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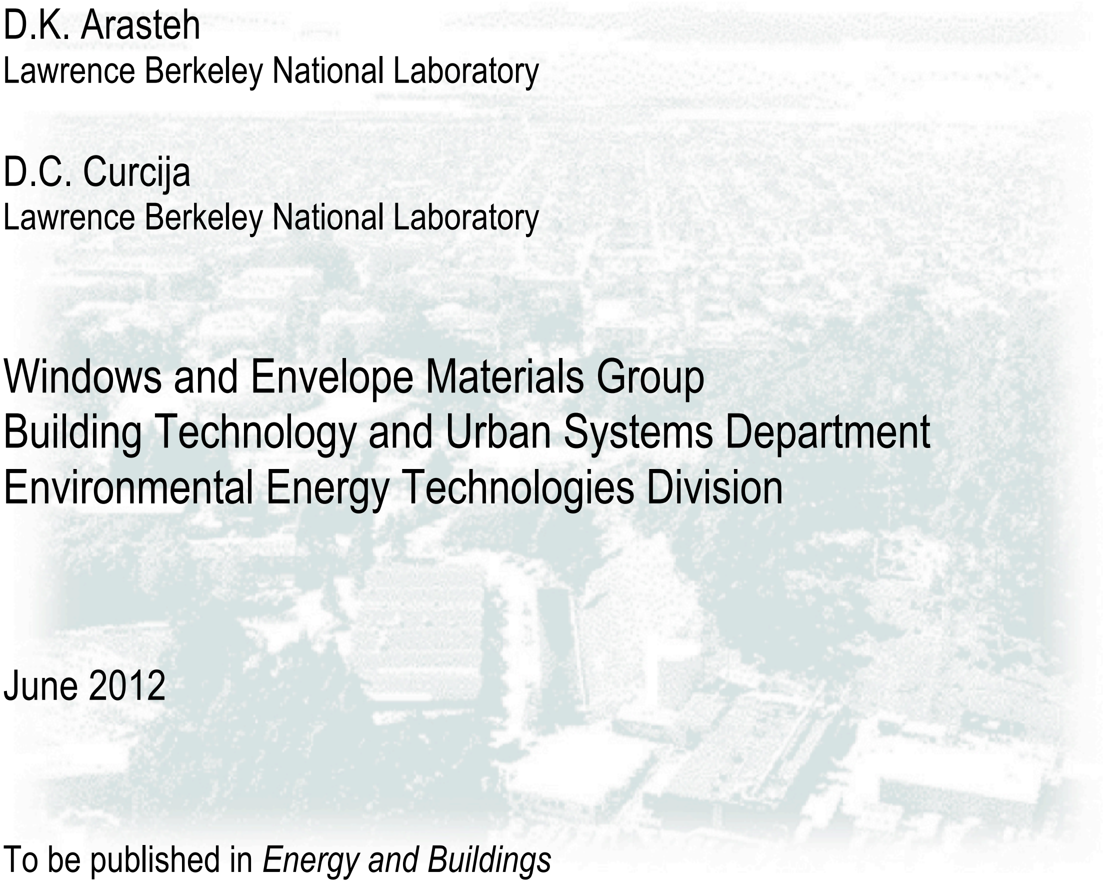

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Thermal Performance Impacts of Center-of-Glass Deflections in Installed Insulating Glazing Units

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Abstract

This study examines the thermal performance impact of center-of-glass (COG) deflections in double- and triple-pane insulating glass units (IGUs) installed at several locations throughout the US. Deflection was measured during summer and winter temperatures; the results show that outdoor temperature variations can be represented a linear change in COG gap width in double- and triple-pane IGUs within the temperature ranges measured. However, the summer-winter temperature-induced deflection is similar in magnitude to the observed spread in COG deflection of similar units at the same temperature, which suggests that factors other than temperature are of equal importance in determining the in-situ deflection of windows. The effect of deflection on thermal performance depends on the IGU's designed gap. Units constructed with smaller-than-optimal gaps often exhibit significant U-factor change due to temperature-induced reduction in gap width. This effect is particularly problematic in high-performance triple glazing where small gap dimension changes can have a large impact on performance.

Key words: Insulating glass unit; U-factor; thermal transmittance; thermal performance; deflection; concave; convex; gap; field test

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1. Introduction

Highly insulating windows have the potential to provide net energy gain to buildings in cold climates, which could save two quads of heating energy use in the U.S [1]. Whether those savings can be achieved in practice depends on actually achieving the designed insulating performance in installed units under normal operating conditions.

Variations between the designed and actual insulating performance of windows can be attributed to many factors. The effects of material properties, such as spacer and frame conductivities, on insulating performance are considered by Gustavsen et al. [2]. However, the largest and therefore usually the most thermally significant area of typical insulating glass units (IGUs) is the center-of-glass (COG). This study examines the thermal performance impact of COG deflections in installed double-and triple-pane units at several locations in the US.

COG deflection, i.e., the difference in gas space width at the COG compared to the edge-of-glass (EOG), as illustrated in Figure 1, can result from several factors; initial manufacturing conditions that establish a bias toward either concave or convex deflection depending on the relative

Abbreviations:
ST: standard *DEV: deviation* *DT: temperature difference*

elevation or atmospheric pressure at the manufacturing facility compared to at that installation location; gas fill temperature offset experienced during fabrication compared to average gas temperature during typical use; dissimilar diffusion rates of gases into or out of gas-filled IGUs over time; and transient natural environmental conditions including temperature, pressure, and wind load, which might induce temporary, reversible deflection.

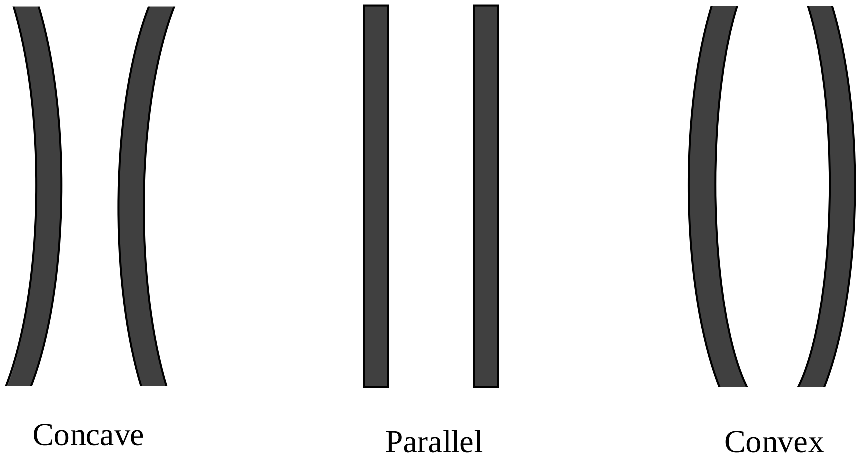

Figure 1. Types of deflection in a double-pane IGU

An industry standard addresses the initial COG deflection of a unit while it is still in the manufacturing facility where it was produced [3], but there are currently no requirements or guidelines on acceptable deflection of installed IGUs. Insulating performance of windows in the U.S. is simulated and validated using the procedures outlined in National Fenestration Council (NFRC) technical documents 100 and 102, respectively. For highly insulating windows, in this paper defined as windows with thermal performance better than U=1.7 watts per square meter per kelvin (W/m^2K), an acceptable validation test per NFRC 100 can vary by up to 0.17 W/m^2K from the simulations. On the most insulating products currently certified (0.51 W/m^2K), this translates to a 33 percent allowable variation. Therefore, validation testing of highly insulating windows might not recognize potential cold temperature thermal degradation.

Previous key investigations of glass deflection have focused on deflection of double-pane IGUs as part of structural-mechanical research, including linear [4] and non-linear [5] plate models. To date, the most notable research extending the analysis of glass plate curvature or deflection to the impacts on IGU thermal performance is by Bernier [6], who calculated gas space thickness reductions of up to 7.3 percent for American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE) type winter conditions (-18°C). He correlated this reduction to a 5.8-percent drop in U-factor for a triple-pane IGU.

