Deconstructing the Window: Let's forget about the center of glass

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ABSTRACT HEADING

With the need to provide daylight and views for building occupants, improved comfort, and low energy consumption, a significant tension has been created around the design of the building envelope. While the use of highly glazed façades allows for sufficient daylight and views, they can create thermal comfort issues for occupants near them, condensation issues because of cold interior surfaces, and can reduce the thermal performance of the façade. However, with the right design, an envelope system can be created which performs well in all three areas. The US DOE predict that the use of highly insulating windows alone (U=0.15 btu/°F.hr.ft^2) can save 1 Quadrillion (10^{15}) BTUs annually if installed the entire US commercial building stock (Arasteh et. al. 2006). Given that commercial buildings consume 20 Quadrillian BTUs in the US annually, this represents a 5% energy savings from just improving the U-factor alone. For years, the industry has relied heavily on the increasing performance of low-e coatings to drive window U-factors (thermal transmittance) lower. However, the full performance of the window is primarily determined by the frame and the edge of glass conductance, and neglecting the window perimeter can result in poorly performing fenestration systems that do not meet code, are uncomfortable to sit next to, and exhibit problematic condensation. The newest US building codes, and the performance of the key fenestration components (frame, edge of glass, and center of glass) that will be necessary to meet their increasingly stringent thermal performance requirements, are reviewed. To help designers specify the appropriate fenestration components to meet needed energy, comfort and condensation performance requirements, the factors that make up the U-factor and condensation resistance of a window are deconstructed, and their sensitivity to edge of glass parameters such as frame, frame bite, sealant height, spacer conductivity, etc. examined. Finally, the impact of frame and edge thermal performance for fenestration in warm climates is discussed.

INTRODUCTION

A significant tension has been created around the design of the building envelope because of the increased stringency of energy codes coupled with the focus on providing daylight and views for building occupants and improved thermal comfort. While the use of highly glazed façades allows for sufficient daylight and views, they can also create thermal comfort issues for occupants near them, condensation issues because of cold interior surfaces (which can become breeding grounds for mold), and reduce the overall thermal performance of the façade (since walls are generally more insulating than windows). In addition, to provide a higher percentage of daylit floor area, buildings need to be narrower, and as such, the impact of the envelope on whole building energy usage is becoming larger.

With the right design, a glazed envelope system can be energy efficient, thermally comfortable and resistant to condensation. The United States Department of Energy (US DOE) predicts that the use of highly insulating windows alone can save 1 Quadrillion (10^{15}) BTUs annually if installed in the entire US commercial building stock (Arasteh et al., 2006). Given that commercial buildings use about 17 Quads annually (International Energy Agency, 2007), this represents a 5% energy savings from just improving the U-factor in existing buildings alone.

To date the industry has relied heavily on the increasing performance of low-emissivity (low-e) coatings to drive down window U-factors (thermal transmittance). However, the center of glass (COG) U-factor, which is influenced by low-e coating performance, does not tell the whole story. To achieve the lowest fenestration thermal transmittance it is necessary to look

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more broadly at the window as a system. The full thermal performance of the window is determined by the conductance of the frame, the edge of glass (EOG), and COG, as well as aspects related to air leakage and installation.

This paper reviews the fenestration component specifications needed to meet the U-factor in the most recent US model codes, and the implications of using center of glass U-factor instead of window U-factor in performance path compliance. The impact of frame and EOG performance relative to the COG performance on whole window U-factor and condensation resistance are demonstrated. The sensitivities of the edge of glass thermal conductance to parameters such as sealant height, spacer effective conductance, edge bite and desiccant quantity and the overall impact on window U-factor are also examined. Finally, the importance of frame thermal transmittance on window performance in a hot climate is demonstrated.

U-FACTOR OF A WINDOW

The U-factor of a window is a measure of how well it thermally insulates the inside from the outside of a building. It is the overall rate of energy transfer through a window. The U-factor of a window is calculated as the area weighted average of the center of glass, the edge of glass and the frame U-factors.

The equation used in the United States (US) for the overall U-factor of a window is:

$$U = \frac{AfUf + AcogUcog + AeogUeog}{Af + Acog + Aeog} \qquad (1)$$

Where:
U = overall thermal transmittance, U-factor, of the window
Af = frame area
Acog = center of glass area
Aeog = edge of glass area
Uf = frame U-factor
Ucog = center of glass U-factor
Ueog = edge of glass U-factor

The European specific equation for fenestration U-factor is similar, but breaks down the edge of glass differently:

$$U = \frac{AfUf + AgUg + \sum(Ig.\Psi)}{Af + Ag} \qquad (2)$$

Where:
U = overall thermal transmittance, U-factor, of the window
Af = Area of the frame
Uf = thermal transmittance of the frame (frame U-factor)
Ag = area of glass
Ug = center of glass U-factor
Ig = perimeter of glass dimension
Ψ = linear thermal transmittance of the edge of glass (glass, spacer, sealants, frame at the edge)

It should be noted that whilst the calculation methods and units of measurement for U-factors and thermal transmission at the edge of glass are different in the United States (US) and Europe, the general trends demonstrated herein generally apply equally to fenestration systems wherever in the world they are located. Both US and European approaches to the calculation are used herein to provide illustrations. Where data in US units (BTU/^{o}F.hr.ft^2) is reported first, the US methodology has been used. Where data with metric units (W/m^{2}K) are reported first, the EU method has been used. Because the methodologies and boundary conditions used are different, the numerical results are not directly comparable even if units are converted, but the trends are the same.

Based on the equations above, it is clear that the edge of glass and frame performance can have significant impact on the U-factor, and that impact increases for smaller window sizes. Furthermore, it is the overall U-factor of a window (at National Fenestration Research Council (NFRC) standard sizes - 1200mm x 1500mm/47"x59" for a fixed window) that is specified by US model building codes, not the center of glass value.

