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**TOWARDS HARMONIZING THE NFRC AND CEN WINDOW
PERFORMANCE SIMULATION METHODS**

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Keywords

Windows, insulated glazing units, window frames, simulation, NFRC, CEN, high performance

Abstract

Studies have found that the CEN and NFRC methods produce different U-values for the same window resulting in confusion when comparing products. A comparative evaluation of the NFRC and CEN U-value calculation methods was conducted for North American residential high performance window products with focus on the most influential parameters in determining the whole window U-value for high performance windows. Using two-dimensional conduction simulation software, four North American high performance frame types with double, triple and quad glazing combinations were simulated and calculated according to the NFRC and CEN standard methods. Overall, the trend showed that for the specific window combinations of this study, the higher the performance of the IGU, the lesser the differences in the whole window U-value of both methods. The results showed an overall difference of 1 to 11% in whole window U-value when using the NFRC and CEN standards, lower than other studies. Generally, the NFRC standard resulted in the lower U-value for each case. Recommendations for harmonization of the two standards include aligning boundary conditions, frame cavity models and material conductivities.

27 **List of Abbreviations**

28	NFRC	National Fenestration Rating Council
29	CEN	European Committee for Standardization
30	IGU	Insulated Glazing Unit
31	Low-E	Low emissivity coating
32	SHGC	Solar Heat Gain Coefficient
33	TBSW	Thermally Broken Solid Wood Frame
34	U_{cog}	Center-of-Glazing U-value
35	U_{cog-NFRC}	Center-of-Glazing U-value in the NFRC method
36	U_{cog-CEN}	Center-of-Glazing U-value in the CEN method
37	U_{edge-NFRC}	Edge-of-Glazing U-value in the NFRC method
38	U_{frame}	Frame U-value
39	U_{frame-NFRC}	Frame U-value in the NFRC method
40	U_{frame-CEN}	Frame U-value in the CEN method
41	U_{frameIGU-CEN}	Frame U-value in the CEN method with the IGU inserted in the frame
42	U'_{frame}	Frame U-value in the CEN method with the Calibration panel in the frame
43	U'_p	Calibration panel U-value
44	U_{window}	Whole window U-value

45 $U_{\text{window-NFRC}}$ Whole window U-value in the NFRC method

46 $U_{\text{window-CEN}}$ Whole window U-value in the CEN method

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1 Introduction

The figurative and historical significance of windows presents a striking opportunity for architects, engineers, builders, manufacturers and homeowners, to challenge themselves in the design process by considering the potential impact of their design decisions on people. A window's thermal performance, size, orientation, visible light transmittance and solar gain, are factors that all need to be considered in creating a home because they influence people's health, well-being, and energy consumption.

Window frames account for 20 to 30% of the whole window area yet can be responsible for more than 30% of the rate of heat transfer (Gustavsen, Arasteh, et al. 2008) and can represent 27% of the space heating needs (Parekh 2010) or 30% to 50% of the losses through the building envelope (Gustavsen et al. 2011). Considering that Canada is the third largest energy consumer per capita in the world (The World Bank 2013), followed by the U.S., a reduction in energy consumption through the use of high performance windows would have a significant effect on reducing our cumulative environmental impact, particularly pollutants that exacerbate climate change, for the benefit of present and future generations.

Presently, it is difficult to directly compare different window products between Europe and North America because the overall U- values are calculated differently and not all of the parameters used are the same. The majority of North American window manufacturers use the National Fenestration Rating Council (NFRC) (Ducker Research Company 2012) calculation method for determining the overall U- value of their window products and Europe manufacturers use the European Committee for Standardization (CEN) (Sack 2013) method. Throughout the literature, it is evident that there is a significant discrepancy between the NFRC and the CEN methods in determining the overall window U- value as to which is more accurate. Further, when comparing different products the two standards may differ in ranking, making selection difficult.

72 This paper conducts a comparative evaluation of the NFRC and CEN U-value calculation methods for
73 North American residential high performance window products and evaluates the parameters that are
74 most influential in determining the whole window U-value for high performance windows when utilizing
75 different assumptions and boundary conditions in various climates. Further, identification of potential
76 parameters to be harmonized between the two methods is concluded.

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2 Pertinent Literature

2.1 Background

In the past, the thermal transmittance of the center-of-glass area was used by window manufacturers to describe the energy performance of the whole window product (Canadian Standards Association 2009). These values were thus also misleading for builders that installed these windows who were lead to believe that they were using a certain U-value when in fact the overall U-value was much less after installation when factoring in the different thermal transmittance values of the window components and their effect on the whole window thermal transmittance.

What compounds the complexity of this situation is that not only do various component details possess different U- values, the calculation methods used to determine whole window product U-values, (U_{window}), in North America and Europe have significant differences. Studies identify that for a specific window, NFRC testing methods generally give an approximation of 10% more heat flow than the value derived from tests according to European standards (J. Straube 2009) (Rosenbaum and White 2009) (Varshneya, Rosaa and Shapiroa 2012). However, according to the literature, when specific windows are evaluated, the results do not align with the generalized assumption of 10%. In a comparative study of three double-glazed windows, (vinyl, fiberglass and certified PH), $U_{\text{window-NFRC}}$ was typically 5-7% higher than $U_{\text{window-CEN}}$ (Hanam 2013). For triple-glazed windows, the differences were smaller (Hanam 2013). When high and low solar heat gain glazing were compared, there was a 12% different between the NFRC and CEN solar heat gain coefficients for the low solar heat gain glazing and only a 1% difference for the high solar heat gain glazing (Hanam 2013).

2.2 Primary Differences between the NFRC and CEN U_{window} Calculation

Methods

2.2.1 Boundary Conditions

The primary differences in the boundary conditions and other parameters between the NFRC and CEN methods for calculating U_{window} and the Solar Heat Gain Coefficient are outlined in Table 1. Key parameters to be highlighted include interior and exterior temperatures, wind velocities, incident solar flux, and surface film coefficients.