Along with reduced insulating performance, COG deflection can concentrate solar energy reflected off the glass surface. These solar reflections have reportedly caused permanent distortion on vinyl siding and damage to other objects in the reflection path [7]. Understanding the extent of deflection in installed units under normal conditions is essential for understanding reflected radiation as well.

2. Procedure

For field measurements, we selected windows installed in several locations throughout the country based on outreach to sites with window types relevant to the testing effort – i.e., both minimum-code-compliant products and higher-performance units - and where the testing would have minimal impact on residents. As a result of reliance on these criteria, the tested windows do not represent statistically average U.S. windows. All windows tested were verified as NFRC-certified units and were no more than three years old at the time of testing.

The team measured IGUs at cold outdoor temperatures at each of the four sites (A-D) in winter (January – March 2011) and warm outdoor temperatures in June 2011 for all sites except A, which was not available in summer. Table 1 briefly describes the four sites, their associated window groups, and the measurements taken.

Table 1. Test site details and associated window groups tested

Site A	Windows	▪ Group A-1: 93 single sliders, 2-pane, 90% Argon gas fill; Typical Size: 845 x 1290 mm ▪ Group A-2: 92 fixed, 2-pane, 90% Argon gas fill; Typical Size: 830 x 380 mm ▪ Vinyl window frames
	Building type	Hotel, conditioned but unoccupied for winter shutdown
	Measurements	Winter only because no equivalent warm-weather shutdown available
Site B	Windows	▪ Group B-1: 70 casements, 2-pane, 90% Argon gas fill; Typical size: 1495 x 760 mm ▪ Group B-2: 32 fixed, 2-pane, 90% Argon gas fill; Typical size: 760 x 355 mm ▪ Group B-3: 30 casements, 3-pane, 90% Krypton gas fill; Typical size: 760 x 1495 mm ▪ Group B-4: 30 casements, 3-pane, 90% Argon gas fill; Typical size: 760 x 1495 mm ▪ Vinyl and aluminum-clad wood window frames
	Building type	Single family homes, conditioned but unoccupied
	Measurements	Winter and summer
Site C	Windows	▪ Group C-1: 48 double hung, 2-pane, 90% Argon gas fill; Typical size: 775 x 1320 mm ▪ Group C-2: 82 double hung, 3-pane, 90% Krypton gas fill; Typical size: 775 x 1320 mm ▪ Vinyl window frames
	Building type	Duplexes, conditioned but unoccupied
	Measurements	Winter and summer
Site D	Windows	▪ Group D-1: 424 double hung, 2-pane, 90% Argon gas fill; Typical size: 850 x 1770 mm ▪ Vinyl window frames
	Building type	Single family homes, conditioned but unoccupied
	Measurements	Winter and summer

There are multiple methods for measuring glass deflection. Handheld laser-pointer-based tools, such as the EDTM model MG1500 and Sparklike Spyglass used for this study, are quick, convenient, and accurate. These devices measure distance using a laser pointer held at a fixed angle, which projects a series of bright reflections that are either read by the operator directly against a measurement scale (EDTM) or collected by an array detector, analyzed, and reported by the device (Sparklike). We used this equipment to measure glass thickness, gap width, and to detect low-emissivity coatings. The width of the tools prevents measurements at the true EOG. Therefore, with the EDTM MG1500 detector, measurements were taken 32.7 or 90 millimeters (mm) from the EOG, depending on orientation; with the Spyglass detector, measurements were taken at 40mm from the EOG. Figure 2 illustrates how the laser reflection measurement devices work.

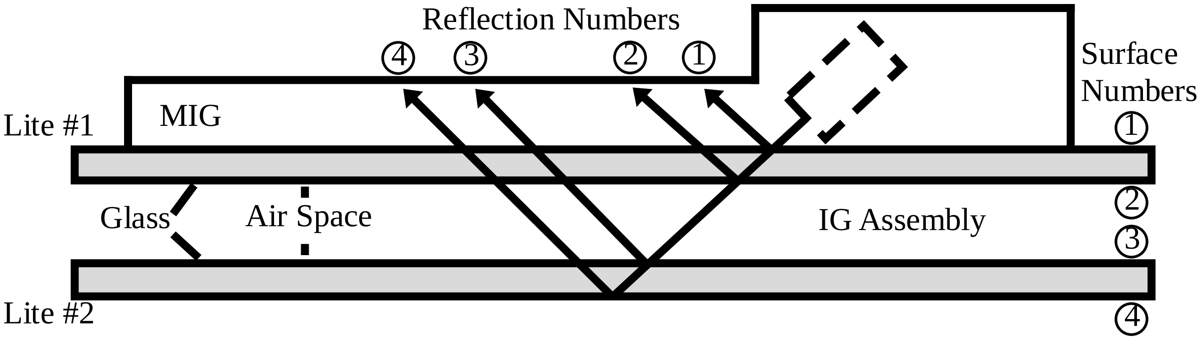

Figure 2. Illustration of EDTM laser reflection measurement device used in this study

We began by surface mapping IGU gaps on the interior glass surface of a limited number of double-pane units from Site A to explore the shape of the entire surface of a deflected IGU. For this purpose, we used the EDTM MG1500 to record the gas gap width for each point on a 50.8 mm –interval-grid over the entire glass surface.

We measured temperature at the COG and EOG of each test unit. Temperature measurements were taken either using thermocouples taped directly to the glass surface or using a non-contact infrared (IR) thermometer device adjusted for a glass surface emissivity of 0.86. The two measurement methods produced similar results and were therefore used interchangeably as needed. The contact thermocouples needed to stabilize before recording temperature, so they were slower than the IR spot measurement device. Therefore, non-contact IR spot measurements were preferred when a large number of field measurements of surface temperature had to be made at one time.

Indoor room air temperature measurements were made using a handheld thermocouple with readings recorded manually or using a small portable temperature data-logger (Onset Hobo U12-011) that recorded automated time stamped recordings. In either case, the temperatures were taken approximately 1.2 meters above the floor, out of direct sun, and in the center of the room where the test IGU was located. Outdoor temperatures were recorded with a portable data-logger that was placed at a single location per test site, out of direct sun and near one of the homes where test units were located.

Additional data recorded for each IGU were: gas fill percentage, internal/external grid locations, spacer type, presence of a screen, sun exposure, proximity to air distribution grilles, and glass treatment (tempered or annealed). These data were not the focus of the study, and the analysis did not attempt to determine the effect of these factors on performance. They were used only to filter out dissimilar units when grouping the units for analysis.

Local atmospheric pressure variations were not measured during testing, but historical weather data from the nearest weather stations show no more than 10.2 millibar variation in any day, or between winter and summer measurements at any location. This translates to a pressure effect equal to approximately 3.3°C. Table 2 summarizes the primary measurements performed on each IGU.

Table 2. Summary of measurements performed on each IGU

Measurement	**Description**
Size and shape	Length and width of the window and IGU were measured to the nearest 5mm.
Glass thickness	Thickness of each glass pane in the IGU was measured to nearest 0.1mm.
EOG gap width	The distance between glass panes was measured on the interior glass pane to the nearest 0.1mm. The location of the edge measurement varied along the perimeter of the IGU. Often, the measurement recorded was the average of 2 to 4 measurements around the perimeter of the unit.
COG gap width	The distance between each pane of glass was measured at the center of the interior glass pane to the nearest 0.1mm. Both gaps of a triple-pane window were recorded together from the interior for most products, but some were measured from both the interior and exterior side of the window when the equipment could not accurately detect the gap because of the configuration of coatings or presence of a thin suspended-film center layer.
Gas fill percentage	The concentration of noble gas fill was measured, where applicable, to the nearest 1.0%.
EOG temperature	Temperature was measured to the nearest 0.1°C on the interior glass surface approximately 25mm from the lower right or left corner of the IGU. Both taped-on contact thermocouples and non-contact IR spot devices were used.
COG temperature	Temperature was measured to the nearest 0.1°C on the interior glass surface at the center of the IGU. Both taped-on contact thermocouples and non-contact IR spot devices were used.

