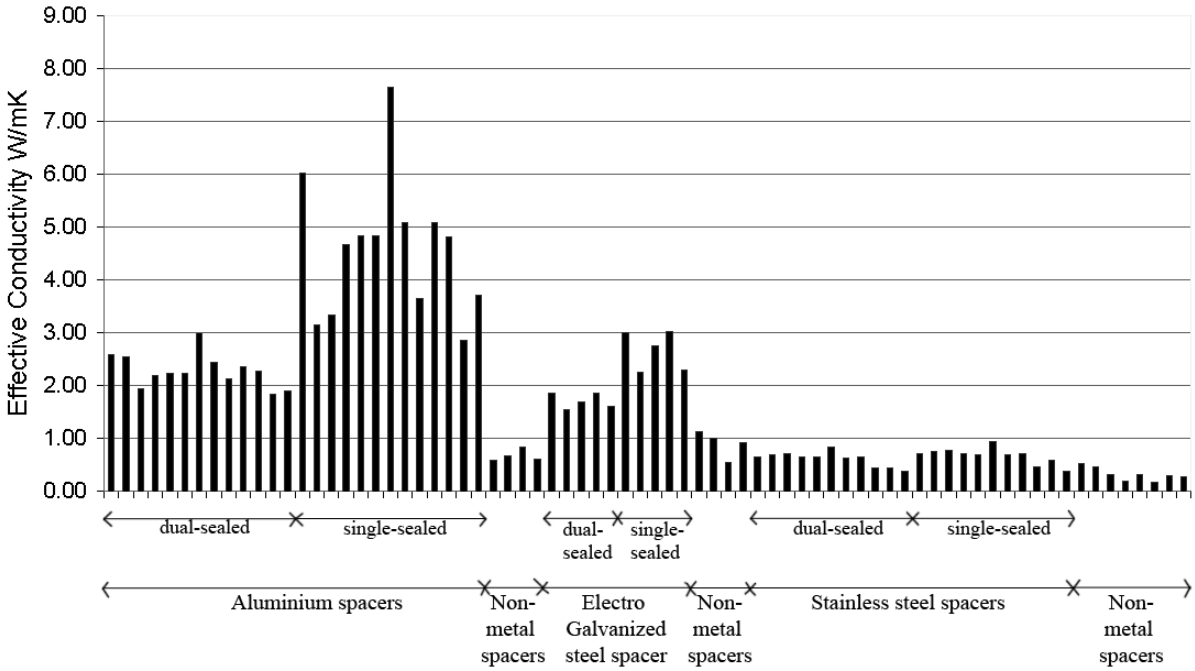


Figure 12 – Spacer system effective conductivity [24]

The impact of different variables on the thermal performance of a fenestration product is addressed in a second phase of the study. These variables include the sealant type, the overall edge seal width (i.e., primary and secondary seal), the primary sealant width, the spacer wall thickness, and the IG unit placement in the frame. It was found that the choice of sealant material, the overall spacer system width, the thickness of the primary sealant, and the wall thickness of stainless steel spacer systems affect the thermal performance of the total fenestration product. Therefore, it is important to properly calculate the spacer system effective conductivity and to account for these design variables. The spacer wall thickness of aluminum and stainless steel spacers and the placement of the IG unit in the frame do not significantly affect the overall product thermal performance.

4.1.3 Commercial spacers: overview of properties

The present work aims to complement the IGMA study by performing market research and analyzing current commercially available spacer systems. Table 2 lists spacer manufacturers and products. The list is based on an internet search and is therefore not exhaustive. Manufacturers of non-metal spacers are the main focus in this market research. For simplicity, aluminum and galvanized steel spacers are referred to by their minimum and maximum thermal conductivities, obtained from the IGMA study [24].

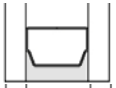
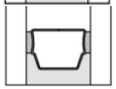
We list dimension characteristics and thermal properties of each product if these are available. The information was collected from manufacturers' product sheets and data sheets, from simulations performed by Bundesverband Flachglas [37], or simulations in THERM [29] based on the stated dimensions and material properties or from the program's add-on Spacer Library [38]. An important distinction must be made between k_{eff} and λ_{eq}. As discussed earlier, these values result from different calculation procedures for estimating spacer system thermal conductivity and should therefore not be compared directly.