Table 1: Key parameter differences between the NFRC and CEN calculation methods for determining the U-value

Parameter	North America (NFRC)	Europe (CEN)
ISO Standard Used	ISO 15099	ISO 10077
<i>Determining U-value</i>		
Interior Temperature	21.1°C	20°C
Exterior Temperature	-18°C	0°C
Exterior Wind Velocity	5.5 m/s	4 m/s
<i>Determining SHGC</i>		
ISO Standard Used	ISO 15099	ISO 10077
Interior Temperature	24°C	25°C
Exterior Temperature	32°C	30°C
Exterior Wind Velocity	2.8 m/s	1m/s
Incident Solar Flux	783 W/m ²	500 W/m ²

Solar Spectrum	NFRC 300 ¹	EN 410 ¹
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Table 2 shows the way in which the surface resistances, parameters which can be very influential in the overall insulative properties of a window (Hutcheon and Handegord 1995), vary between both methods.

Table 2 Surface Resistances (horizontal heat flow) of the CEN and NFRC Calculation Methods

Calculation Method	Position	Exterior, R_{se} (W/m ² K)	Interior, R_{si} (W/m ² K)
ISO 10077-2 (CEN)	Normal (plane surface)	25	7.69
ISO 10077-2 (CEN)	Reduced radiation/convection [in edges between two surfaces]	25	5
NFRC	Aluminum	26	3.29
	Thermally Broken Frame	26	3.00
	Thermally Improved Frame	26	3.12
	Wood/Vinyl Frame	26	2.44

2.2.2 U_{frame} and Edge Effects

Due to methodological differences between the standards, U_{frame} values of both methods are not directly comparable. One of the key differences between the CEN method and the NFRC method is that the CEN method uses a calibration panel, with a low thermal conductivity (i.e. 0.035 W/mK), to determine $U_{frame-CEN}$. With the use of a calibration panel, the thermal transmittance of the frame itself is acquired without the influence of the thermal properties and configurations of the IGU. The use of a

¹ NFRC 300 and EN 410 are both standards that outline the procedure to measure and calculate the transmittance and reflectance over the solar spectrum through glazing materials. The standards are very similar with some calculational differences.

calibration panel to determine $U_{\text{frame-CEN}}$ gives a common standard element that can be used to compare frames on the same level. In addition, the calibration panel allows for the measurement and comparison of the incremental effect of the thermal performance of IGUs when combined with a frame configuration. Whereas in the NFRC method, the U_{frame} is determined by incorporating the simulated frame with the actual glazing system instead of a calibration panel (Gustavsen, Petter Jelle, et al. 2007).

Simulating the actual glazing system in the frame, when determining the thermal transmittance of the frame in the NFRC method, results in a U_{frame} value that includes a portion of the edge effects that occur from the heat transfer interactions of the actual glazing, spacer and frame materials. In addition, ISO 15099 (2003) states that the difference between the $U_{\text{frame-NFRC}}$ and $U_{\text{frame-CEN}}$ is that the former incorporates “some of the heat transfer caused by the edge seal whereas $U_{\text{frame-CEN}}$ does not”. Thus, the edge effects are accounted for in the NFRC method by $U_{\text{edge-NFRC}}$ and $U_{\text{frame-NFRC}}$ and solely by the Ψ -value in the CEN method

Seeing that the two methods have different calculations and thus explanations for the thermal transmittance of the frame, in effect, the ISO (2003) suggests that the same calculation be used for window products in order to compare them on the same grounds.

The approach to take into account transition effects between the frame and glazing differs. $U_{\text{edge-NFRC}}$ uses a length of 63.5 mm and CEN method uses a linear thermal bridge approach. Carpenter and Elmahdy (1994) and Elmahdy (2004) showed that a 63.5mm region gave sufficient results for ten different windows, however, Curcija and Goss (1994)’s study found that 100 mm accounted for the frame and spacer 2-D heat transfer effects on the glazing, in a wood-framed window, more accurately than the 63.5mm region. In addition, Weitzmann et al. (2000) found that the 63.5 mm rule did not sufficiently encompass the two dimensional edge-of-glazing effects between the spacer, frame and glazing for a typical Danish wood-framed window. Rather, this study concluded that an edge-of-glass length of 150 mm was more accurate. Blanus et al. (2007) confirms the two methods differ in the way

in which they treat the spacer and its interactive effects on the heat transfer of the frame and edge-of-glazing area.

ASHRAE (2009) acknowledged that due to the advance in technological innovations in the high performance window industry, the 63.5 mm value may not be sufficient for all windows. Determining the suitability of the 63.5 mm edge-of-glazing area by testing various high performance windows with a thermographic camera and measuring the edge effects of those captured images is acknowledged as an area that requires further research and is beyond the scope of this paper.

2.2.3 Frame Cavities

Frame cavities are assumed to be a 'solid' and are assigned an effective conductivity (k_{eff}) value that incorporates radiative and convective heat transfer effects in that area. The convective heat transfer coefficient in the k_{eff} equation, according to the NFRC and CEN methods, uses the conductivity of air as the primary conductivity of this 'solid' region (ISO 2003; ISO 2012; LBNL 2012). The effective conductivity incorporates the geometry, heat flow direction, surface emissivity and temperature of the surrounding surfaces of the cavity region (LBNL 2013).

The NFRC method employs two different radiation models for frame cavities, simplified and detailed:

1. **Simplified Radiation Model:** Based on the ASHRAE SPC 142P method, radiation heat transfer effects are modeled as "an effective conductance based on the temperature and emissivity of the two parallel [surfaces] perpendicular to the heat flow" (LBNL 1998). The default values frame cavity surface temperatures are 7°C and -4°C and the emissivity's of those surfaces are 0.90 (LBNL 1998).
2. **Detailed Radiation Model:** Based on the computer program FACET, this model determines radiant heat transfer by incorporating the temperature and emissivity of the surrounding materials of a frame cavity and performs "an element-by-element view-factor calculation" (LBNL 1998).