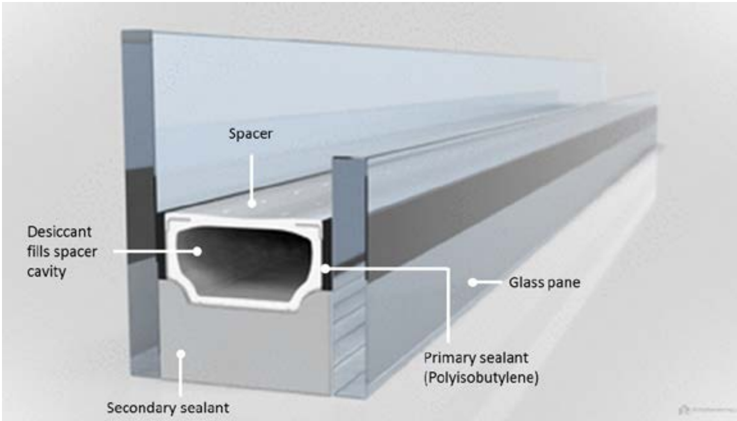


Figure 1. Edge of Glass Schematic showing spacer and sealants.

Heat is transferred at the window perimeter by conduction through the frame and edge of glass, convection and to a lesser extent radiation. The thermal conductance through the edge of glass (see figure 1) depends on the effective conductance of both the insulating glass edge spacer and accompanying sealants. The primary purpose of the spacer is to hold the glass lites apart at the perimeter of the insulating glass unit to create a cavity between them which reduces conduction and convection across the center of the glass. In addition, the spacer must also carry desiccant to keep the cavity dry during its service life, minimize moisture vapor and inert gas permeation into and out of the cavity respectively to maximize service life, manage climatic loads due to pressure, temperature and wind loads, as well as minimizing thermal conduction.

WINDOW U-FACTOR REQUIREMENTS IN MOST RECENT US MODEL ENERGY CODES

The prescriptive U-factor requirements in the most recent International Energy Conservation Code (IECC) and American Society for Heating, Refrigeration and Air Conditioning Engineers' (ASHRAE) Standard 90.1 have become more stringent and, as a result, the previous focus on reducing center of glass U-factors to meet the model code requirements is no longer effective in isolation from the rest of the window system.

Table 1 shows the U-factor requirements for ASHRAE Standard 90.1-2016 and IECC 2015 and 2018, plus those for the above baseline ASHRAE standard 189.1-2017. The latter is a stretch sustainability code which contains more stringent energy requirements than the baseline ASHRAE 90.1.

Table 1. Prescriptive Fenestration U-factor* Requirements in US Codes

Climate Zone	0	1	2	3	4A & 4B	5	6A & 6B	7	8
ASHRAE 90.1-2016	0.50	0.57	0.54	0.45	0.38	0.38	0.36	0.33	0.29
IECC 2015/2018		0.50	0.50	0.46	0.38	0.38	0.36	0.29	0.29
ASHRAE 189.1-2017	0.45	0.54	0.51	0.43	0.34	0.36	0.34	0.31	0.28

**U-factors are given in btu/^{o}f.hr.ft^2 and are for fixed metal vertical fenestration.*

In order to achieve the U-factor requirements in climate zones 4 and above, strategies that improve the performance of the frame and edge of glass, as well as the center of glass must be implemented. In fact, as it will be demonstrated below, the frame and edge of glass must have high thermal performance in order to allow a high performing center of glass to have the greatest impact on the whole window performance.

Guide for Fenestration Component Specification to Meet Baseline Model Codes

In order to design fenestration to meet the code requirements in table 1, there are a number of different strategies associated with frame, edge of glass and center of glass that can be combined in order to achieve the target U-factors in aluminum fenestration for commercial buildings. These strategies are listed below:

1. Simple aluminum thermal break (frame)
2. One low-e coating (surface #2 or #3) in a dual pane low-e (center of glass)
3. Warm-edge spacer (edge of glass)
4. High performance aluminum thermal break (frame)
5. Argon filled insulating glass (center of glass)
6. A fourth surface low-e coating (on the room side lite) in a dual pane (center of glass)
7. Triple pane with 2 low-e coatings and glass fill (center of glass)

Climate zones 4 (Washington DC) and 5 (Chicago). To meet the U-factor requirements for these zones (0.38 btu/^{o}f.hr.ft^2), fenestration needs to have a simple aluminum thermally broken frame and a dual pane low-e glazing, plus use one additional strategy selected from #3-6 above (higher performance thermally broken frame, or warm-edge spacer, or argon filled insulating glass, or a fourth surface low-e coating) (Culp, 2017).

Climate zone 6 (Minneapolis). For fenestration installed into buildings in climate zone 6, a simple thermally broken frame and dual pane low-e glazing plus *two* of the additional strategies #3-6 listed above will most likely be needed to meet the 0.36 btu/^{o}f.hr.ft^2 U-factor (Culp, 2017).

Climate zone 7 (northern Minnesota, northern North Dakota, southernmost Alaska). IECC and ASHRAE 90.1 have two different U-factor requirements for this climate zone. Achieving ASHRAE 90.1's U-factor of 0.33 btu/^{o}f.hr.ft^2 requires fenestration to have a simple thermally broken frame and dual pane low-e glazing plus *three* of the additional strategies #3-6 listed above. To meet the significantly lower value of 0.29 btu/^{o}f.hr.ft^2 required by IECC 2015 and 2018, all of the first 6 strategies listed above will likely be needed or, alternatively, designers may feel it is more appropriate to use a high performance thermally broken frame with triple pane glazing in-fill with two low-e coatings and a warm-edge spacer (Culp, 2017).

Climate zone 8 (most of Alaska). The IECC and ASHRAE U-factor requirements of 0.29 btu/^{o}f.hr.ft^2 can be met in the same manner as described above for IECC 2015/2018 in climate zone 7. In these climate zones it is most likely that triple glazing with two low-e coatings and warm edge spacer in a high-performance frame is specified (Culp, 2017).