3. Analysis and Results

3.1. Surface mapping

The COG gaps of selected units from Site A were mapped as previously noted. Figure 3 shows the deflection shapes of these six fixed- and movable-sash IGUs, four of which measured 1220 mm x 815 mm and two of which measured 455 mm x 815 mm. Maximum deflection occurs at or near the center of all units, and, in general, the deflection shapes follow a similar pattern regardless of the degree deflected, frame configuration, or unit size. Based on these results, we took the COG spot measurements at the center of the interior glazing surface for all remaining units. This is assumed to be the point of maximum deflection.

In all the mapped units, there is a trend of greater deflection at the EOG along the greatest unit dimension. The bias of greater deflection on the left side seen in most units was introduced by our measurement method and the laser alignment of our equipment. Based on the deflection shapes, we made the remaining EOG spot measurements with the plane of the laser parallel to the frame. The recorded measurement was an average of measurements taken at 2 to 4 locations around the perimeter of the unit, to account for variations along the perimeter.

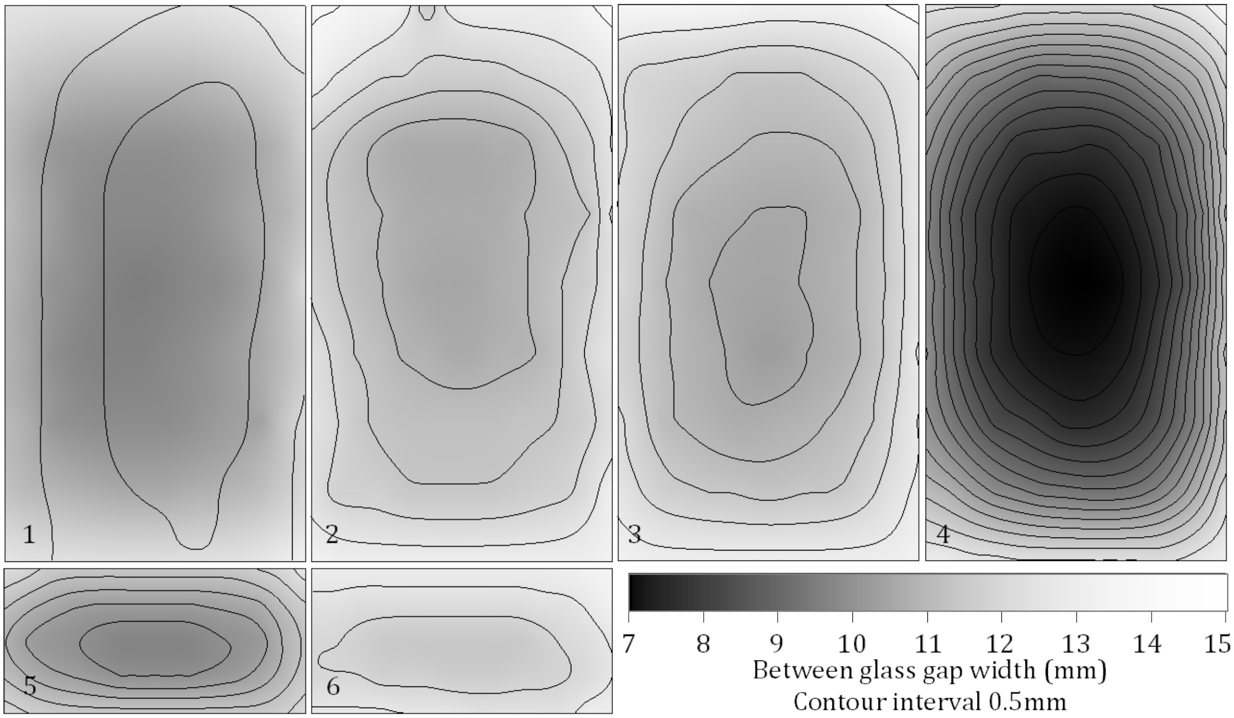

Figure 3. Surface maps of selected units from Groups A-1 and A-2, showing general deflection shapes

3.2. Total deflection

Figures 4a and 4b show COG deflection for the 1807 total measurements made in this study. The data shown represent all measured windows and include instances of failed IGUs and units in direct sun. Units from Site A were measured in winter only, and one house from Site D was measured in summer only, as indicated in the figures. The difference between the mean winter deflection and mean summer deflections was 0.80 mm. The mean deflection for the measurements is different from the mean absolute value deflection since there are both positive and negative deflections. This explains the small mean deflection with a large standard deviation in the summer measurements. The average indoor temperature rose by 4.8°C from winter to summer; the average outdoor temperature difference was much greater, 21°C from winter to summer. Table 3 summarizes measured deflection and environmental temperatures.

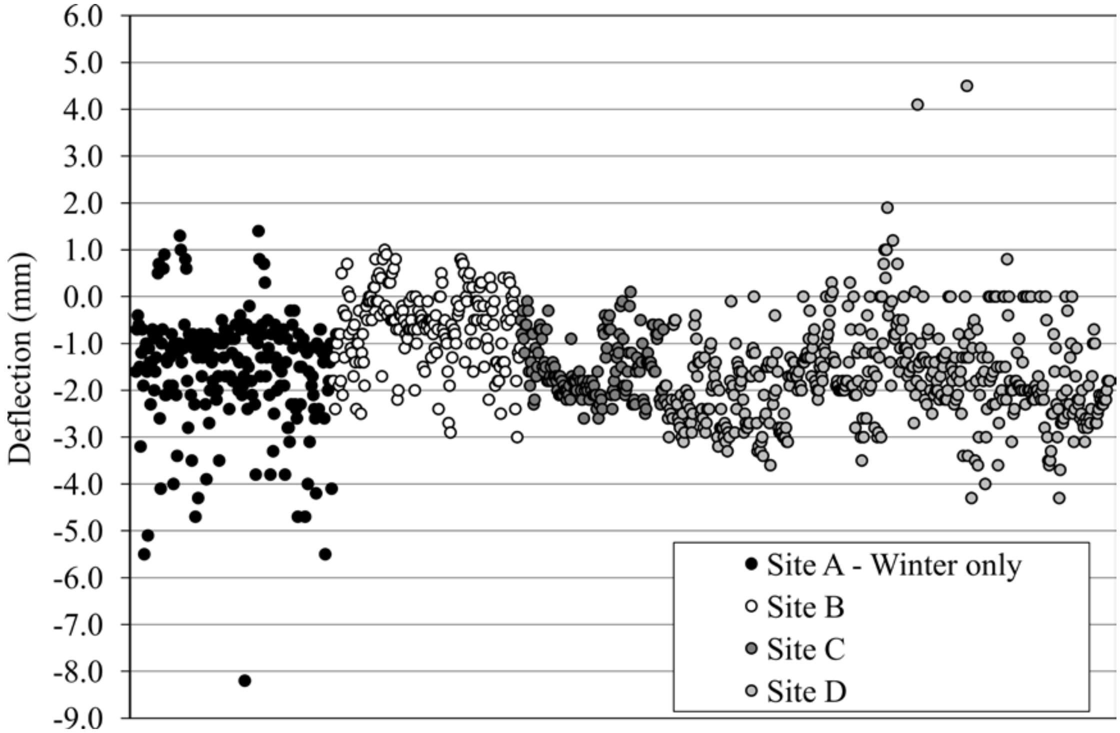

Figure 4a. Winter COG deflection measurements. Positive deflection is convex; negative deflection is concave