The CEN employs a simplified radiation model that replaces frame cavities with a relatively equivalent rectangular cavity with walls that have a constant temperature (LBNL 1998).

The radiative heat transfer coefficient h_r is calculated according to Roth (1998) which is referred to by the former working group ASHRAE SPC 142. Since the foundational calculations in both methods are identical, the CEN and NFRC detailed radiation models are essentially the same.

The convective heat transfer coefficient in the CEN simplified radiation model uses a 10K temperature difference in its equation between the two frame cavity surfaces perpendicular to the heat flow; the thermal conductivity value of air at 10°C is used (ISO 2012). The NFRC method uses different default temperatures for the frame cavity surfaces than ISO 15099 (2003): the ISO 15099 uses 0 and 10°C and the NFRC uses 7 and -4°C which is an 11°C temperature difference (LBNL 1998). Although the difference in delta T between both methods is only 1°C, the different default temperatures used by both methods may influence the variations in U-value results.

2.2.4 Unventilated and Ventilated Frame Cavity Models

The NFRC method refers to the cavity model as outlined in ISO 15099 and the CEN method refers to the cavity model outlined in ISO 10077-2. No apparent differences exist between methods.

2.2.5 Whole Window U-values Differences

When using different boundary conditions with the same calculation method, Roth (1998) showed that the NFRC boundary conditions give higher U-values than the CEN boundary conditions. In other studies,

187 Blanusa (2001) and Weitzmann et al. (2000) found when comparing boundary conditions, the CEN
188 method gave higher U-values than the NFRC method.

189 The influence of the different thermal transmittances of the frame and glazing on the overall window U-
190 value increases with differently sized windows. Blanusa (2001) and Blanusa et al (2007) report the
191 difference in U_w -values between the two calculation methods decreases as the total area of the window
192 increases with differences of 1.4% for smaller windows and 0.6% for larger windows. Despite using the
193 same boundary conditions, Roth (1998) found the two methods gave different results for smaller
194 windows: a difference of 3.5% for a thermally broken aluminum framed window, 3% for a PVC framed
195 window and 2.3% for a wood framed window. Agreement between the methods was found to be
196 dependent upon the geometry of the window (Blanusa, Goss, et al. 2007). Since the CEN method uses a
197 lower temperature difference, European windows tend to have a lower U-value result (Young 2012).

199 Gustavsen et al. (2008) suggests that the current methods in the ISO 15099 standard are not sufficient
200 to model the heat transfer through low conductance frames, yet it is sufficient for modelling high
201 conductance frames. Rather, more intricate algorithms are needed in order for current modelling
202 programs are to be used for the design and improvement of low-conductance frames. The study found
203 that low conductance frames could be modeled accurately with computational fluid dynamic (CFD)
204 models.

205 RDH (2014) researched the differences between the CEN and NFRC calculation methods using two North
206 American windows, vinyl and fiberglass-frames, and a vinyl-framed European window; all with argon gas
207 infill and a thin-wall stainless steel, dual seal spacer. The relevant findings included: (i) $U_{\text{cog-NFRC}}$ values
208 between zero and 23% higher than $U_{\text{cog-CEN}}$ values; larger gap sizes gave the larger differences (14-23%),
209 (ii) $U_{\text{window-NFRC}}$ values found to be 14% lower to 18% higher than the CEN values, (iii) U_{frame} values differed
210 where the NFRC U_{frame} were found to be 5% lower to 24% higher than CEN values, (iv) SHGC values for

the whole window were up to 50% lower than the center-of-glazing SHGC values, and (v) NFRC SHGC values for the center-of-glazing were between 1% and 8% lower than CEN SHGC values. The study concluded that the difference in the U_{frame} values of each method is attributed to the fundamentally different U_{frame} calculation approaches (RDH Building Engineering Ltd. 2014). Further, recommendations suggested the NFRC and CEN U-values cannot be compared due to being based on different calculation procedures.

3 Methodology

Using THERM and WINDOW simulation software (LBNL 2009), the effects of changing various parameters and boundary conditions upon the thermal transmittance of four high performance windows with various glazing combinations, were simulated and calculated according to the NFRC and CEN standard methods. The four frame cross-section types that were used are: an insulated fiberglass window frame, a thermally broken solid wood frame, a U-PVC frame and a solid wood frame. U_{window} , U_{cog} , and U_{frame} were evaluated by comparing the use of different boundary conditions and assumptions in the NFRC and CEN calculation methods in determining thermal transmittance by using variables in different combinations from the simulation matrix shown in Table 3. The chosen frame, IGU and spacer configuration was based on both prior research (Wright 2012, RDH 2014) and interviews with several North American high-performance window manufacturers.

Table 3 Simulation Matrix

Variable								
Exterior Temperature	Frame Material	Glazing Combination	Spacer	Material Thermal Conductivity	Frame Cavity	Wind Speed	Surface film coefficients	SHGC
-40C to 40C	Insulated	Double IGU;	Higher	NFRC 101	NFRC	Sheltered	NFRC	NFRC

	fiberglass	high and low SHGC	Performance: A					
	Solid wood	Triple IGU; high and low SHGC	Standard: B	CEN (ISO 10077-2)	CEN	Exposed	CEN	CEN
	TBSW*	Quad IGU; high SHGC	Higher Performance: C					
	U-PVC							

*Thermally broken solid wood

3.1 Simulation Inputs

This study compares the NFRC and CEN standards through the lens of high performance windows. In our discussions with north American window manufacturers and builders throughout the continent, the importing of European windows is primarily occurring at the high performance level in order to attain levels dictated by standards like Passive House, R2000 and other similar efforts. As such, the authors felt a comparison of the two standards through the lens of high performance windows addresses the current concerns expressed in the industry. Specific inputs are as listed below:

- single casement windows were simulated (using the NFRC standard size of casement windows is 1.5 m x 0.6 m for both methods). This standard size was chosen in order to maintain alignment with the standard simulation practice.
- Four simulated frame materials: a thermally broken solid wood frame (TBSW), insulated fiberglass frame, U-PVC frame and a solid wood frame as shown in Figure 1 (these frames were sourced from various North American certified PHIUS windows).
- Three simulated spacers used from different manufacturers as shown in Figure 2.
- The glazing configurations were chosen based on the technical specifications of several high performance North American window manufacturers. The gas infill in each of the triple and quadruple glazing configurations comprised 90% krypton and 10% air (using NFRC and CEN

properties). Krypton was chosen as a conservative approach, knowing the effects observed using this inert gas would be equal or less than for Argon. Further, glazing manufacturers have suggested Krypton is growing in market share within the high performance glazing market.

Figure 1 Frame Types (Solid Wood, uPVC, Fiberglass, TBSW; from left to right)

Figure 2 Spacers A, B and C

3.2 Winter and Summer Design Conditions

Standard winter and summer boundary conditions were specified for the NFRC method and CEN method (ISO 10077-1) as summarized in Table 4.

259 **Table 4: NFRC and CEN Winter Boundary Conditions**

Winter Design Conditions		
	North America (NFRC)	Europe (CEN)
ISO Standard Used	ISO 15099	ISO 10077
Interior Temperature	21.1°C	20°C
Exterior Temperature	-18°C	0°C
Exterior Wind Velocity	5.5 m/s	4 m/s
Exterior Radiant Mean Temperature	$T_{r,m} = T_{\text{exterior}}$	$T_{r,m} = T_{\text{exterior}}$
Interior Radiant Mean Temperature	$T_{r,m} = T_{\text{interior}}$	$T_{r,m} = T_{\text{interior}}$
Summer Design Conditions		
Standard	NFRC 200-2010	ISO 15099
Interior temperature	24°C	25°C
Exterior temperature	32°C	30°C
Interior convective surface heat transfer coefficient, hcv,int	7.7 W/(m²K) (NFRC 102 hc int and ASTM E1423)	2.5 W/(m²K)
Exterior convective surface heat	15 W/(m²K)	8 W/(m²K)

transfer coefficient, hcv, ext		
Radiant Mean Temperature, Tr,m	Texterior	Texterior
Solar irradiance, Is	783 W/m ²	500 W/m ²
Wind Velocity	2.75 m/s	4 m/s

3.3 Gap Sizes

U_{cog} is calculated differently by the NFRC and CEN method; the CEN method is considered more simplified. The U_{cog} values of the test high performance windows with different gap sizes were simulated according to the exterior temperature boundary conditions of various climate zones for the NFRC and CEN methods, to see the effect of various temperature ranges on different gap sizes. For the double and triple glazing units, the U_{cog} values were simulated using the NFRC and CEN methods and standard boundary conditions as a base case scenario. The gap size range was between 6-20 mm in increments of 2mm for a single spacer, as drawn from RDH Building Engineering Ltd. (2014) and LBNL studies (Kohler 2012).

3.4 Location Specific Wind Velocities in North America's Climate Zones

To determine the impact of wind velocity on the U_{window} and U_{cog} , various values based on different climates were simulated. It is important to note that the wind velocity can be changed in WINDOW however, in THERM, the wind velocity is accounted for in the surface film coefficient on the exterior side. In the NFRC method, each frame material is assigned a convective surface heat transfer coefficient that has a constant value and is temperature dependent as outlined by each method (LBNL 2013).

3.5 Material Thermal Conductivities

Some of the thermal conductivity values of the materials that are referenced to in each calculation method have been assigned different values. This difference may have a significant effect on the U_{window} , U_{frame} and U_{cog} . For each calculation method, the values of the materials that have different thermal conductivities for each test window were drawn from the following documents: *ISO 10077-2*, *the NFRC 101-2010 and Procedure for Determining Thermophysical Properties of Materials for Use in NFRC-Approved Software*. For a list of the material thermal conductivities used in the simulated frame types, see Table 5. The primary materials that have significant different thermal conductivities are fiberglass and typical softwood; these values were used in the simulations.

Each test window was simulated according to:

- the NFRC method with NFRC thermal conductivities and compare with the CEN method using ISO thermal conductivities (using standard boundary conditions)
- the NFRC and CEN method using NFRC thermal conductivities
- the NFRC and CEN method using CEN thermal conductivities

Table 5: Different NFRC and CEN Material Thermal Conductivities

Frame Type: Material	NFRC (W/mK)	CEN (ISO 10077-2) (W/mK)
Solid wood: Douglas fir	0.111	0.13
Fiberglass: PE Resin	0.3	0.4

TBSW:		
Meranti (hardwood)	0.16	0.18 general; 0.13 light red, 0.16 dark red
Pine (softwood)	0.14 (general)	0.13 scots-EU; 0.11 lodgepole NA

291

292 3.6 Surface Film Coefficients (Boundary Conductances)

293 The surface film coefficients used in each of the calculation methods were assigned different values
 294 (refer to Table 6). The degree of influence of these different surface film coefficients on the U_{window} and
 295 U_{frame} were evaluated for each of the test high performance windows. The CEN method's surface film
 296 coefficients combine the convective and radiation coefficients; whereas the NFRC method does not
 297 include the radiation component in the surface film coefficient value as it is included in the radiation
 298 model in the simulations. Therefore, when replacing CEN surface film coefficient values with NFRC
 299 values, the radiation component is being neglected and thus this is only a theoretical scenario to
 300 determine the effect of various surface film coefficient values upon U_{window} and U_{frame} .