When choosing which strategies to use, additional considerations such as long-term reliability, product cost and condensation resistance performance are appropriate. For example, adding a fourth surface low-e to a standard low-e IGU could add more cost than, say, adding a warm-edge spacer. Also, because a fourth surface low-e reduces the surface temperature of the inboard lite (by approximately 9^{o}F or 5^{o}C under NFRC conditions), condensation may be problematic in some applications. Even though these coatings are designed to be more hard wearing than typical low-e coatings used inside a sealed cavity, there may be more susceptibility to damage and wear over time given the exposed surface. A warm-edge spacer generally provides a consistent reduction in the overall window U-factor of about 0.02-0.03 btu/^{o}F.hr.ft^2 (see figure 8a below) which will be reliably maintained through the life of the unit and can be used as an alternative to argon gas filling. Important aspects of the edge of glass and frame performance and their impact on overall U-factor are discussed in more depth below.

The Performance Approach To Code Compliance: A Potential Pitfall

An alternative code compliance path is the performance approach where designers demsonstrate that their building design is better than that of the code baseline through building energy modeling. This path is being used more and more for code compliance, especially for green building designs where building energy modeling is a requirement in order to achieve for example USGBC's LEED certification, and where the designed window to wall ratio is above the prescriptive limits of 30% for IECC (40% if lighting controls are used in more areas) or 40% for ASHRAE 90.1. In the latter case, the designers are able to show through building modeling that a more hollistic design approach in which the performance of the envelope and/or other building systems are improved to meet or exceed the code baseline building performance.

Building energy models require U-factor information for the whole window system either inputed for each window component (e.g. frame, center of glass) or as a whole window U-factor. One significant issue that can, and does occur, is the mistaken use of center of glass U-factor instead of whole window U-factor as inputs to the modeling. Oftentimes the center of glass U-factor is confused with the overall window U-factor. This is likely in-part because the center of glass U-factor is so easy to obtain, whereas the whole fenestration U-factor is much harder to calculate and is less easily available. Moreover, the center of glass U-factor is generally lower than the whole fenestration assembly U-factor, and in some cases, it is lower by a significant amount. For example, a typical center of glass U-factor for an air-filled dual pane insulating glass unit with a double silver low-e coating is 0.30 btu/^{o}f.hr.ft^2 (1.7 W/m^{2}K), whereas a typical overall U-factor for a aluminum window wall containing that same glazing infill could be as much as 0.45 btu/^{o}f.hr.ft^2 (2.6 W/m^{2}K) or even higher. Therefore, when the center of glass value is used by mistake in energy modeling, significant errors in energy use intensity (EUI) estimation can occur, making the EUI of the model look better than the as-built design.

Figure 2 illustrates the potential under-estimation in perimeter zone EUI and heating energy that could be caused by using a center of glass value of 0.30 btu/^{o}f.hr.ft^2 (1.7 W/m^{2}K) rather than the whole window value of 0.45 btu/^{o}f.hr.ft^2 (2.6 W/m^{2}K) in a building energy model for a building located in Minneapolis, MN. This data was generated using the Department of Energy's Energy Plus modeling software to create (i) a simple model of a 5m (16 feet) deep by 8m (25 feet) wide by 3m (10 feet) high perimeter zone with 70% window area to illustrate the impact by single elevation (single elevation model) and (ii) a whole building model of dimension 10m (33ft) x 10m (33ft) x 3m (10ft) with a 70% window to wall ratio to demonstrate the impact on the entire perimeter zone (figure 3) (Malekfazali, 2017). Note that in the latter case, the building model size is small enough that the entire area would be considered perimeter zone, and so the results reported here are scaleable to the perimeter zone of larger buildings rather than to the whole building EUI.

The single elevation perimeter zone model shows that on each elevation (north, south, east, west), the perimeter zone EUI is around 5 % too low with the result being pretty independent of elevation. The impact of making the COG for whole unit U-factor mistake over all four elevations of the prototypical building in Minneapolis is an underestimate in perimeter EUI of 15% and an underestimate in perimeter heating energy of 28%. This underestimation is significant for energy use at the building level, especially for buildings designed with good natural daylighting that have a high perimeter zone to core areas. It also has implications related to occupant thermal comfort. If the perimeter zone heating system has been undersized because of the incorrect U-factor inputs, thermal comfort at the perimeter will likely be negatively impacted.

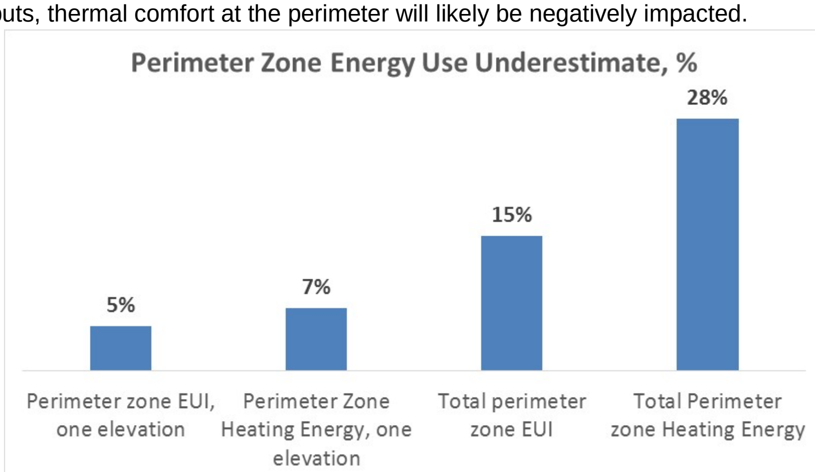


Figure 2 The percentage underestimate of perimeter zone EUI and heating energy that is caused by using the center of glass U-factor of 0.30 btu/^{o}f.hr.ft^2 (1.7 W/m^{2}K) rather than the whole window U-factor of 0.45 btu/^{o}f.hr.ft^2 (2.6 W/m^{2}K) for a prototypical building located in Minneapolis, MN. The total perimeter zone data assume a 70% window to wall ratio on all four sides of the building (see figure 3), the single elevation data also assumes a 70% window to wall ratio.