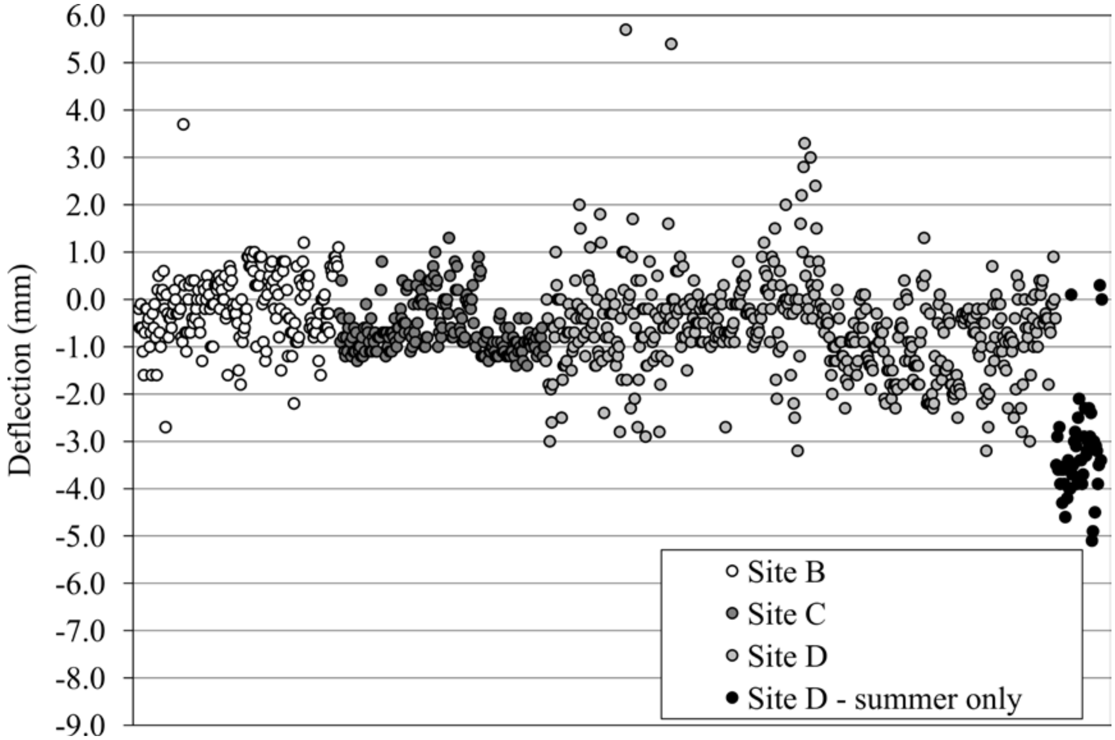

Figure 4b. Summer COG deflection measurements. Positive deflection is convex; negative deflection is concave

Table 3. Deflection and temperature summary

	Deflection				**Outdoor Temperature**			**Indoor Temperature**		
	Mean (mm)	**St. Dev. (mm)**	**Min (mm)**	**Max (mm)**	**Mean (°C)**	**Min (°C)**	**Max (°C)**	**Mean (°C)**	**Min (°C)**	**Max (°C)**
Winter	-1.43	1.09	-8.2	4.5	5.3	-3.3	16.4	19.2	13.0	29.0
Summer	-0.63	1.13	-5.1	5.7	26.3	20.1	30.0	24.0	20.6	27.7

3.3. Deflection correlations

The first step in analyzing the tested units was filtering to remove as much dissimilarity from the direct winter-to-summer measurement comparisons as possible. Units were grouped by site and type to account for specific sizes, aspect ratios, frames, spacers, and installations. Units were removed from the direct comparison if they had been measured when in direct sun or had recently been in direct sun; had inert gas fill of less than 80 percent; or showed significant size variation, different glass thickness or heat treatment process, or direct coverage by active air vents. Based on these criteria, we eliminated approximately 30 percent of the tested units from the final trend analysis.

All units that are directly compared in this study were designed to have identical COG and EOG gaps from the factory. Because of relatively large variations in EOG measurements (up to 1mm in individual units), we evaluated individual units based on COG gap measurements. Deflection data used for temperature trend and U-factor analyses in the remainder of this paper are calculated based on average COG and EOG measurements for each group’s units, to eliminate the bias of individual unit variances. Each unit group had unique test conditions and associated responses to external conditions. However, the trends are consistent for each group. Therefore, the analyses presented in this report are representative of the trends for all groups even when we focus on only one group. The final analyses results for each group of units are presented in Tables 4, 5, and 6.

There is a strong trend toward greater COG gap width when outdoor temperatures are higher. As shown in Figure 5 with indoor-outdoor temperature difference, this trend is uniform among units within a group subjected to the same environmental conditions. The magnitude of total gap change typically (but not always) varied for different sites, unit configurations, and measured outdoor temperature range, but the trend shown in Figure 5 is representative of windows analyzed at all sites. The deflection of ~1.5 mm induced by winter-summer temperature difference, shown in Figure 5, is of similar magnitude to the observed spread of deflection among similar units in either winter or summer (i.e. all exposed to the same or similar temperatures), ~2mm. This consistent trend in the data for windows from all groups, which represent several different manufacturers and installation locations, suggests that other factors are of equal importance to temperature in determining in-situ deflection of windows.

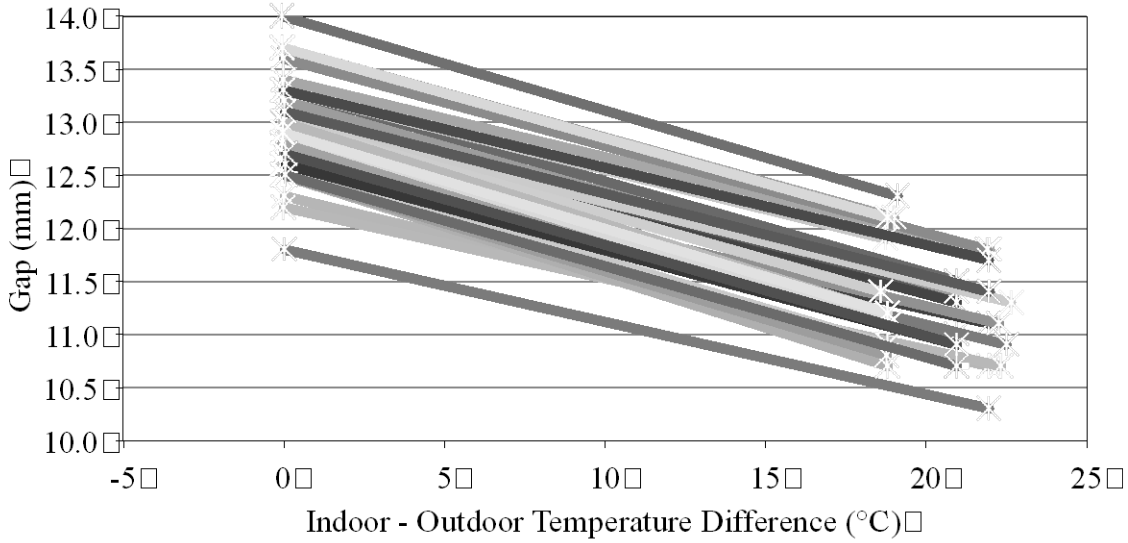

Figure 5. COG gap response to indoor-outdoor temperature difference in a selection of IGUs from Group D-1

The frequency distribution of the spread of gap widths approximately follows a normal distribution model, as shown in Figure 6. The window samples in our data set are a subset of a much larger population (random effect) and consist of paired winter and summer gap measurements. We used the REstricted or REsidual Maximum Likelihood (REML) Method for fitting mixed models in JMP Version 8 for the statistical analysis, with individual windows as a random nominal variable and the indoor-outdoor temperature difference as an independent linear variable. The slopes of gap size versus indoor-outdoor temperature difference, and intercepts, for each window group are reported in Table 4, along with the standard errors (SE). The coefficient of determination (R^2) provides a measure for how well the fit represents the measured data, with a value of 1 being a perfect fit. The t-test, and the resulting P-value, determines if the measured differences between paired winter and summer measurements are statistically significant. Values less than 0.05 are considered significant results for this study. The indoor-outdoor temperature range for each data set is the presumed range of validity for each fit, and is based on the typical measured indoor and outdoor temperatures presented in Table 3.