301 Each test window was simulated according to:

- 302 • the NFRC and CEN method using NFRC surface film coefficients
- 303 • the NFRC and CEN method using CEN surface film coefficients

304 Note: It was found that switching the surface film coefficients of both methods was not possible in real
 305 terms due to the radiation coefficient calculation being temperature dependent according to the EN ISO
 306 6946 (2007). The NFRC radiation coefficient is slightly lower than the CEN radiation coefficient due to
 307 the lower exterior temperature used in the NFRC method. Although the convective coefficients are
 308 interchangeable, a small difference of 1.5 m/s in the wind speeds of both methods (i.e. NFRC = 5.5 m/s;

CEN = 4 m/s) was not considered a significant influence on U_{window} simulations, based on simulations during preliminary investigations; an average between the two values would suffice. Representative simulations of the inland and coastal locations which use the various winter design temperatures and wind velocities specific to each location, gives a more accurate comparison of surface film coefficient values for each method.

Table 6: Surface Film Coefficients used by the NFRC and CEN methods

Calculation Method	Position	External, R_{se} (W/m ² K)	Internal, R_{si} (W/m ² K)
ISO 10077-2 (CEN)			
	Normal (plane surface)	25	7.69
	Reduced radiation/convection [in edges between two surfaces]	25	5
NFRC			
Aluminum frame	Vertical (convection only)	26	3.29
Thermally broken frame	Vertical (convection only)	26	3.00
Thermally improved frame	Vertical (convection only)	26	3.12
Wood/Vinyl frame	Vertical (convection only)	26	2.44

3.7 Frame Cavity Methods

The way in which the two calculation methods treat frame cavities are complex. ISO 15099 is similar to ISO 10077-2 in determining what is ventilated and what is not, however, they differ in the way equivalent simplified geometries are given in order to give an equivalent thermal conductivity to the cavities. ISO 15099 is generally more complex than ISO 10077-2. The differences of these two calculation methods were analyzed with the high performance windows that have frame cavities.

The surface film coefficients and frame cavity methods were simulated using winter boundary conditions for all test simulations seeing that in smaller temperature differentials, there is less opportunity for thermal transmittance by radiation, convection and conduction.

4 Results and Discussion

4.1 Solar Heat Gain Coefficient Simulations

Difference in procedure exists between the two standards when quantifying SHGC. The NFRC standard method takes into account the frame of the whole window unit with the glazing when calculating the SHGC, whereas, the CEN method only considers the glazing by itself at a 1000 mm height and width.. The NFRC method also takes into account the glazing at the height of the actual window unit rather than the default 1000 mm height in WINDOW: for example, for a casement window, a height of 1500 mm and 600 mm width is used in the SHGC calculation. Including the solar radiation transmission through the frame and the actual glazing height results in a large discrepancy between NFRC and CEN SHGC values.

Table 7: NFRC and CEN SHGC: IGU only

	NFRC	CEN	% Change
Glazing Only			
Double High SHGC	0.69	0.65	6%
Double Low SHGC	0.27	0.25	8%
Triple High SHG Heat Mirror	0.54	0.52	4%
Triple Low SHG Heat Mirror	0.24	0.23	4%
Triple High SHG Glass	0.56	0.54	4%
Triple Low SHG Glass	0.24	0.23	4%
Quad High SHGC Heat Mirror	0.46	0.45	2%
Quad Low SHGC Heat Mirror	0.22	0.21	5%
Quad Glass High SHGC	0.42	0.41	2%
Fiberglass Frame			
Double High SHGC	0.48	0.65	-26%
Double Low SHGC	0.19	0.25	-24%
Triple High SHGC	0.39	0.54	-28%
Triple Low SHGC	0.17	0.23	-26%
Thermally Broken Solid Wood Frame			
Double High SHGC	0.37	0.65	-43%
Double Low SHGC	0.15	0.25	-40%

Triple High SHGC	0.3	0.54	-44%
Triple Low SHGC	0.13	0.23	-43%
Quad High SHGC	0.22	0.41	-46%
Solid Wood Frame			
Double High SHGC	0.36	0.65	-45%
Double Low SHGC	0.15	0.25	-40%
Triple High SHGC	0.3	0.54	-44%
Triple Low SHGC	0.13	0.23	-43%
U-PVC Frame			
Double High SHGC	0.35	0.65	-46%
Double Low SHGC	0.14	0.25	-44%
Triple High SHGC	0.29	0.54	-46%
Triple Low SHGC	0.13	0.23	-43%

338

339 The results for the four frame types simulated using double and triple IGUs with Spacer C are shown in
340 Table 7. The NFRC SHGC values including frames were found to be 24- 46% lower than CEN SHGC
341 values due to the inclusion of the frame and the actual IGU product dimensions in the NFRC SHGC
342 method. For glazing only, the NFRC SHGC values were 2% to 8 % higher than CEN values. This is similar
343 to the findings of RDH (2014) where the NFRC SHGC values were up to 50% lower than CEN values.
344 Seeing that the SHGC measures the solar radiation transmittance between the exterior and interior
345 surfaces, the height and width of the frame is a significant influence on the amount of solar radiation
346 transmitted through the window where the larger the glazing area the more solar radiation transmission
347 occurs and would therefore contribute to a higher SHGCs. The high SHGC IGUs had slightly larger
348 percentage change differences for all the frame types; this may be attributed to surface area of the

glazing with a higher solar transmittance is referenced in the SHGC calculation is much smaller than the CEN SHGC calculation. Glazing that has lower solar transmittance characteristics, (i.e. low SHGC), is less affected by the decreased surface area when using the NFRC SHGC calculation method.

For glazing only, the results showed that the NFRC SHGC values were 2-8% higher than CEN values. The double IGUs with a high and low SHGC, as well as the Quad IGU with a low SHGC and heat mirrors, had the largest percentage change whereas the Quad IGU with glass panes had the lowest percentage change between the two methods.