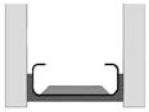
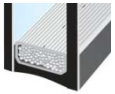
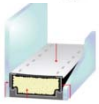
To compare the k_{eff} of spacer systems, the IGMA study fixed the values of all other variables. The overall system thickness and width in the IGMA study were fixed at 12.7 mm and 11.11 mm, respectively, and the analysis also assumed a PS secondary sealant and a 0.25 mm PIB primary sealant. All of these parameters have been proven to significantly influence thermal conductivity. However, it is not appropriate to use fixed parameters when analysing new spacer designs because manufacturer recommendations, compatibility between spacer bar and sealants, and specific product dimensions must be taken into account. Assuming fixed parameters when analyzing new spacer designs could result in calculation of a thermal conductivity for a product that does not exist. For instance, calculating the conductivity of a composite spacer system with separately simulated primary and secondary sealant and a total width of 11.11 mm would misrepresent a product such as Duraseal from TruSeal, which is 7.4 mm high and contains only one component. When interpreting λ_{eq}, it is important to bear in mind that this value only accounts for the actual spacer dimensions and assumes a 3-mm PS secondary sealant. The actual sealant material or edge construction thickness of a product might vary from these assumptions.

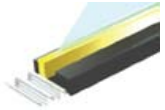
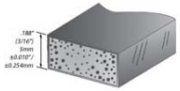
Table 2 gives the system dimensions and parameters that are used to calculate thermal properties. These dimensions and parameters should be taken into account when judging thermal performance or using the values calculated. For consistency, the thermal conductivity is given for a spacer width of 12 mm or 12.7 mm. We emphasize that the values presented in Table 2 are *indications* of thermal performance, not absolute values. To be valid, thermal performance values must account for the actual dimensions and details of the specific spacer design. Moreover, as noted above, values for k_{eff} and λ_{eq} do not compare well because of the different calculation procedures used to obtain these values. Alternatively, a comparison of spacer thermal performance could be carried out by simulating the spacers between glass panes and evaluating the thermal performance of such an assembly. For the abovementioned reasons, we opted not to present the values graphically because a figure showing these values could be a misinterpreted. Nevertheless, some trends become clear from analysing the table:

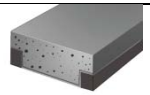
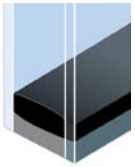
1) Thermal performance improves significantly when traditional metal spacers are replaced with improved metal spacers and non-metal spacers.
2) Stainless steel spacers reach effective and equivalent conductivities that are less than 1 W/(mK). The wall thickness of the spacer bar is an important factor that determines the conductivity (e.g., in the Nirotec series from Lingemann-gruppe/Helima). Several spacers among the improved metal spacers and the non-metal spacers achieve effective and/or equivalent conductivities below 0.5 W/(mK).
3) Within the category of improved metal spacers, hybrid spacers perform relatively well. Thermally broken aluminum appears to be a reasonable alternative to traditional aluminum spacer bars.
4) The performance of non-metal spacers is superior to that of metal spacers; non-metal spacers are therefore regarded as a promising direction for future window spacer designs.
5) Foam exhibits overall good thermal performance and generally somewhat better performance than TPS. Composites and foams allow for design details that result in variations in thermal properties. For example, a significant improvement results when aluminum elements used as vapor barrier or stabilizer material are replaced with a stainless steel membrane or a plastic stabilizer, respectively.
6) Foam spacers have a very low λ_{eq} because of conditions inherent to the calculation procedure of equivalent conductivity. The two-box model assumes a spacer bar sealed with a PS secondary sealant (i.e., λ_{PS} = 0.400 W/(mK)). However, manufacturers of foam spacers have recommended hot-melt butyl as a secondary sealant [i.e., λ_{butyl} = 0.240 W/(mK)]. Therefore, in the case of foam spacers, the equivalent conductivity method results in a misleading characterization of actual thermal performance. Instead, it is recommended to use the actual material properties (thermal conductivity and density) of the foam material.

Table 2 – Overview of commercial spacer systems and their available dimensions and properties; manufacturer contact information is given in Appendix A .