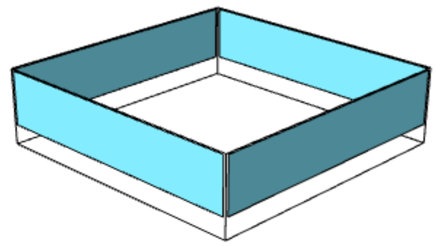


Figure 3 A schematic of the whole building model of dimension 10m (33ft) x 10m (33ft) x 3m (10ft) with a 70% window to wall ratio used to demonstrate the impact of using center of glass U-factor rather than whole window U-factor on the entire perimeter zone (Malekfazali, 2017).

The New Buildings Institute reported on the measured energy performance compared to the as-designed energy performance of LEED buildings in 2008 and showed there was a significant performance gap (NBI, 2008). The performance of what was being designed was not that measured in the as-built structures. Based on more recent articles, the "performance gap" as it is now known still remains, and the issue is present in Europe as well as North America, with many buildings reportedly not living up to their energy design performance (Conniff 2017, UK Government 2016, Cali et. al. 2016). In a recent study of building energy modelers (Imam et. al. 2017), much of blame is laid at the door of poor modeling. The use of center of glass U-factor by mistake could well be a contributor to this energy performance gap.

WHOLE WINDOW U-FACTOR: WHY THE EDGE OF THE WINDOW MATTERS

The window frame and edge of glass are key to creating a high performance window system and are the foundations of the overall window performance. Using the analogy of the flow of water in a river to the flow of heat through a window: In a river, if you dam the center to stop water flow, but you don't dam the river all the way to its edges, the water still flows around the barrier. No matter how well the dam stops the flow in the center, the water will continue to flow through until the river is fully "dammed" from edge to edge. Similarly, for the flow of heat, no matter how well you stop the flow of heat through the center of the glass, if the frame and edge of glass are not well insulating, the heat will flow through edge of the window, finding the path of least resistance.

Figure 4 illustrates how the window U-factor varies with the center of glass, frame and edge of glass (spacer) performance and demonstrates how the frame and edge of glass controls the overall U-factor performance. Changing the center of glass performance from 0.29 to 0.24 (equivalent to adding argon to a double pane low-e insulating glass unit) provides only a 5% reduction in window U-factor when installed in a non-thermally broken frame with an aluminum spacer. Yet, without making any change to the center of glass performance, the change to a high performance thermally broken frame with a warm-edge insulating glass spacer reduces the overall window U-factor by 36%. The implication is that when specifying a fenestration system, the first focus should be on improving the performance of the frame (biggest influence) and edge of glass. Having a high-performance perimeter is an enabler for achieving a high-performance window system, and it can provide greater flexibility in glass choice because the highest COG U-factor may not be needed.

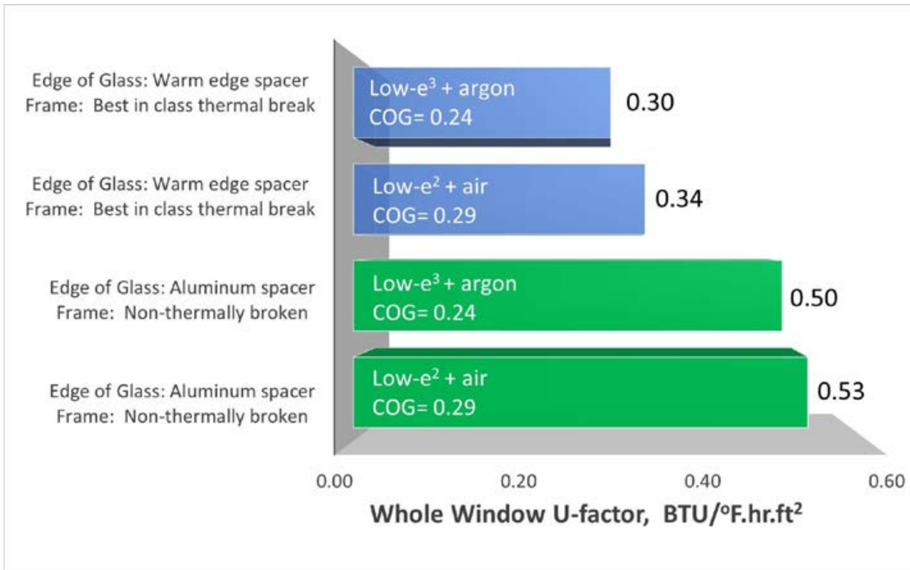


Figure 4. The variation of overall window U-factor with center of glass, frame and edge of glass performance. Calculations using NFRC window sizes and dual pane glazing infill. Calculations using THERM and NFRC standard size fixed window.

The thermal performance of the perimeter of the window also has a significant impact on it's condensation resistance (figure 5). Until the frame and edge of glass performance are very high, the center of glass has barely any impact. This is because the lowest interior surface temperatures of a window determine condensation resistance, and these are driven primarily by thermal bridging at perimeter of the window. Depending on the severity of condensation on cold interior surfaces of windows, water damage can occur to both windows and nearby walls, and can harbor mold growth that has a negative impact on indoor air quality. Since high condensation resistance does not corelate with low window U-factor, it is critical that fenestration be specified with both thermal transmittance and condensation resistance in mind, and that both are specified separately.