The observation of larger differences between both methods with high SHGC IGUs is multifaceted. An IGU with a low SHGC decreases the thermal transmittance of the glazing more efficiently than an IGU with a high SHGC. Portions of long wave radiation are reflected by the low-E layers present on low SHGC glazing. Due to this occurrence, combine with increasing interior and temperature differences, less heat is transferred towards the frame. The frame temperature can thus be lower than for a frame with a high SHGC, depending on the thermal efficiency of the frame. The low-E layer adds more material to the glazing allowing more heat transfer through conduction to place. In addition, more thermal transmittance occurs for the double IGUs at increasing temperature differentials due to the larger gap width size. The larger the gap width size, the more temperature plays a role in increasing the effect of heat transfer through convection.

There was a minor discrepancy between the NFRC and CEN SHGC values when the glazing, by itself, was analyzed in the U_{cog} simulations. In using the default height and width of 1000 mm, and by considering the glazing by itself, this approach narrowed the differences between the NFRC and CEN methods in determining the solar transmittance through the glazing. The primary factors that attribute to these differences are the following boundary conditions: the interior and exterior temperatures, wind speed, and solar irradiance.

In the NFRC method, when the exterior temperatures for the SHGC boundary conditions are changed, the center-of-glazing SHGC changes. Increasing the wind speed (and thus the surface film coefficient) to 5 m/s decreases the SHGC by 0.002, wind speeds in the summer are generally very low therefore this factor is negligible. Changing the SHGC exterior temperature in the eight climate zones only results in 0.005 decrease where the greatest change in value only occurs for the lowest summer design temperature of 14°C in Iqaluit, however, the SHGC only changes by 0.01 when rounded to two decimal places. Likewise, in the CEN method there are minimal changes.

With an interior temperature of 20°C, EN 673 determines the solar transmittance across a temperature difference of 15K and does not outline summer boundary conditions. For the CEN simulations, the summer boundary conditions outlined in ISO 15099 are used for the SHGC calculations. The NFRC SHGC values were 2-8% higher due to the NFRC's larger interior and exterior temperature difference of 8°C, and a higher exterior temperature by 2°C. Although the NFRC surface film coefficients are higher than the CEN values and increasing those alone decreases the SHGC value, the effect of the higher NFRC exterior temperature, the greater difference between interior and exterior temperatures, and the greater difference between the interior and exterior surface film coefficients, contribute to the higher NFRC center-of-glazing SHGC values.

Furthermore, the NFRC method's higher solar irradiance also contributes to larger NFRC center-of-glazing SHGC values in (i.e. 783 vs 500 W/m²). Lowering the solar irradiance value to 500 W/m² in the NFRC method in effect lowers the SHGC by 0.01. In addition, raising the wind speed to 4 m/s in the NFRC method lowers the SHGC by 0.004 which is significant when combined with other factors that slightly change the SHGC value (i.e. surface film coefficients). Thus, the cumulative effect of the different irradiances, interior and exterior temperatures and surface film coefficients of both methods, account for the higher NFRC center-of-glazing SHGC values.

4.2 U_{cog} Simulations

4.2.1 Climate Specific U_{cog}-NFRC and U_{cog}-CEN

Double, triple and quad IGUs with high and low SHGCs were simulated using various exterior design temperatures. The larger differences at 30 and 40°C in the CEN method are due to the different summer boundary conditions, particularly the lower surface film coefficients and higher interior temperature. For comparative reasons, the temperatures that lie 20°C and below that used the standard boundary conditions are discussed.

Figure 3: High and Low SHGC; NFRC vs CEN U_{cog} values; Triple and Quad IGUs (above), Double IGUs: (below) [percentage values show how the NFRC differs in relation to the CEN standard]

407

408 The trend in Figure 3 shows the direct relation between increased IGU thermal performance and less
409 difference between U_{cog} simulation method results up to 20°C, thus supporting harmonization in this
410 metric.

411 Examining the heat transfer equations for U_{cog} , the interior and exterior temperature differential is
412 integral in formulating the radiative and convective heat transfer coefficients. The heat transfer
413 coefficients measure the thermal conductance of the gas spacing and glazing materials. Temperature
414 values are placed in the majority of calculations that formulate the heat transfer coefficients, as seen,
415 for example, in the radiation conductance equation, and the Grashof number in the Nusselt equations
416 (part of the gas conductance equation). For windows with double IGUs, the mean temperature
417 difference across the gas space is 15K and the mean temperature is 10°C (CEN 1997) (RDH 2014). Thus,
418 a degree Celsius incremental change can change the U_{cog} significantly for each standard.

419 The NFRC method, in accordance with ISO 15099, is more detailed than the CEN method in several ways.
420 The external and internal facing surface temperature of each glazing layer is calculated using a meshing
421 sequence at finite intervals (ISO 2003). Temperature values are integral in the radiative component of
422 the thermal transmittance of the glazing in the NFRC method as well (ISO 2003). The 15K mean
423 temperature difference between bounding glazing surfaces is also true for double IGU windows in the
424 NFRC method when visually analyzing the isothermal lines in THERM simulations of this study.
425 Therefore, the different thermal conductivities of the gas infill mixtures slightly contribute to the
426 different U_{cog} results.

427 Foremost, the different surface film coefficient sets; the effect of the exterior and interior temperature
428 boundary conditions upon these sets and upon the material and gas properties of the IGU; and the

different U_{cog} calculation methods, altogether significantly contributes to the difference in the U_{cog} values between the standards.

4.2.2 U_{cog} Values with Different Gap Spacing Sizes

The U_{cog} values of double and triple glazing IGUs with high and low SHGCs were simulated in the annual average temperatures of locations using various exterior design temperatures. Figure 4 represents the standard NFRC and CEN U_{cog} values with different gap spacing sizes; which were used as a baseline.