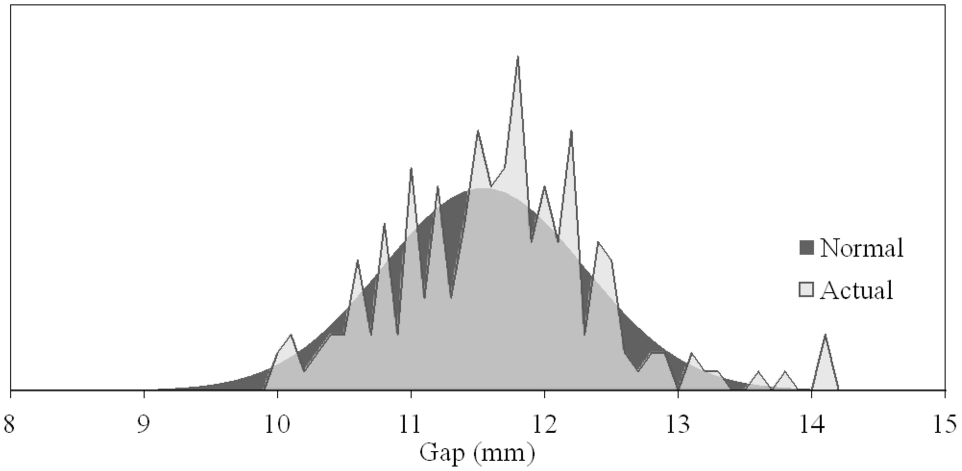

Figure 6. Distribution of Group D-1 winter COG gap overlaying a normal distribution

Table 4. Calculated linear fits for measured winter to summer gap widths

Site-Group			Slope (mm)		Intercept (mm)		R^2	P-value	DT Range (°C)	
			Mean	SE	Mean	SE			Min	Max
2-Pane										
B-1		**COG**	-0.070	0.004	9.757	0.178	0.986	<0.0001	-3.9	17.0
		EOG	-0.015	0.003	9.824	0.059	0.910	<0.0001		
B-2		**COG**	-0.075	0.003	11.769	0.111	0.984	<0.0001	-3.3	17.0
		EOG	-0.025	0.005	11.620	0.081	0.878	<0.0001		
C-1		**COG**	-0.095	0.004	12.656	0.039	0.915	<0.0001	-3.2	17.5
		EOG	-0.030	0.002	13.818	0.020	0.834	<0.0001		
D-1		**COG**	-0.070	0.001	12.982	0.055	0.983	<0.0001	-6.0	27.3
		EOG	-0.015	0.001	13.943	0.015	0.864	<0.0001		
3-Pane			**I: Interior Gap E: Exterior Gap T: Total Unit**							
B-3	**I**	**COG**	-0.001	0.005	7.945	0.049	0.273	0.8800	-2.4	19.2
		EOG	-0.002	0.002	8.017	0.021	0.368	0.4825		
	E	**COG**	-0.052	0.005	7.768	0.064	0.877	<0.0001		
		EOG	-0.026	0.005	8.016	0.048	0.553	<0.0001		
	T	**COG**	-0.051	0.008	15.707	0.091	0.742	<0.0001		
		EOG	-0.027	0.006	16.033	0.064	0.559	0.0002		
B-4	**I**	**COG**	-0.029	0.009	7.644	0.246	0.965	0.0200	-3.5	7.4
		EOG	-0.006	0.005	7.643	0.015	0.855	0.2202		
	E	**COG**	-0.281	0.008	8.016	0.243	0.995	<0.0001		
		EOG	-0.219	0.008	8.555	0.079	0.989	<0.0001		
	T	**COG**	-0.310	0.016	15.660	0.223	0.981	<0.0001		
		EOG	-0.225	0.009	16.198	0.073	0.983	<0.0001		
C-2	**I**	**COG**	-0.022	0.003	6.015	0.071	0.881	<0.0001	-6.2	21.5
		EOG	-0.006	0.001	6.216	0.030	0.924	<0.0001		
	E	**COG**	-0.045	0.001	5.486	0.058	0.988	<0.0001		
		EOG	-0.014	0.001	6.001	0.029	0.969	<0.0001		
	T	**COG**	-0.067	0.003	11.501	0.117	0.961	<0.0001		
		EOG	-0.020	0.001	12.218	0.056	0.967	<0.0001		

Figure 7 shows the COG and EOG gap responses to changes in the indoor-outdoor temperature difference for double-pane units in Group D-1, with the mean and 95% confidence interval of the mean fit lines from Table 4. As expected, the EOG gap remains relatively constant with temperature, with only a small increase in width as temperature rises. This increase can be attributed primarily to thermal expansion of the spacer system and a deviation in the measured gap resulting from the limitation of having to measure gap thickness several centimeters from the EOG, which means that a fraction of COG deflection might be included in the measurement.

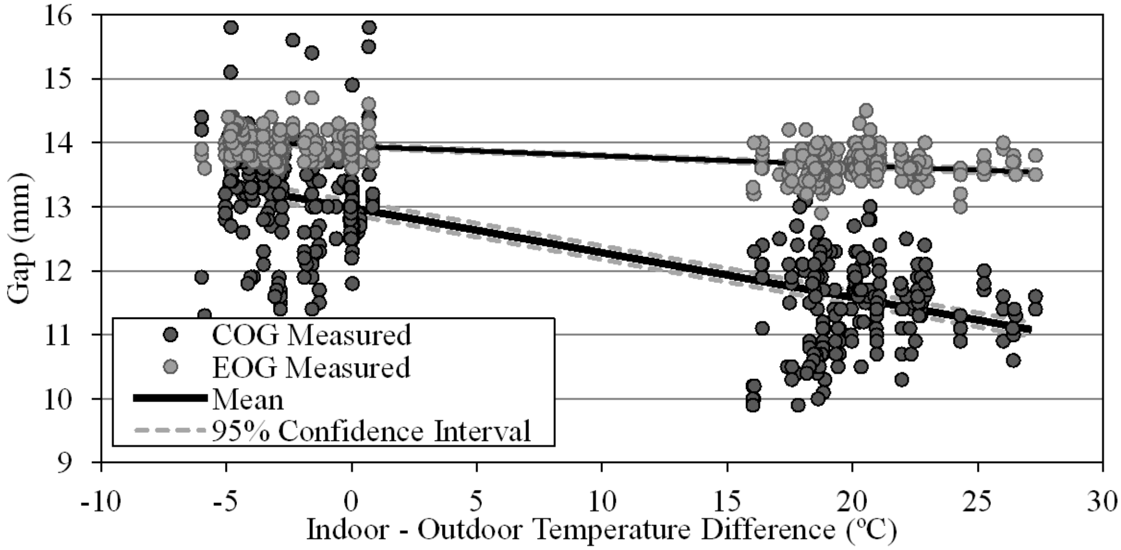

Figure 7. Group D-1 double-pane COG and EOG gap trends with indoor-outdoor temperature difference

In typical insulating glass construction, triple-pane units have two adjacent sealed and isolated gas chambers. It is expected that the outside-facing (exterior) chamber will be exposed to wider swings in average gas fill temperature because that chamber is closer to the extreme temperature conditions of the exterior environment. As a result, the exterior COG gap is expected to experience larger changes than the interior COG gap. Our typical triple-pane window measurements were consistent with this expectation, while in one of the three triple pane units tested the variation in COG interior gap was determined to be statistically insignificant.

Triple-pane windows with a thin suspended center film layer have a small hole in the film that equalizes pressure between the chambers. For triple-pane windows with thin suspended center film layers, it would be expected that, because of the pressure-equalized chambers, there would be no greater deflection in the exterior gap than in the interior gap. Figure 8 shows the COG gap responses to changes in the indoor-outdoor temperature difference for Group B-3 IGUs, which are constructed using a suspended film center layer with pressure-equalized chambers. Even though a gas volume change can be equally distributed through the approximately 2-mm-diameter hole in the center layer, the measurements indicate asymmetric changes for exterior and interior gaps similar to those in units with typical fully divided chambers. The intermediate temperature measurements shown by Group B-3 in Figure 8, as well as several other groups, support the linear trend representation used throughout this analysis for the temperature ranges tested. EOG trends were similar to those of the double-pane unit groups and are omitted here.