SPACER TYPE	Manufacturer	Product type or name	Product description and material properties	Illustration	(a) k_{eff} (W/(mK))	(b) λ_{eq} (W/(mK))	Available thickness t (mm)	Spacer bar width w_s (mm)	**Dimensions and parameters applied in calculating conductivity:** thickness (t), primary sealant, width (w), secondary sealant	Ref.
METAL										
ALUMINUM										
	e.g., Allmetal GmbH, Alumet, Helima, Hygrade	"Aluminum"	Hollow aluminum spacer bar		-	4.89 - 6.59		6.5	(b) t = 12 mm to 18 mm, w = 9 mm	[30]
		Single-sealed			3.0 - 7.6	-			(a) t = 12.7 mm, 0.25 mm PIB, w = 11.11 mm, PS	[24]
		Dual-sealed			1.8 - 3.0	-			(a) t = 12.7 mm, 0.25 mm PIB, w = 11.11 mm, PS	[24]
GALVANIZED STEEL										
	e.g., Allmetal GmbH, Hygrade, RollTech	Single-sealed			2.0 - 3.0	-			(a) t = 12.7 mm, 0.25 mm PIB, w = 11.11 mm, PS	[24]
		Dual-sealed			1.5 - 2.0	-			(a) t = 12.7 mm, 0.25 mm PIB, w = 11.11 mm, PS	[24]
STAINLESS STEEL										
	"Stainless steel"	Single-sealed			0.5 - 1.0	-			(a) t = 12.7 mm, 0.25 mm PIB, w = 11.11 mm, PS	[24]
		Dual-sealed			0.4 - 0.8	-			(a) t = 12.7 mm, 0.25 mm PIB, w = 11.11 mm, PS	[24]
	Allmetal GmbH	Air spacer			-	0.69 - 0.72		6.5	(b) t = 12 mm to 18 mm	[37]
	Alumet	Insulseam air spacer			-	-				
	Hygrade				-	-				
	Lingemann-gruppe/ Helima	Nirotec 0.20	wall thickness 0.20 mm		0.63	0.76	5.5 - 19.5	7.0	(a), (b) t = 12 mm, 0.30 mm butyl, w = 10 mm, PS	[29],[38]
	Lingemann-gruppe/ Helima	Nirotec 0.17	wall thickness 0.17 mm		0.60	0.68 - 0.72	7.5 - 19.5	7.0	(a) t = 12 mm, 0.30 mm butyl, w = 10 mm, PS (b) t = 12 mm to 16 mm	[29],[38], [37]
	Lingemann-gruppe/ Helima	Nirotec 0.15	wall thickness 0.15 mm		0.55	0.61 - 0.65	11.5 - 17.5	7.0	(a) t = 12 mm, 0.30 mm butyl, w = 10 mm, PS (b) t = 12mm to 16mm	[29],[38], [37]
	Glaswerke Arnold GmbH	WEP Classic	wall thickness 0.20 mm		-	0.85 - 0.89		6.5	(b) t = 12 mm to 16 mm	[37]
	Glaswerke Arnold GmbH	WEP Premium	wall thickness 0.15 mm		-	0.64 - 0.67		7.2	(b) t = 12 mm to 16 mm	[37]
	RollTech	Chromatech Plus	wall thickness 0.15 mm		-	0.66 - 0.69		7.0	(b) t = 12 mm to 16 mm	[37]
	RollTech	Chromatech	wall thickness 0.18 mm		-	0.78 - 0.82		6.5	(b) t = 12 mm to 16 mm	[37]
	Cardinal Glass Industries	XL Edge	Stainless steel, PIB primary seal and Si secondary sealant		0.40	0.42	6.0 – 20.5	7.9	(a) , (b) t = 12 mm, 0.40 mm PIB, w = 7.9 mm, silicone	[29],[38]
SPACER TYPE	**Manufacturer**	**Product type or name**	**Product description and material properties**	**Illustration**	**(a) k_{eff} (W/(mK))**	**(b) λ_{eq} (W/(mK))**	**Available thickness t (mm)**	**Spacer bar width w_s (mm)**	**Dimensions and parameters applied in calculating conductivity:** thickness (t), primary sealant, width (w), secondary sealant	**Ref.**
METAL										
IMPROVED METAL SPACERS										