Figure 4: $U_{\text{cog-NFRC}}$ and $U_{\text{cog-CEN}}$ with Double (upper) and Triple (lower) IGUs: Various Gap Spacing Widths [percentage values show how the NFRC differs in relation to the CEN standard]

The results show that the locations within the climates with higher extremes in temperature, in reference to the same interior temperature of 21°C, thermal transmittance increases with larger gap widths. Seeing that the larger gap widths entail larger volumes of infill gas, there is more potential for heat transfer to occur through convection and radiation with higher temperature extremes. Therefore, depending on the climate, larger gap widths do not always give lower U_{cog} values. In effect, there is potential for more variance in gap spacing size within design processes using average annual U_{cog} values for each climate zone (F. Speier 2014).

The double IGUs showed a slightly greater difference between the two SHGCs than the triple IGUs due to the larger gap spacing size and thus greater thermal transmittance through convection. The IGUs with a low SHGC had greater differences due to increased conduction through the presence of more low-E coatings and their effect on the thermal conductivity of the gas infill. There were negligible differences between the U_{cog} values of the double IGUs for both methods. For the triple IGUs, the largest percentage change between both methods occurs in very cold climate zones (e.g. northern Canada) with gap widths from 14-20 mm due to larger gap widths and larger interior and exterior temperature differences result in increased conductive and radiative heat transfer.

4.3 U_{frame} Simulations

4.3.1 $U_{\text{frame-NFRC}}$, $U_{\text{frame-CEN}}$ and $U_{\text{frameIGU-CEN}}$ Calculation Methods

The results show that $U_{\text{frame-NFRC}}$ values are 7% lower to 1% higher than the $U_{\text{frame-CEN}}$ values (while including the IGU) for all frames. The trend showed that greater differences in $U_{\text{frame-CEN}}$ values of both methods occurred for the solid wood and TBSW compared with the U-PVC and fiberglass frames (refer to Figure 5). The greater the length of the sightline to the edge of the frame, and the greater the frame width, the greater the differences in $U_{\text{frame-CEN}}$ values. Differing thermal conductivities, frame cavity methods, surface film coefficients and calculation methods contribute to the variation in values. The

463 different exterior temperatures of both methods do not impact the U_{frame} seeing that the results showed
464 that U_{frame} did not change between the temperatures of -40 to 40°C.

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Figure 5: $U_{\text{frame-NFRC}}$ vs $U_{\text{frame-CEN}}$ $U_{\text{frameIGU-CEN}}$ for TBSW (upper), U-PVC (upper middle), Fiberglass (lower middle) and Solid Wood (lower)

Although $U_{\text{frame-CEN}}$ and $U_{\text{frameIGU-CEN}}$ are modeled differently, $U_{\text{frameIGU-CEN}}$ is typically higher than $U_{\text{frame-CEN}}$. $U_{\text{frameIGU-CEN}}$ due to the relatively high conductive effects of the IGU and spacer compared to the calibration panel with a very low thermal conductivity (i.e. 0.035 W/mK). For high performance glazing and spacers, the NFRC and CEN U_{frame} values with the IGU would be closer, since there is less heat transfer interactions taking place from the frame towards the spacer and glazing than a lower performing window unit. The primary differences here are in the boundary conditions, for example, the edge effects lengths are 65 and 190 mm for the NFRC and CEN methods respectively and different surface film coefficients. Overall, the $U_{\text{frame-CEN}}$ can give a fair comparison of frames due to the use of a calibration panel, which also allows for various IGU combinations to be compared and the incremental effect of their thermal performance can be measured when combined with the frame. $U_{\text{frame-CEN}}$ thus gives a more in depth picture of the thermal interactions that are responsible for the degree of differences between both methods.

4.3.2 $U_{\text{frame-CEN}}$ with CEN and NFRC Frame Cavity Methods

Seeing that the $U_{\text{frame-CEN}}$ method gives the thermal transmittance value of the frame without the influence of the IGU, the $U_{\text{frame-CEN}}$ method was used to simulate the four frame types with different

boundary conditions. The effect of using different frame cavity methods, thermal conductivities and surface film coefficients were simulated with triple IGUs with a high SHGC and Spacer C. Figure 6 shows that using the CEN frame cavity method gave $U_{\text{frame-CEN}}$ values that were 3% lower to 4% higher than the $U_{\text{frame-CEN}}$ using the NFRC frame cavity method.

Considering the CEN frame cavity method takes into account the surface temperatures of each side of a rectangular cavity, the surface characteristics become more influential. For example, structural reinforcement such as galvanized steel (i.e. 62 W/mK thermal conductivity) will contribute to increased heat flows in the frame cavities when all surfaces are taken into account. The NFRC frame cavity method only takes into account two facing frame cavity surface temperatures, therefore, higher conductive materials surrounding the frame cavities have less an effect on the frame's thermal transmittance.

Figure 6: CEN U_{frame} : CEN vs NFRC Frame Cavity Methods (FCM)

The TBSW frame had the second highest percentage change and this may be due to the effect of the oxidized aluminum siding placed on the exterior, with a thermal conductivity of 237 W/mK. This high

thermal conductivity influences the thermal transmittance in the frame cavity areas next to it, however, the extremely low conductivity of the insulation foam and EPDM efficiently reduce the impact of the aluminum's conductivity upon the entire frame.

The fiberglass frame had no percentage change between the two methods for the head and sill due to the low thermal conductivity of fiberglass, U-PVC and weather stripping components, combined with EPS insulation. The placement of the EPS insulation and other components with a low thermal conductivity impedes the thermal transmittance across frame cavities from various directions, thus stabilizing frame cavity surface temperatures. The CEN frame cavity method gave a 3% lower $U_{\text{frame-CEN}}$ value than the NFRC frame cavity method for the jamb due to the effect of gravity and the frame cavity configuration within the jamb. The frame cavities are elongated in the downward direction, which is the same direction as the heat flow and gravity. Therefore, since air at a lower temperature in the frame cavities sinks with the gravitational pull, and that the NFRC method only accounts for the two surface temperatures, there is a slightly higher temperature differential between the top and bottom of the jamb.