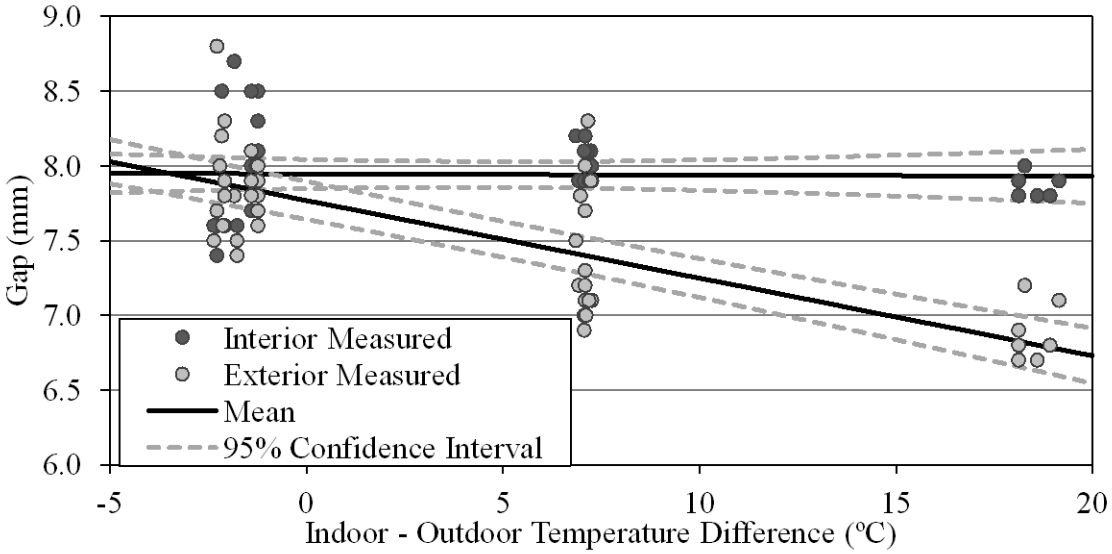

Figure 8. Group B-3 triple-pane interior and exterior chamber COG gap trends with indoor-outdoor temperature difference

The fits from Table 4 were used to determine the mean characteristics shown in Table 5. The design gap is the mean EOG gap when interior and exterior temperatures are equal. The design gap is assumed to be the intended COG gap width from the manufacturer at neutral temperature conditions. The actual COG gap at zero degrees (0) indoor-outdoor temperature difference (DT) is found from the COG intercept of the fit data. The gaps at 20°C DT (winter) and -5°C DT (summer) are calculated from the same fit curves. ASHRAE type (-18°C winter, 20°C summer) winter conditions fall outside of this range on the cold side and were not considered appropriate boundary conditions because it is unknown whether the linear deflection approximation used holds when extrapolated.

Table 5. Calculated mean COG gap and deflection of measured IGU groups

Site-Group		**Design Gap (mm)**	**0°C DT**		**20°C DT (Winter)**		**-5°C DT (Summer)**	
			Gap (mm)	**Deflection (mm)**	**Gap (mm)**	**Deflection (mm)**	**Gap (mm)**	**Deflection (mm)**
2-Pane								
B-1		9.82	9.76	-0.07	8.36	-1.17	10.11	0.21
B-2		11.62	11.77	0.15	10.26	-0.86	12.15	0.40
C-1		13.82	12.66	-1.16	10.75	-2.47	13.13	-0.83
D-1		13.94	12.98	-0.96	11.58	-2.08	13.33	-0.68
3-Pane		**I: Interior Gap E: Exterior Gap T: Total Unit**						
B-3	**I**	8.02	7.95	-0.07	7.93	-0.06	7.95	-0.08
	E	8.02	7.77	-0.25	6.73	-0.77	8.03	-0.12
	T	16.03	15.71	-0.33	14.68	-0.81	15.96	-0.21
B-4	**I**	7.64	7.64	0.00	7.07[a]	-0.45	7.79	0.11
	E	8.55	8.02	-0.54	2.39[a]	-1.79	9.42	-0.23
	T	16.20	15.66	-0.54	9.46[a]	-2.23	17.21	-0.11

C-2	**I**	6.22	6.01	-0.20	5.57	-0.53	6.13	-0.12
	E	6.00	5.49	-0.52	4.59	-1.13	5.71	-0.36
	T	12.22	11.50	-0.72	10.16	-1.66	11.84	-0.48

[a] Winter measurement was at a 7°C DT; therefore, reported gap is extrapolated.

3.4. U-factor analysis

At low Nusselt numbers (Nu) and small deflections a representative average gap width may be reasonably assumed, although large deflections or temperature differences between glass plates will influence convective flow and may make this assumption invalid. The U-factors presented in the following analysis are calculated using Lawrence Berkeley National Laboratory's WINDOW 6 software program, and are based on the average of the COG and EOG mean gap widths, as presented by Bernier [6]. To represent a typical configuration, 3 mm clear glass was used in all models with a spectrally selective low-e coating of emissivity 0.04 on surface 3 of double pane units and surface's 2 and 5 of triple pane units. Gas fill was modeled per the design for each group, as provided in Table 1. All insulated glass units were assumed to be 1000 mm x 1000 mm with a vertical orientation. Even though the environmental temperature differences and wind speed associated with the data are not the ASHRAE type winter test conditions, U-factor modeling was performed at NFRC standard winter environmental conditions, for consistency with U.S. standards [8]. It is worth noting that this is a "generous" estimate of the actual winter test condition performance because all of the measured windows would have even smaller gaps at the ASHRAE-specified winter temperature of -18°C, and the U-factor would increase. The U-factor SE is calculated based on the difference in U-factor from the mean at the gap width of a given DT +/- the gap width SE. This procedure gives approximate values for the mean and standard error. We use it in preference to the standard procedure in that it more appropriately displays the asymmetry in the standard error that arises from the non-linear relationship between U-factor and gap width.

The gap between glass panes is dominated by conduction at gap widths below 4-5 mm, after which the onset of convection occurs. At gap width greater than 4-5 mm the heat transfer rate decreases steadily then levels off at approximately 11 mm for Argon (13 mm for Air and 9 mm for Krypton) at which point boundary layer dominated convection starts. Boundary layer convection creates an isothermal core in the middle of the cavity, making further increases in gap width essentially inconsequential to overall heat transfer.

Figures 9a and 9b show the calculated U-factor for measured units and the mean of IGU configurations from groups B-1 and B-2 respectively. Both unit types have similar aspect ratios and gap changes with temperature. Their primary differences are in size (area and gap width) and glass thickness. The design gap width of the B-2 group is 11.6 mm, where the U-factor of Argon-filled gaps is relatively flat. Therefore, the average thermal performance drop resulting from deflection at the 20°C temperature difference is a relatively small 1.1 percent of the design condition, as can be seen in the nearly flat fit curve in Figure 9b. However, in the smaller, 9.8 mm, design gap width of the B-1 units shown in Figure 9a, the U-factor is significantly affected by temperature and a 20°C temperature difference reduces thermal performance by 4.6 percent. A summary of calculated gap widths and U-factors for the measured 2-pane groups is shown in Figure 9c.