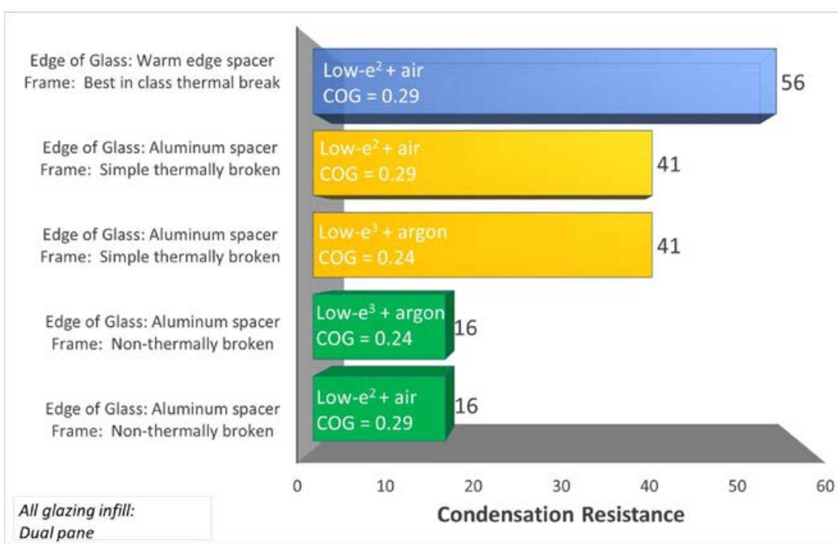


Figure 5. The condensation resistance for different window systems comparing the impact of the frame, edge of glass and center of glass performance. Calculations using THERM, NFRC window sizes and dual pane glazing infill.

Edge of Glass U-Factor: Sensitivity Analysis

The U-factor of the edge of glass depends on many factors: The effective thermal transmission of the spacer, the sealant height (figure 6a), the frame bite (figure 7a) and also the amount of desiccant, and desiccant type in the spacer. Using the European edge of glass methodology, the impact on the linear thermal transmittance (ψ) of sealant height, frame bite and desiccant type and quantity have been calculated according to DIN ISO 10077-2 and is shown in figures 6b, 7b, 8a and 8b respectively. The calculation uses an aluminum window with a glass area of 1.27m^2 and a frame area of 0.55m^2, and a plastic hybrid stainless steel warm-edge spacer.

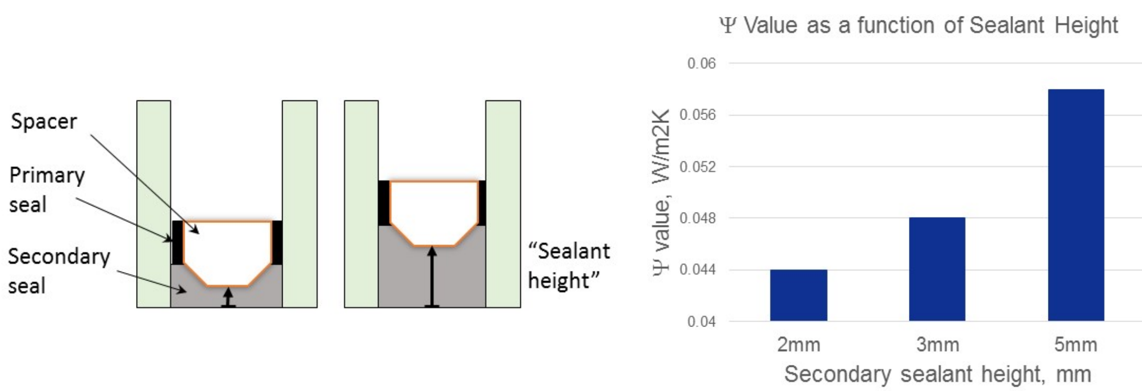


Figure 6. (a) Schematic of the edge of glass showing variable sealant heights, (b) The linear thermal transmission of the edge of glass as a function of sealant height. Frame bite is held constant at 15mm.

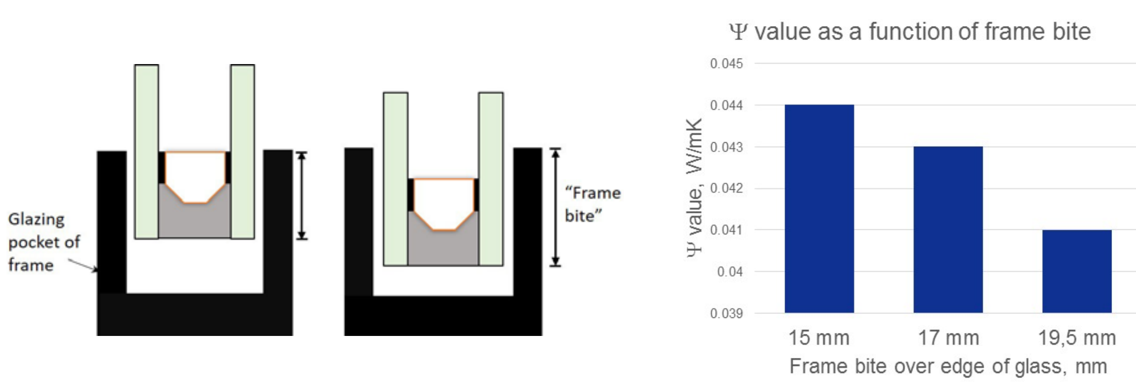


Figure 7. (a) Schematic showing different "frame bites" on the edge of glass, (b) the linear thermal transmittance of the edge of glass as a function of frame bite. Sealant height is held constant at 2mm.