U-shaped									
GED Intercept	Tinplate (single-sealed)	U-shaped galvanized steel [thickness 0.25 mm, λ = 62 W/(mK)]		0.56	-	5.5 - 22	7.6	(a), (b) t = 12.7 mm, hot-melt butyl, w = 9.3 mm	[29]
	Tinplate (dual-sealed)			0.62	1.80	5.5 - 22	7.6	(a), (b) t = 12.7 mm, 0.63 mm PIB, w = 9.3 mm, PU	[29]
	Ultra (single-sealed)	U-shaped stainless steel [thickness 0.20 mm, λ = 13.63 W/(mK)]		0.25	-	5.5 - 22	7.6	(a), (b) t = 12.7 mm, hot-melt butyl, w = 9.3 mm	[29]
	Ultra (dual-sealed)			0.27	0.26	5.5 - 22	7.6	(a), (b) t = 12.7 mm, 0.63 mm PIB, w = 9.3 mm, PU	[29]
	Tinplate LOW (single-sealed)	U-shaped galvanized steel [thickness 0.25 mm, λ = 62 W/(mK)]		0.55	-	5.5 - 22	6.4	(a), (b) t = 12.7 mm, hot-melt butyl, w = 8.1 mm	[29]
	Tinplate LOW (dual-sealed)			0.62	0.95	5.5 - 22	6.4	(a), (b) t = 12.7 mm, 0.63 mm PIB, w = 8.1 mm, PU	[29]
	Ultra LOW (single-sealed)	U-shaped stainless steel [thickness 0.20 mm, λ = 13.63 W/(mK)]		-	-	5.5 - 22	6.4		
	Ultra LOW (dual-sealed)			-	-	5.5 - 22	6.4		
Hybrid spacer									
Hygrade	Thermal Edge™ - low profile	Stainless steel with plastic top		-	-	8 - 13.5			
Hygrade	Thermal Edge™ - heat mirror	Stainless steel with plastic top		-	-	6 - 14			
Lingemann-gruppe/ Helima	Nirotec Evo	Stainless steel [thickness 0.06 mm, λ = 15 W/(mK)] with biopolymer top [thickness 0.4 mm, λ = 0.172 W/(mK)]		-	0.39 - 0.40		6.6	(b) t = 12 mm to 16 mm	[37]
RollTech	Chromatech Ultra	Stainless steel [thickness 0.10 mm, λ = 15 W/(mK)] with polycarbonate top [thickness 1.12 mm, λ = 0.24 W/(mK)]		-	0.34 - 0.33	8 - 24	7.0	(b) t = 12 mm to 16 mm	[37]
THERMIX	Thermix® TX.N®	Stainless steel [thickness 0.10 mm, λ = 15 W/(mK)] with highly insulating plastic polypropylene [thickness 1.3 mm/0.8 mm, λ = 0.23 W/(mK)]		-	0.32 - 0.33	8 - 24	7.0	(b) t = 12 mm to 16 mm	[37]
Technoform Glass Insulation GmbH	TGI spacer	Stainless steel [thickness 0.10 mm, λ = 15 W/(mK)] with plastic top [thickness 0.6 mm/0.8 mm, λ = 0.195 W/(mK)]		-	0.34 - 0.34	8 - 24	7.0	(b) t = 12 mm to 16 mm	[37]
Thermally broken Aluminum									[37]
Azon Warm Light	Aluminum Spacer	Roll-formed aluminum with urethane thermal break		0.50	0.55	11.5 - 19.5	8.0	(a), (b) t = 12.7 mm, 0.25 mm PIB, w = 9.3 mm, Si	[29],[38]
	Aluminum Low Profile			0.53	0.61	12.7 - 16	6.3	(a), (b) t = 12.7 mm, 0.25 mm PIB, w =7.6 mm, Si	[29],[38]

SPACER TYPE	Manufacturer	Product type or name	Product description and material properties	Illustration	(a) k_{eff} (W/(mK))	(b) λ_{eq} (W/(mK))	Available thickness t (mm)	Spacer bar width w_s (mm)	Dimensions and parameters applied in calculating conductivity: thickness (t), primary sealant, width (w), secondary sealant	Ref.
NON-METAL										
COMPOSITE										
	"plastic with Aluminum foil"				-	0.63 - 0.71		6.6	(b) t = 12 mm to 18 mm	[30]
	TruSeal Technologies	Duraseal (single-sealed)	5 components in 1: desiccated topcoat, moisture resistant adhesive (butyl), continuous 3-sided foil moisture vapor barrier (high-density polyethylene), non-metallic stiffener (polypropylene), and a flexible corrugated aluminum stabilizer, no secondary sealant		0.32* 0.45**	-	6 - 21	7.4	(a) * k_{lin} , t = 13 mm (a) ** t = 12.7 mm, w = 7.4 mm, no individual primary or secondary sealant	*[39] **[29],[38]
		Duralite (single-sealed	Analogous to Duraseal but with a non-metallic flexible stabilizer, i.e., corrugated plastic (polycarbonate)		0.080* 0.13**	-	6 - 21	7.4	(a) * k_{lin} , t = 13 mm (a) ** t = 12.7 mm, w = 7.4 mm, no individual primary or secondary sealant	*[39] **[29],[38]
		DecoSeal (single-sealed	Corrugated metal with moisture resistant adhesive (butyl), without secondary sealant		0.53	-	9.5 - 19	7.4	(a) t =12.7mm, w = 7.4 mm	[29],[38]
		DecoSeal (dual-sealed)	Corrugated metal with moisture resistant adhesive (butyl) and secondary sealant		0.57	0.81	9.5 - 19	7.4	(a) t =12.7mm, w = 9.4 mm, Si	[29],[38]
	Swisspacer	Swisspacer	Composite plastic SAN [styrol acryl nitril copolymer with 35 % glass fiber, thickness 1.0 mm, λ = 0.16 W/(mK)] with thin aluminum membrane [thickness 0.003 mm, λ = 160 W/(mK)]		-	0.56 - 0.62	8 - 27	6.5	(b) t = 12 mm to 16 mm	[40]
		Swisspacer V	Analogous to Swisspacer but with thin stainless steel membrane [thickness 0.001 mm, λ = 15 W/(mK)]		-	0.18 - 0.18	8 - 27	6.5	(b) t = 12 mm to 16 mm	[40]
FOAM										
	Edgetech	Super Spacer Premium	Flexible, silicone foam spacer with desiccant-filled pre-applied side adhesive		0.16	0.05	5 - 20	4.8	(a), (b) t = 12.7 mm, w = 9.5 mm, hot-melt butyl, λ foam = 0.102 W/(mK)	[29],[38]
		Super Spacer Premium plus			0.15	0.06	3 - 20	6.4	(a) , (b) t = 12.7 mm, w = 11.11 mm, hot-melt butyl, λ foam = 0.102 W/(mK)	[29],[38]
		Super Spacer Material nXt	Flexible silicone foam, pressure-sensitive acrylic adhesive, and 360 integral multi-layer vapor barrier		0.17	0.06	6 - 19	4.8	(a) , (b) t = 12.7 mm, w = 9.5 mm, hot-melt butyl, λ foam = 0.114 W/(mK)	[29],[38]
		Super Spacer Standard	Flexible EPDM foam, pressure-sensitive acrylic adhesive, and multi-layer vapor barrier		0.18	0.07	5 - 20	4.8	(a) , (b) t = 12.7 mm, w = 9.5 mm, hot-melt butyl, λ foam = 0.127 W/(mK)	[29],[38]