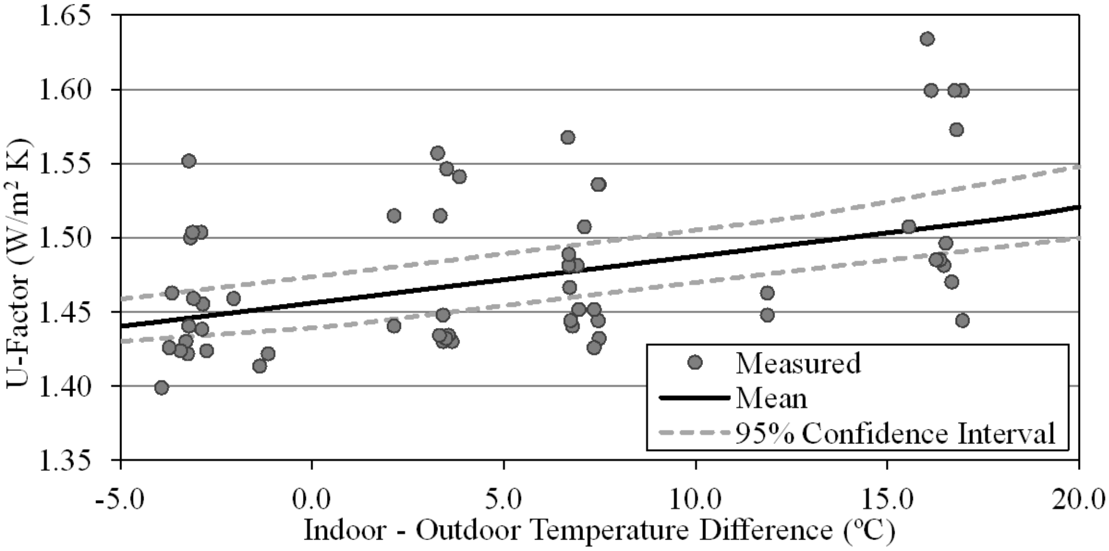

Figure 9a. Group B-1 U-factor range at tested conditions

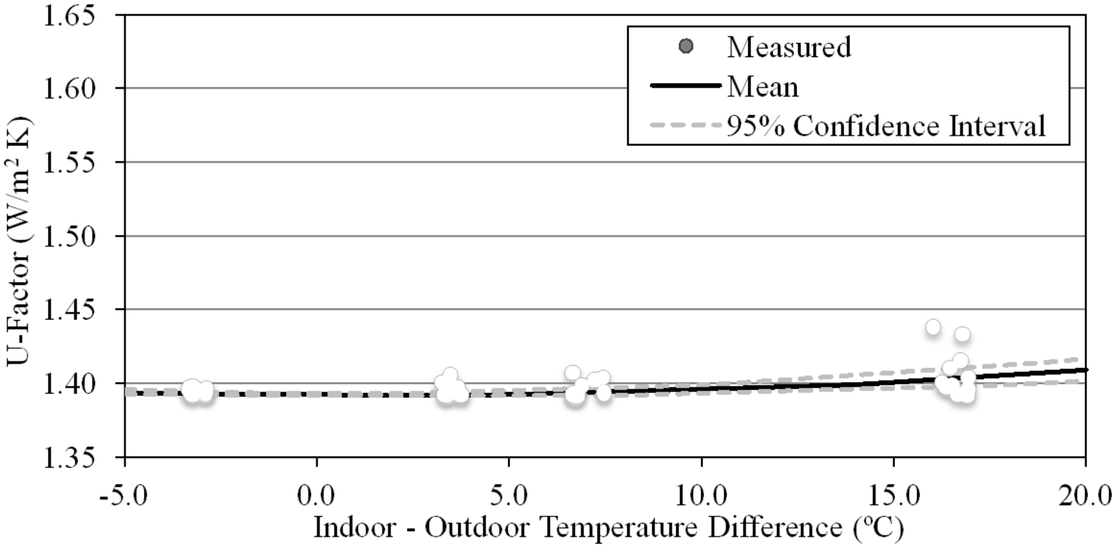

Figure 9b. Group B-2 U-factor range at tested conditions

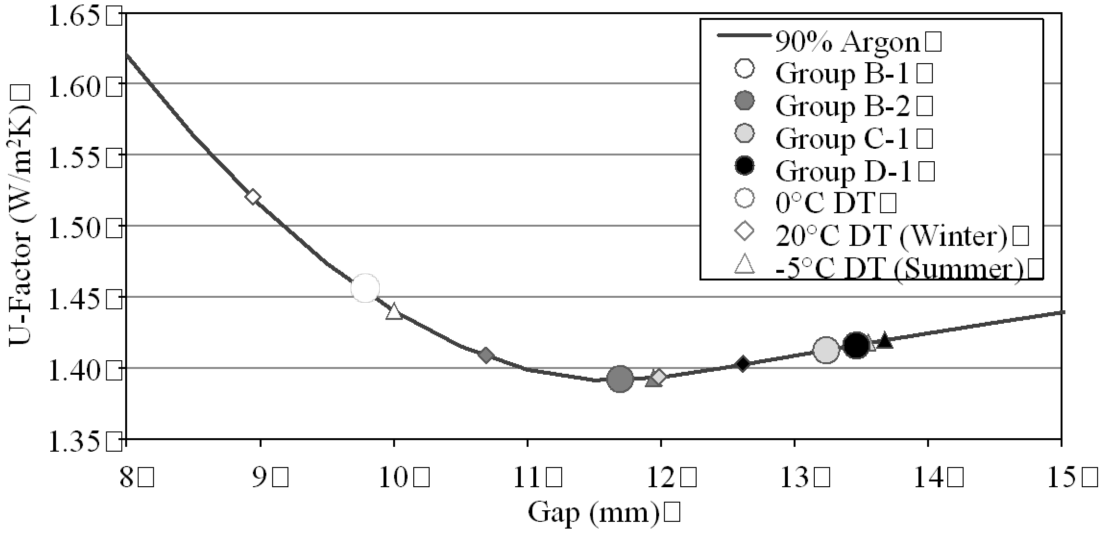

Figure 9c. Summary of 2-pane U-factor ranges for measured groups

Figure 10a shows U-factor changes for triple-pane units in Group B-3. The design exterior gap width of 8.0 mm for the B-3 Group is less than the approximately 9.0-mm gap width for optimum thermal performance of a triple-pane Krypton-filled IGU in this configuration. Because of the low baseline U-factor of this Krypton-filled unit, the relatively small 0.022 W/m^{2}K average U-factor reduction at the 20°C temperature difference reduced thermal performance by a relatively significant 3.4 percent.

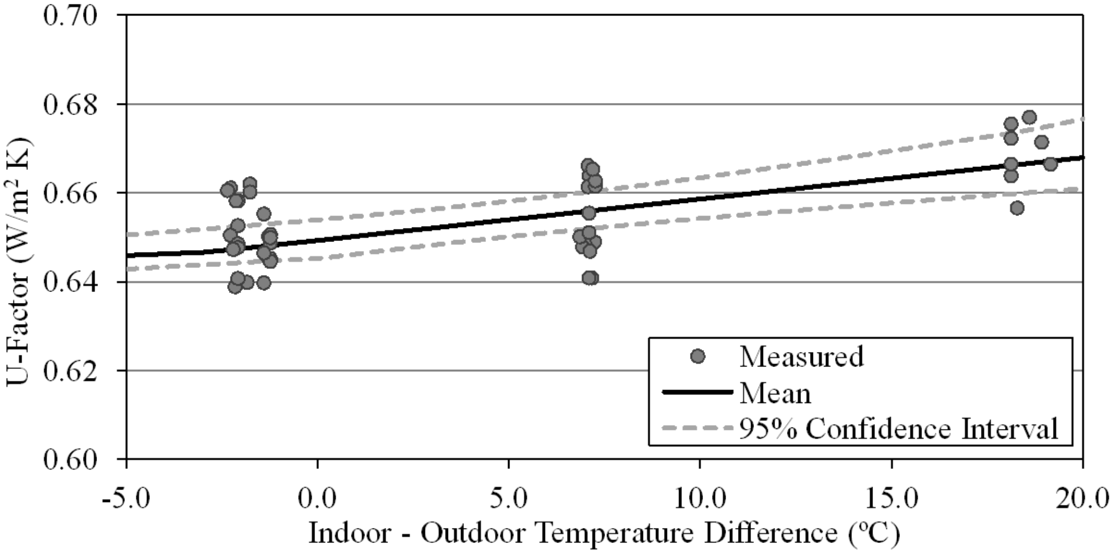

Figure 10a. Group B-3 U-factor range at tested conditions

Figures 10b (krypton) and 10c (Argon) show the as-measured relationship between the interior and exterior COG gaps of triple-pane unit groups, plotted on U-factor contours. Although the designed width of both gaps is equal, the winter measurements, represented in light grey, show a bias toward larger gaps on the interior of 0.8 mm on average. Summer data, represented in dark grey, indicate that although both interior and exterior gaps increase with warmer outdoor temperatures, there is a greater change in the exterior gap, and the bias toward larger gaps on the interior is reduced to 0.3 mm on average. The change in gap bias is shown by the shift of warm temperature units away from the line of symmetry in cold temperatures. The figures also show the decreased thermal performance of the cold-temperature units due to the internal and external gap width decreases. Again, it is clear that the change in U-factor associated with temperature change is of similar magnitude to the variation in U-factor at a given temperature.