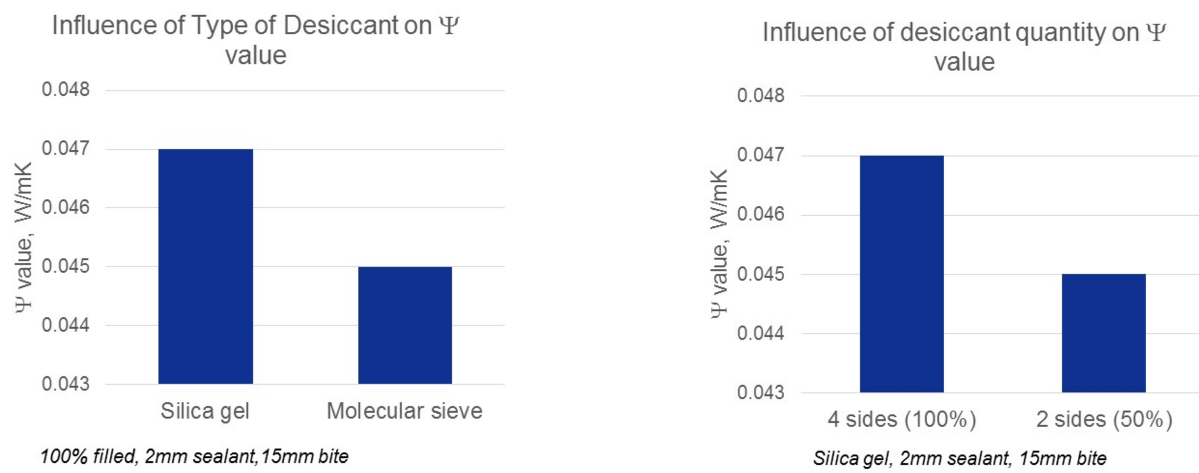


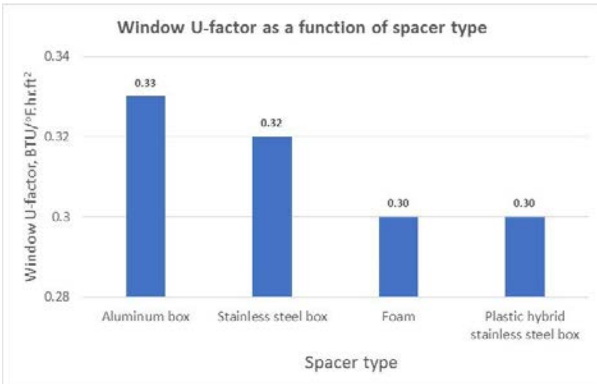
Figure 8. (a) The impact of desiccant type on the linear thermal transmittance of the edge of glass, (b) the impact of desiccant quantity on the linear thermal transmittance of the edge of glass. Sealant height 2mm and frame bite 15mm.

The linear thermal transmittance of the edge of glass is significantly impacted by the amount of sealant used (24% change from 5mm to 2mm sealant) and the bite of the frame (7% change from 15mm to 19.5mm bite), and to a lesser extent by the desiccant type and quantity. To put this into context, a sealant height change of 2mm to 5mm is enough to change the whole window U-factor by 0.05 W/m^2K (0.01 $BTU/^oF.hr.ft^2$) for a 1mx1m aluminum window with a frame width of 100mm, a center of glass U-factor (European) of 1.1 W/m^2K (0.19 $BTU/^oF.hr.ft^2$) and a frame U-factor of 1.6 W/m^2K (0.28 $BTU/^oF.hr.ft^2$). This can be enough to change a window's reported (European) U-factor (to one decimal place). The impact will be less for larger windows, with more glass to frame area. The impact will be more for smaller windows with less glass to frame area.

The implications of this result are that it is very important to compare like with like when comparing the thermal performance of edge of glass systems and components, such as spacer. When looking at comparison data it is important to confirm the same sealant height and edge bite assumptions are used. It is particularly important to model the edge of glass with the amount of sealant that is required to build an insulating glass that meets the durability requirements and any structural glazing specifications for sealant height. For example, using a 2mm sealant height would be inappropriate from a unit durability and structural perspective for most commercial applications, with more typical values being 4.5 to 6mm. In fact, in structural glazing applications, sealant heights may need to be more than 6mm to withstand high negative wind loads, especially in large units.

Impact of Spacer on the Window U-Factor

The thermal transmittance of an insulating glass spacer is determined not just by its bulk material properties, but by also by the spacer shape and material thickness which determine the path length and cross-sectional area through which the heat flows. Thin gauge metal, or the addition of plastic in combination with thin gauge metal in a spacer profile (hybrid spacer) which extends the thermal path length can significantly reduce thermal transmittance. In the case of the latter plastic-metal hybrid spacer, profiles can be created that has the same effective performance in a window system as a completely non-metal spacer made from, say, 100% plastic or foam material. Figures 9a and b show the impact of different spacer types (aluminum box, stainless steel box, foam and plastic hybrid stainless steel) on overall window U-factor and condensation resistance for an NFRC standard size thermally broken aluminum window. Sealant heights, edge bites and desiccant fill are kept constant to provide a fair comparison.



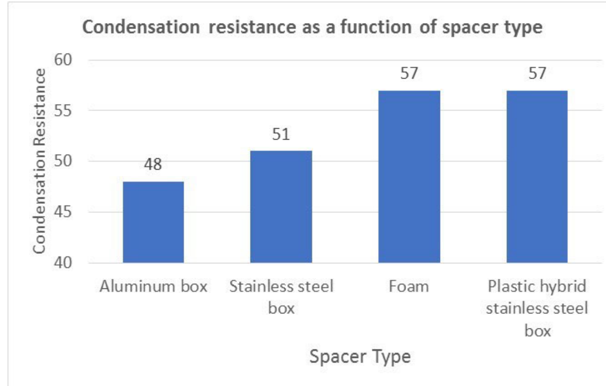


Figure 9. (a) The impact of spacer type on window U-factor (NFRC 100), (b) The impact of spacer type on Condensation Resistance (NFRC 500)

The data show that when comparing spacer, even though the thermal transmittance of foam spacer is lower than that of a plastic hybrid stainless steel spacer, this difference does not result in a meaningful difference in overall window performance when appropriate amounts of sealant are included in the edge seal, and it is integrated into a frame with the same edge bite. Additionally, although the US market often thinks of stainless steel as a "warm-edge" spacer solution, the data illustrates that the performance of standard wall thickness stainless steel (0.008", 0.2mm) is closer to that of an aluminum box spacer than it is to the higher thermally performing options of plastic hybrid stainless steel and foam.