SPACER TYPE	Manufacturer	Product type or name	Product description and material properties	Illustration	(a) keff (W/(mK))	(b) λeq (W/(mK))	Available thickness t (mm)	Spacer bar width ws (mm)	Dimensions and parameters applied in calculating the conductivity: thickness (t), primary sealant, width (w), secondary sealant	Ref.
NON-METAL										
FOAM		Super Spacer Triseal Premium	Silicone foam [thickness 7.2 mm, λ = 0.16 W/(mK)], mylar foil [thickness 0.10 mm, λ = 1.1 W/(mK)], and PIB primary seal		0.22	0.17	5 - 20	6.3	(a) , (b) t = 12.7 mm, PIB,w = 13.65 mm, silicone, λ foam = 0.13 W/(mK)	[29],[38]
		Super Spacer Triseal Premium Plus			0.20	0.16	8 - 22	7.3	(a) , (b) t = 12.7 mm, PIB, w = 12.65 mm, PS, λ foam = 0.117 W/(mK)	[29],[38]
		Super Spacer T-Spacer	Silicon foam [thickness 7.2 mm, λ = 0.16 W/(mK)], mylar foil [thickness 0.10 mm, λ = 1.1 W/(mK)]		-	0.18 - 0.18	8 - 22	7.3	(b) t = 12 mm to 16 mm	[37]
	Glasslam	Air-Tight silicone foam S-spacer	Single-sealed, silicone foam matrix with > 40 % desiccant content, a multi-layer metallized vapor barrier, and enhanced acrylic pressure-sensitive adhesive		0.18	0.07	5 - 21	4.8	(a) t = 12.7 mm, w = 9.5 mm, hot-melt butyl, λ foam = 0.125 W/(mK)	[29]
		Air-Tight silicone T-spacer	Analogous to Air-Tight silicone foam S-spacer but with PIB primary sealant		0.17	0.10	8 - 21	7.1	(a) t = 12.7 mm, w = 11.11 mm, hot-melt butyl, λ foam = 0.125 W/(mK)	[29]
THERMOPLASTIC (TPS)										
	Viridian	ThermoTech™	Synthetic rubber PIB [λ = 0.20 W/(mK)] with desiccant (3A)		0.28* 0.26**	0.21	6 - 18	> 7.5	(a) * at 23C (a) ** t =12.7 mm, w = 11.11mm, PS, PIB = 0.200 W/(mK)	*[41] **[29]
	Kömmerling	Ködimelt TPS	Polyisobutylene [6mm, λ = 0.25 W/(mK)], with desiccant		0.29	0.25 - 0.25	6 - 20	6.0	(a) t = 12.7 mm, w = 11.11mm, PS, PIB = 0.245 W/(mK) (b) t = 12 mm and 16 mm	[37], [29], [33]

4.2 Sealant technologies

Secondary sealant type has a significant impact on a fenestration product's thermal performance [24]. However, neither k_{eff} nor λ_{eq} addresses the importance of the secondary seal. Table 3 lists the thermal conductivities of frequently used sealant types. The thermal properties of sealants are not within the scope of this article. The reader can find information on this topic in the available literature, e.g. [48].