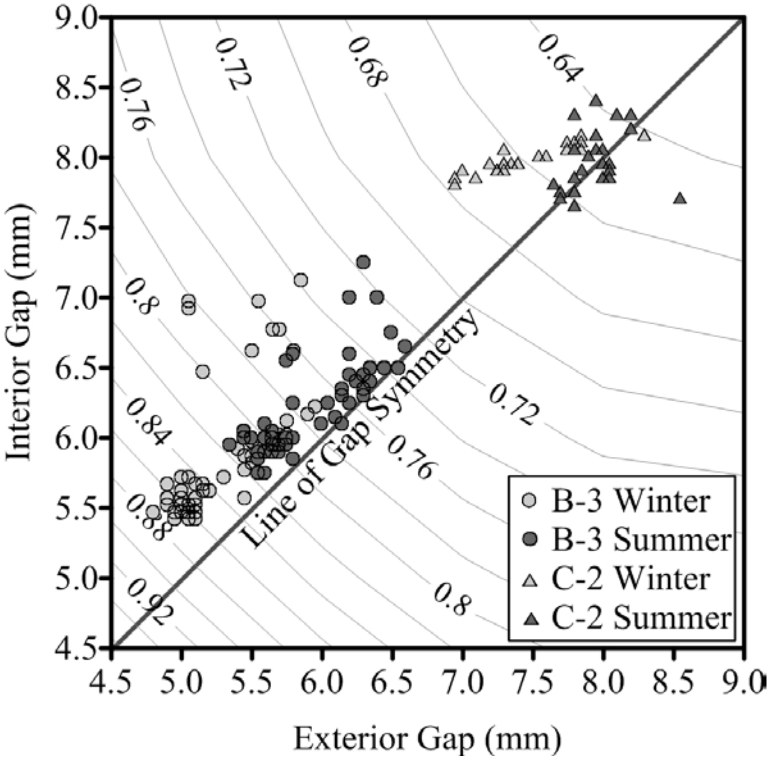

Figure 10b. Krypton filled Groups C-2 and B-3 U-factor at as-measured interior and exterior COG gap dimensions

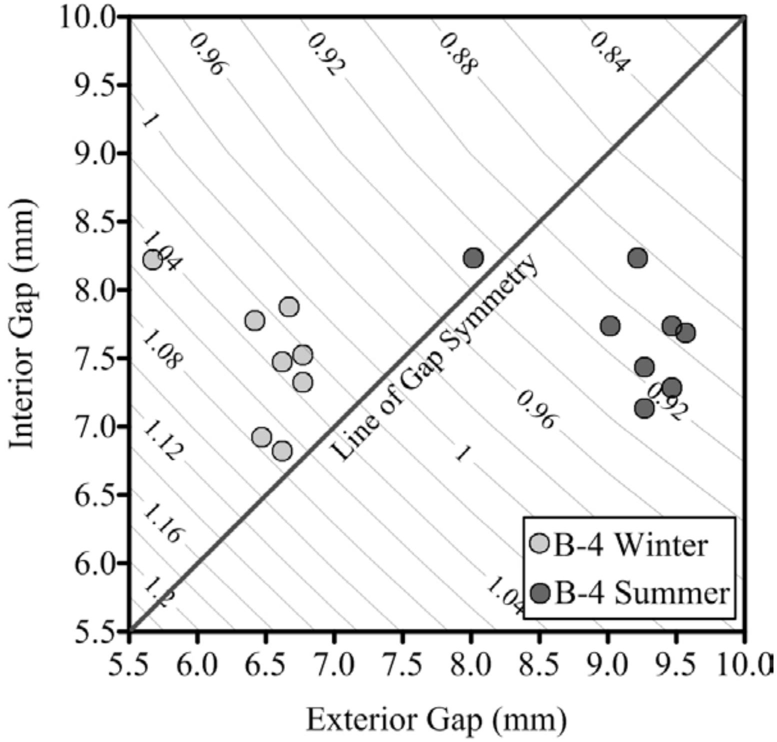

Figure 10c. Argon filled Group B-4 U-factor at as-measured interior and exterior COG gap dimensions

The absolute, and percent U-factor deviation from the design condition is shown in Table 6 for the measured unit groups.

Table 6. Calculated average U-factors of measured IGU groups

	Design (W/m2K)	0°C DT (W/m2K)			20°C DT (Winter) (W/m2K)			-5°C DT (Summer) (W/m2K)		
Site-Group	**U**	**U**	**% Dev**	**SE**	**U**	**% Dev**	**SE**	**U**	**% Dev**	**SE**
2-Pane										
B-1	1.453	1.456	-0.2%	0.009	1.521	-4.6%	0.012	1.440	0.9%	0.007
B-2	1.396	1.395	0.0%	0.001	1.412	-1.1%	0.005	1.394	0.1%	0.001
C-1	1.422	1.413	0.6%	0.000	1.394	2.0%	0.000	1.418	0.3%	0.001
D-1	1.424	1.416	0.5%	0.001	1.403	1.5%	0.001	1.420	0.3%	0.001
3-Pane										
B-3	0.646	0.649	-0.5%	0.002	0.668	-3.4%	0.004	0.646	0.0%	0.002
B-4	0.934	0.945	-1.2%	0.013	1.288[a]	-37.8%	0.037	0.894	4.3%	0.012
C-2	0.769	0.787	-2.3%	0.004	0.833	-8.2%	0.006	0.776	-0.9%	0.005

[a] Winter measurement was at a 7°C DT; therefore, calculated U-factor is based on extrapolated gap width.

4. Summary and Conclusions

Outdoor temperature variations can be represented by a linear change in the COG gap width of double and triple-pane IGUs for the summer to winter temperature ranges measured. The degree of deflection observed varied with the location, configuration, and test conditions for the units studied and could also be attributed to several other unmeasured and unknown effects.

The temperature-induced deflection observed from winter to summer is of similar magnitude to the observed spread of deflection among similar units all exposed to the same temperature in winter and in summer. This was true for windows from several different manufacturers and installation locations, which suggests that there are other factors of equal importance to temperature that determine in-situ deflection of windows.

The impact of deflection on thermal performance is based on the designed gap of the IGU. Units designed with smaller-than-optimal gaps may have significant U-factor changes associated with inherent gap variability compounded with temperature-induced gap reduction. This is particularly problematic for high-performance triple glazing where small gap dimension changes can have a large impact on performance. It is possible to design an IGU with a gap wide enough to mitigate any deflection effects on performance.

5. Future work

Field measurements clearly show a correlation between gap width deflection and temperature, but it is difficult to draw any definitive conclusions from our data regarding the correlation because this study was performed in uncontrolled indoor and outdoor conditions. In addition, it is not possible to isolate correlations with specific window physical properties because of the limited variation in properties among the test units. The next step should be to perform COG measurements under controlled laboratory conditions to quantify deflection shapes and sizes. Mathematical model verification should be performed in parallel with laboratory testing. Deflection calculations based on research from Texas Tech University [5] and U-factor calculations based on computational fluid dynamics/finite element analysis should be compared to the calculation methods used in this study as well as laboratory and field test results.

Acknowledgements

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