U-FACTOR: HOT CLIMATES

It is commonly thought that window U-factor doesn't matter for buildings in hot climates and that it is the solar heat gain of the center of glass which dominates the performance. It is certainly true that solar heat gain dominates the energy performance in such climates, however, what is not commonly recognized is that the solar heat gain of the opaque elements of the window can be significant and is a function of its solar absorptance *and* its U-factor. This is because the frame absorbs solar heat from the sun, and then that heat is transmitted from the outside of the frame to the inside of the frame through conduction (and through some convection and radiation). This is where U-factor performance comes in. The U-factor measures the ability of the frame to thermally insulate the outside from the inside. In hot climates the outside of the frame is hot (primarily because of solar absorption), and so the lower the U-factor of the frame, the less transfer of that absorbed energy occurs from outside to inside. Thus, a lower solar heat gain for the frame is achieved by having a low frame U-factor, i.e. providing a well thermally broken frame. The same rationale can be made for improving the thermal performance of the edge of glass, although the impact of thermally breaking the frame is more significant. Equation 3 provides the relationship between frame solar heat gain coefficient, and its U-factor (SERIS 2014).

$$SHGC(frame) = \propto f \, \frac{Uf}{h(Afw/Af)} \qquad (3)$$

Where:
SHGC (frame) = solar heat gain coefficient of the frame
α f = the solar absorptance of the outer surface of the frame
Uf = the U-factor of the frame
Afw = the total (wetted) surface area of the outside of the frame
Af = the projected frame area
h = the external surface heat transfer coefficient of the frame

By way of example, equations (2) and (3) have been used to calculate the overall U-factors and frame solar heat gain coefficients for two windows, one with a non-thermally broken and one with a thermally broken aluminum frame. The glazing infill for both is a dual pane insulating glass unit with low-e coating and an aluminum spacer. The overall window solar heat gain coefficients are also calculated using an area weighted average of frame and center of glass. The data for the window system and the resulting window performance calculations are shown in table 2 below. In this scenario introducing a thermal break into an aluminum frame can reduce the solar heat gain coefficient of the frame by 65% and the solar heat gain coefficient of the whole window by 13%.

Table 2. Calculating the impact of thermally broken frames on overall solar heat gain coefficient of a window

Window System	Non-thermally broken Aluminum frame	Thermally broken insulated aluminum frame
Frame area (Af)	0.5m^2	
Glass area (Ag)	1.5m^2	
Fenestration projected area (A)	2.0 m^2	
Perimeter glass dimension, ig	4.5 m	
Frame to window ratio (Af/A)	25%	
Ratio of wetted surface area to projected frame area	1.2	
Frame external solar absorptance (αf)	0.7	
External frame surface heat transfer coefficient, h	18 W/m^{2}K	
Center of glass U-factor (Ucog)	1.6 W/m^{2}K	
Center of glass Solar Heat Gain Coefficient	0.35	
Linear thermal transmittance of edge of glass (Ψg)	0.05 W/mK	0.11 W/mK
U-factor of frame (Uf)	7 W/m^{2}K	2.5 W/m^{2}K
SHGC of frame	**0.23**	**0.08**
U-factor of window (U)	**3.1** W/m^{2}K	**2.1** W/m^{2}K
SHGC of window	**0.32**	**0.28**

Figure 10 shows an air conditioned testbed used by the Solar Energy Research Institute of Singapore to measure window frame temperatures when exposed to a hot climate (SERIS 2014). Four different window frame systems each in two colors (light and dark) were installed and fully instrumented for frequent temperature measurement. The four frame systems were (i) a non thermally broken aluminum frame (frame U-factor = 7 W/m^{2}K), (ii) a frame with low performance thermal break (frame U-factor = 3-4 W/m^{2}K), (iii) a frame with a medium performance thermal break (frame U-factor = 2.5 W/m^{2}K) and (iv) a frame with a high performance thermal break (frame U-factor = 1-2 W/m^{2}K).

Figure 11 shows the maximum interior (room side) frame surface temperature on a typical day for the light colored frames. The conicident exterior solar irradiation was 690 W/m^2, the outside air temperature was 99^{o}F (37^{o}C), and the interior room temperature was 75^{o}F (24^{o}C). Because of the lower solar absorption compared to darker, more absorbing frames, this represents a best case in terms of exterior and interior temperatures. The data clearly shows how well thermal break technology reduces the transfer of heat from outside to inside; the better the thermal performance of the frame, the lower the interior temperature. The maximum interior temperature of the system with the high performance thermal break is 23^{o}F (13^{o}C) lower than that of the non-thermally broken aluminum frame which is typically installed in these types of hot climates. For the worst case dark colored frames, and the interior room side temperature of the non-thermally broken frame reached a high of 127^{o}F (53^{o}C) on a typical representative day, whereas the interior temperature of the high performing thermally broken frame was over 27^{o}F (15.5^{o}C) lower on that same day (SERIS 2014).

Figure 10. a) Site of the test installation used to obtain the physical temperature measurements of window frame temperature during natural weather exposure in Singapore. b) The outdoor view of the completed frame installation. The window opening was replaced with mulitple frame samples so all frame samples were exposed together. Key: 1. Light color non-thermally broken frame, 2. Dark color non-thermally broken frame, 3. Light color, low performance thermally broken frame, 4. Dark color, low performance thermally broken frame, 5. Light color medium performing thermally broken frame, 6. Dark color, medium performing thermally broken frame, 7. Light color, high performance thermally broken frame, 8. Dark color, high performance thermally broken frame (SERIS 2014).