Table 3 – Primary and secondary sealant thermal conductivities [49]

Sealant	Density (kg/m^3)	Thermal conductivity (W/mK)
Butyl rubber (hot melt)	1,200	0.240
Polysulphide (PS)	1,700	0.400
Polyurethane (PU)	1,200	0.250
Silicone (Si)	1,200	0.350
Polyisobutylene (PIB)	930	0.200

5 Future perspectives

This section outlines research opportunities for improving the thermal performance of IG unit edge seals and discusses some existing alternative solutions.

5.1 Research opportunities

Through the simplified equation (4) and Figure 1, we understand that edge seal thermal performance can be improved by working in three areas: reducing the width of the edge seal (w); reducing its thermal conductivity (λ); and increasing its thickness (t), i.e., increasing the length of the path along which the heat loss travels.

$$q = w\frac{\lambda}{t} \tag{4}$$

Decreasing the width of the spacer bar and secondary sealant reduces the heat transfer area, and thus the size of the thermal bridge at the edge of glass. Table 2 shows that new systems aim to reduce total edge seal width. Total widths of 7 mm to 10 mm are common. Foam spacer bars achieve widths as small as 4.8 mm. Reducing or omitting the secondary sealant also implies a thermal improvement but requires that the structural strength of the edge seal be guaranteed by other means.

Significant thermal improvement can be achieved by reducing the thermal conductivity (λ) of the applied materials. Omitting high-thermal-conductivity components such as aluminum and other metals (that are used for spacer bar profiles or in metallized foils, for example) and using highly insulating materials in their place will improve thermal performance. Materials are available that have considerably lower thermal conductivities than the materials that are commonly used in spacer designs. Examples of highly insulating materials on the market include polyurethane foam with a λ of 26 mW/(mK) [33], aerogels with λ of 13 mW/(mK) [50], and vacuum insulation panels (VIPs) with λ as low as 4 mW/(mK) [51]. Currently, no spacer systems on the market utilize these materials. Although the low thermal conductivities of these materials are desirable in spacer systems, other requirements, such as structural strength, moisture and vapor tightness, and durability, must also be taken into account. Thus, it would be interesting to explore new composite designs combining highly insulating materials with other materials to create a component that meets all of the above requirements. Development of new materials with low conductivity is another path that bears investigation for spacer applications.

The best secondary sealant available today has a conductivity of about 0.240 W/(mK). Therefore, improvements in the thermal conductivity of secondary sealants are theoretically possible. However, good adhesion and durability are more important required qualities in a secondary sealant than low thermal conductivity. The need for good adhesion and durability might limit the thermal improvements that are realistically possible. Other areas of potential improvement are reducing the area of the secondary sealant and the manner in which it is implemented, as described below in Section 5.2.2.

Increasing the edge seal thickness or path length for heat transfer through the spacer bar will also contribute to better thermal performance in the edge-of-glass region. One potential area of research toward this goal would be to develop a corrugated material, possibly filled with highly insulating bulk material for structural stability. This idea is represented schematically in Figure 13 [left]. Such a technology could also accommodate triple-pane glazing, which normally requires two edge seals, increasing both costs and the risk of primary or long-term failure of the unit. A corrugated spacer would make it possible to design a triple-pane, single-spacer IG unit and thus reduce cost and opportunities for failure. Figure 13 [center] depicts the idea of a triple-pane IG unit with secondary sealant. Figure 13 [right], shows reduced application of secondary sealant as a strategy to improve thermal properties.
Since this paper focuses mainly on the review part, the effect of these techniques on the overall thermal performance of windows has not yet been investigated in detail. Future research will aim to provide for numerical and experimental results on these improved techniques.

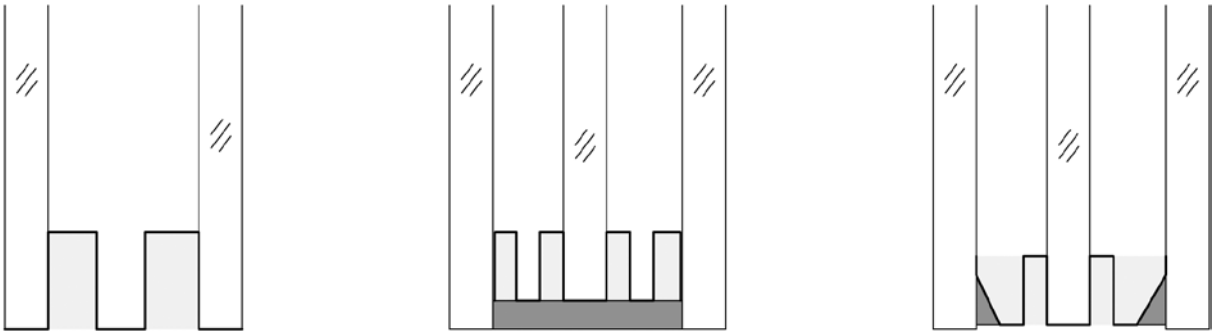


Figure 13 – Schematic principle of a corrugated material spacer for double- and triple-pane glazing.

5.2 Existing alternative solutions

Some alternative edge seal solutions on the market today include vacuum glass [1], suspended film technology [1], and integrated window products [1]. Vacuum glass, which is an alternative to typical IG construction, consists of two (or three) sheets of glass separated by a narrow vacuum space with an array of support pillars that hold the two sheets of glass apart. The edge seal design is critical to the performance of vacuum glass units and is currently an area of major development focus for these units. Another variation on the more common multi-layer IG units with gas fill is the use of suspended coated film (SCF) between the outer and inner panes. The film acts like a third or fourth glass pane, thus reducing the total weight of the window. Edge seal designs are being adapted to accommodate this technology. Integrated windows and edge seals with reduced secondary sealant are discussed below.

5.2.1 Integrated window production

Integrated windows are available as alternatives to common multiple-pane units. Rather than fabricating a separate IG unit that is fitted into a sash, integrated technology produces a window with glass panes directly adhered to the sash. The advantages are that the entire window is produced in one successive production line, which should result in a consistent-quality product; transportation costs of different materials to different installation sites are reduced; and orders should be able to be completed more quickly than for traditional windows because all production of integrated window products is at a single location. This technology does not use conventional edge seals composed of spacer bars and sealants but instead employs an adapted sash. Desiccants and sealants adapted to the integrated design are used, and the glazing panels are directly bonded to the sealant on both sides of the window sash profile. Wetting-out is accomplished by either vacuum compression or roller compression technology. Integrated windows are produced by manufacturers such as Sashlite™.

Bystronic Glass has adopted the Sashlite™ technology and in its “sashline” production line [53]. The effect of the edge seals used in these products depends on the frame properties. The edge seal’s effect on the edge-of-glass region is thus inherent to each system and has not yet been estimated yet. Future research should estimate the impact of alternative integrated window designs on the U-value of the fenestration products.

5.2.2 Reduced secondary sealant

Our review has indicated that the secondary sealant has a significant effect on the overall thermal performance of a fenestration product. Reducing or omitting the secondary sealant would therefore considerably improve the thermal performance in the edge-of-glass region. Two available alternatives to reduce the applied secondary sealant are the Cardinal XL and the Six-O-Four spacer systems depicted in Figure 14. In these alternatives, the

shape of the spacer bar is adjusted to reduce the sealant application, while still meeting the criteria for durability and adhesion. In addition to improving thermal performance, reducing the amount of secondary sealant saves materials costs and reduces the total width of the edge seal. Applications for non-metal spacers should be investigated.

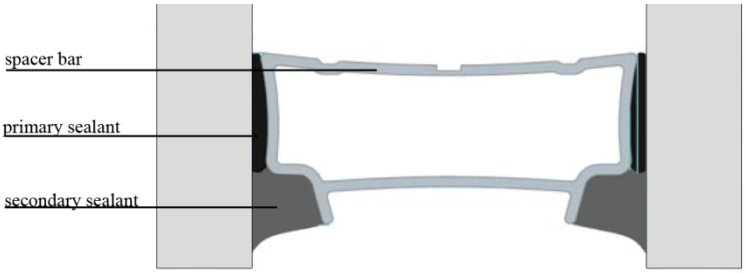


Figure 14 – Six-O-Four spacer design with reduced secondary sealant thermal conduction path [54]

6 Summary and Conclusions

Several requirements must be taken into account when designing edge seals, including structural functionality, moisture and vapor transmission, life expectancy, and thermal performance. From our review of the literature on the state of the art in fenestration edge seals, it is clear that edge seal thermal performance has a significant effect on the U-value of a fenestration product and that, for best thermal performance, windows should use the best available spacers. Different strategies for defining thermal conductivity were discussed (i.e., the linear conductivity (k_{lin}), effective conductivity (k_{eff}), and equivalent conductivity (λ_{eq})). Each method has strengths and weaknesses inherent to their calculation procedures. Both k_{eff} and λ_{eq} are used for characterizing the thermal performance of the edge seal systems investigated in the market review.

Our market review categorized existing spacer systems according to their design and geometry in relation to their thermal performance. Although we did not investigate the relative merits of the different designs, it is clear that non-metal spacers are the most promising future approach for window spacer designs. Among non-metal spacer materials, foams exhibit overall good thermal performance, generally somewhat better than that of thermoplastic spacers (TPSs). One composite spacer has good thermal performance compared to some foam and TPSs.

Optimization the thermal performance of individual spacers is necessary. Further research should be undertaken to improve insulating edge seal systems as well as to develop and investigate alternative materials and design possibilities.