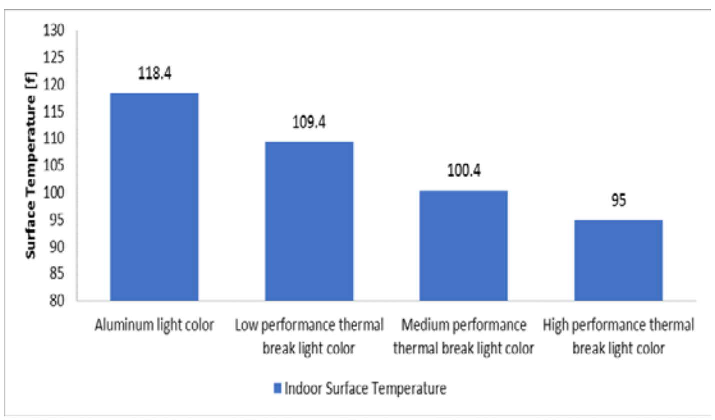


Figure 11. A graph showing the maximum measured room side surface temperature of four different window frames during a typical day. The four different window systems are as follows (i) aluminum with no thermal break (ii) aluminum with low performance thermal break, (iii) aluminum with medium performance thermal break and (iv) aluminum with high performance thermal break. At the time of measurement, the outside air temperature was 99^{o}F (37^{o}C), the indoor air temperature was (75^{o}F) 24^{o}C, and the solar irradiance was 690 W/m^{2}.

THERMAL COMFORT

Not only can poor performing windows waste energy and cause condensation, sitting next to poor performing windows can be uncomfortable for building occupants. Thermal discomfort can be caused when an occupant sits next to a surface that has a temperature markedly different from their skin temperature. When there is a temperature difference, there is radiative heat transfer from the hotter surface to the colder surface. The larger the temperature difference, the more heat transfer there is, and the more discomfort the occupant feels. Therefore discomfort issues can be caused whether the window surfaces are hot (because of solar absorption by opaque elements and resultant conduction to the inside), or they are cold (because of conductance of heat from inside to outside in winter). In the former case, heat is transferred to the occupant, who then starts to feel hot. In the example shown in figure 10 of windows in a hot climate, an occupant sitting next to the non-thermally broken frame (interior surface at 118^{o}F) will feel much more uncomfortable than if they were sitting next to a very well thermally broken frame (interior surface at 95^{o}F).

In the winter, cold climate case, heat is transferred from the occupant to the window and so the occupant feels cold. In addition, because cold air falls and warm air rises, convection currents can be set up near cold windows which adds an uncomfortable cold draft on top of the discomfort already experienced from the radiative heat transfer.

One might think that decreasing the frame area is an appropriate design strategy to relieve thermal discomfort from the opaque elements and decrease overall U-factor, but the window perimeter cannot be considered in isolation. Discomfort from direct solar radiation impingement through the glass itself is also a significant factor that also needs to be considered. In any climate zone, choosing a frame and edge of glass with high thermal performance, selecting an appropriate glass performance that considers both U-factor and solar heat gain, and balancing the window area, are all design requirements to achieving a high performance building envelope.

ASHRAE Standard 55 lays out a method for determining thermal comfort based on a number of factors including radiant temperature of adjacent surfaces and direct solar heat gain through windows and there is literature regarding how to model the window downdraft effect. The Center for the Built Environment (CBE) have developed software to assess comfort based on ASHRAE 55 and compliance with this standard is required to achieve the Thermal Comfort Credit in USGBC's LEEDv4.

CONCLUSION

From cold climates to hot climates, the perimeter of the window matters tremendously to energy performance, to condensation control, to solar heat gain and to occupant thermal comfort in buildings. There has been such a focus on the center of glass that the impact of the frame and the edge of the glass on the whole window performance can often be forgotten. It is not the desire of the authors to persuade the reader to forget about the center of glass completely, but to increase the awareness of the significant impact that the perimeter of the window has on overall window performance. When specifying fenestration, by making the thermal performance of the frame and edge of glass a primary focus for improving the whole window, improvements in other aspects of performance such as condensation resistance and thermal comfort will also result. In addition, it will also provide more design freedom with the choice of glazing in-fill. Improving the edge of glass and frame may, for example, mean that argon filling the glazing will not be needed to meet U-factor requirements. Improving the façade to deliver improved thermal comfort in close proximity also allows the "no-go" thermally uncomfortable areas which are often present around the perimeter of a building to be reclaimed for regular occupancy, allowing improved floor area utilization and flexibility. Reducing chiller and heating system size and achieving a better balance of HVAC zones between perimeter and core can also be achieved.

The data described herein serves to create a more balanced view of how to achieve optimum performance (thermal, condensation, comfort, solar heat gain) through appropriate specification of the components of a window. The key take-aways are:

1. **Meeting new model energy code**: A more hollistic view of window specification is needed to meet the new model code requirements for U-factor. Frames with thermal break technology and dual pane low-e are a must, plus additions of warm edge spacer, higher performance thermal breaks, room side low-e or argon fill, or even triple pane glazing, depending on the climate zone.
2. **Don't confuse COG with whole U-factor**: Take care to use the whole window U-factor for code compliance and energy modeling to avoid significant variances in building energy estimates.
3. **Focus on the Window Perimeter First**: Having a high performance perimeter is an enabler for achieving a high performance fenestration system – for U-factor, resistance to condensation and thermal comfort – and can provide a greater flexibility in glass choice.
4. **Condensation Resistance:** Condensation resistance is not correlated to U-factor and should be specified separately to window U-factor. Improving the the thermal performance of the frame and edge of glass has the greatest impact on improving condensation resistance, as compared to the center of glass.
5. **Edge of Glass:** The edge of glass thermal performance is influenced strongly by sealant quantity and frame bite, as well as spacer effective conductivity. When comparing edge systems, ensure that sealant height and edge bite are the same. Non-metallic spacer (e.g. foam and plastic) and plastic hybrid spacer produce the same 0.02-0.30 btu/^{o}f.hr.ft^2 reduction in overall window U-factor given the same frame bite and sealant height. In contrast, stainless steel spacer results in a significanly lower reduction of 0.01 btu/ ^{o}f.hr.ft^2.
6. **Frame and edge of glass U-factor matters even in hot climates**: The solar heat gain coefficient of the frame is proportional to it's U-factor. Creating a thermal break at the edge of the window prevents absorbed

solar radiation from being conducted to the inside.

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