Improvement in edge seal thermal performance can be achieved by reducing the heat transfer width of the edge seal, reducing its thermal conductivity, and increasing its thickness (i.e., increasing the path length for heat loss). Decreasing the width of spacer bar and secondary sealant reduces the size of the thermal bridge at the edge of glass, thus increasing thermal performance. Spacer bars widths as small as 4.8 mm are currently available. Solutions to reduce the secondary sealant width are searched, but structural strength and durability must be retained. Composites provide for an interesting research field to reduce the edge seals thermal conductivity and the overall edge seal width. New composite designs could be explored that combine highly insulating materials such as polyurethane foam, aerogels, and vacuum material with other materials to create a component that meets all requirements. Corrugated edge seal designs are a potential area of research to increase the path length for heat transfer through the spacer bar. This idea could be adapted to accommodate triple-pane IG units, with a single spacer.

Acknowledgments

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, Building Technologies Program, of the U.S. Department of Energy, under Contract No. DE-AC02-05CH11231.

Appendix A – Spacer manufacturers and contact information

Manufacturer	Contact information	Further information
Metal spacers		
Allmetal, Inc.,	One Pierce Place, Suite 900, Itasca IL 60143, USA Tel.: +1 630 250 8090 Fax: +1 630 250 8387 info@allmetalinc.com	www.allmetalinc.com
Alumet	3803 136th St. NE, Marysville,WA 98271, USA Tel.: +1 800 343 8360 Fax: +1 360 653 9884 lpeterson@alumet.com	www.alumet.com
Arnold Glas	Frau Beatrice Altena, Alfred-Klingele-Straße 15, 73630 Remshalden, Germany info@arnold-glas.de	www.glaswerke-arnold.de
AZON USA Inc.,	643 W. Crosstown Parkway, Kalamazoo MI 49008-1910, USA Tel.: +1 866 494 7688	www.warmedge.com
Cardinal Glass Industries	775 Prairie Center Dr # 200, Eden Prairie MN 55344, USA Tel.: +1 952 229 2600 Fax.: +1 952 935 5538	www.cardinalcorp.com
Ensinger GmbH	Niederlassung Ravensburg, Mooswiesen 13, 88214 Ravensburg, Germany Tel.: +49 (0) 751 / 3 54 52 -0 Fax: +49 (0) 751 / 3 54 52 -22 info@thermix.de	www.thermix.de
GED Integrated Solutions	9280 Dutton Drive, Twinsburg OH 44087-1967 USA, Tel.: +1 330 963 5401 Fax: +1 330 963 0584 TechSupport@GEDUSA.Com	www.gedusa.com
Hygrade Components	1990 Highland Avenue, Bethlehem PA 18020, USA Tel.: +1 800 645 9475 Fax: +1 610 866-3761 sales@hygrademetal.com	www.hygrademetal.com
Lingemann-Gruppe, Helima	Postfach 10 10 12, D-42010 Wuppertal, Germany Tel.: +49 (0)202 70 94-0 Fax: +49 (0)202 70 94-288	www.helima.de
RollTech A/S	W. Brüels Vej 20, DK-9800 Hjørring, Danmark Tel.: +45 96 23 33 43 Fax: +45 96 23 33 11 info@rolltech.dk	www.rolltech.dk
Technoform Glass Insulation GmbH (TGI)	Matthäus-Merian-Straße 6 / D-34253 Lohfelden, Germany Tel.: +49 (0)561 9583-100 Fax: +49 (0)561 9583-121	www.glassinsulation.co.uk
Non-metal spacers		
Swisspacer, Saint-Gobain (International) AG,	Sonnenwiesenstrasse 15, 8280 Kreuzlingen, Switzerland Tel: +41 (0)71 686 92 79 Fax: +41 (0)71 686 92 75 swisspacer@saint-gobain.com	www.swisspacer.com
TruSeal Technologies	6680 Parkland Blvd., Solon OH 44139, USA Tel.: +1 216 910 1500 Fax: +1 216 910 1505	www.truseal.com
Edgetech	800 Cochran Avenue, Cambridge OH 43725, USA Tel: +1 740 439 2338 info@edgetech-europe.com	www.edgetechig.com
Glasslam	1601 Blount Road, Pompano Beach FL 33069, USA Tel: +1 954-975-3233 Fax: +1 954-975-3225 sales@glasslam.com	www.glasslam.com
Viridian	95 Greens Road, Dandenong VIC 3175, Australia Tel.: +61 1800 810 403	www.viridianglass.com
Kömmerling Chemische Fabrik GmbH	Zweibrücker Str. 200 D-66954 Pirmasens, Germany, Tel.: +49 6331 56-2000 Fax: +49 6331 56-1999 info@koe-chemie.de	www.koe-chemie.de

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