The solid wood frame had 0-1% differences between the two methods since there are a minimal number of frame cavities and their size is extremely small.

4.3.3 $U_{\text{frame-CEN}}$ Comparison with CEN and NFRC Surface Film Coefficients

The CEN method includes the radiation and convective components in the surface film coefficient values, whereas the NFRC method does not include the radiation component (it is included in the radiation model in the simulations.) Therefore, when replacing CEN surface film coefficients with NFRC values, the radiation component is being neglected and thus this is only a theoretical scenario. However, this was an experiment to investigate how different surface film coefficient values impacted the $U_{\text{frame-CEN}}$ values. The different surface film coefficients used in the NFRC and CEN methods had a

large impact on the $U_{\text{frame-CEN}}$ values. The $U_{\text{frame-CEN}}$ values were 19-34% higher than the $U_{\text{frame-CEN}}$ values using the NFRC surface film coefficients. The largest impact in descending order was for the solid wood, U-PVC, fiberglass and TBSW frames. The effect of different surface film coefficients upon $U_{\text{frame-CEN}}$ values depends upon the thermal performance of the frame. The results showed that the higher the thermal performance of the frame, the less of an impact that the surface film coefficients had upon $U_{\text{frame-CEN}}$. The NFRC surface film coefficients had the most impact on the U-PVC frame and the least impact on the TBSW frame due to its higher thermal performance.

4.3.4 $U_{\text{frame-CEN}}$ Comparisons with Various Material Thermal Conductivities

$U_{\text{frame-CEN}}$ comparisons were conducted for the fiberglass, TBSW and solid wood frames with a calibration panel for the frames that fit a triple IGU (Refer to Figure 7). These simulations demonstrate the effect of different thermal conductivities of the frame materials on the $U_{\text{frame-CEN}}$. Using CEN thermal conductivities for softwood for the TBSW frame resulted in 5% higher $U_{\text{frame-CEN}}$ values than values with NFRC thermal conductivities. The solid wood $U_{\text{frame-CEN}}$ values were 10-11% higher than U-frame values using NFRC thermal conductivities. Different thermal conductivities of the frame material result in a 5-11% difference for softwood materials. The $U_{\text{frame-CEN}}$ values for the fiberglass frame showed that the higher NFRC thermal conductivity for fiberglass gave 9% higher $U_{\text{frame-CEN}}$ values than when the CEN thermal conductivity values were used.

Figure 7: U_{frame-CEN}: CEN and NFRC Thermal Conductivities

4.4 U_{window} Simulations

4.4.1 U_{window-NFRC} and U_{window-CEN} Standard Comparison

All of the window configurations were simulated using Spacer C in the standard CEN and NFRC methods (Refer to Figure 8). The quad IGU was only simulated with the TBSW frame as per the manufacturer's specifications since it is not typically installed in other frame types.

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Figure 8: TBSW (upper), Solid Wood (upper middle), Fiberglass (lower middle) and U-PVC (lower) Frames, NFRC and CEN

Uwindow Values

The $U_{\text{window-NFRC}}$ values range from 1% lower to 6% higher for the triple and quad high performance window combinations. For all of the frame types, the trend shows that $U_{\text{window-NFRC}}$ values are primarily larger than $U_{\text{window-CEN}}$ values for most of the IGU combinations and the differences between both methods decrease as the thermal performance of the IGU improves. Therefore, the methods have potential to be harmonized when simulating higher performing frames and IGUs. The greater differences seen in the double IGU combinations suggest that the differences in U_{cog} procedures are accentuated in lower performing window combinations.

Since the U_{cog} is highly variable with the exterior temperatures and are increasingly variable with larger temperature differences between the interior and exterior environments, the longer the length of the sightline to the edge of the frame, the lesser the differences that occur between the NFRC and CEN U_{window} values. The solid wood frame had the highest conductivity, and in descending order: U-PVC, fiberglass and TBSW. This occurrence is partially due to the thermal interactions of the higher IGU U -value transferring to the frame. The larger frame surface area and width of the solid wood frame contributes more conductive heat transfer through the frame. Therefore, the discrepancies in U_{cog} NFRC and CEN values are reduced by the thermal interactions of the IGU being transferred through the frame. Although the TBSW frame is less conductive than the fiberglass frame, the TBSW frame has lesser

differences between both methods due to the longer length from the sightline to the edge of the frame. Again, the transfer of the thermal interactions of the IGU is less effective the longer the length of the high performance frame between the sightline and frame edge.

Out of all the frames simulated, the fiberglass frame showed the larger differences where $U_{\text{window-NFRC}}$ values were between 5-11% higher than CEN values. From the thermal conductivity comparative results above, it would be assumed that the $U_{\text{window-NFRC}}$ results would be lower than the CEN values given CEN's lower thermal conductivity for fiberglass (i.e. 0.3 vs 0.4 W/mK). However, since the NFRC values are higher, other boundary conditions are influential here. Specifically, the different exterior temperatures, surface film coefficients, frame cavity and center-of-glazing approaches specific to each method all contribute to the discrepancies in the U_{window} results.

The result of changing CEN simulation's exterior temperature to the NFRC value of -18°C , was an $U_{\text{window-NFRC}}$ value that was 1% higher than the CEN value for the double IGUs and a 2% lower value for the triple IGUs. Therefore, for the double IGUs, the difference in exterior temperatures used in both methods gives a minimal contribution to a higher $U_{\text{window-NFRC}}$ value. For the triple IGUs, the difference in exterior temperatures slightly lowers the $U_{\text{window-NFRC}}$ value and thus doesn't explain the higher NFRC values.

The effect of using different surface film coefficients of both methods does not explain the higher $U_{\text{window-NFRC}}$ values. The surface film coefficient comparative results show that for the fiberglass frame, the $U_{\text{window-NFRC}}$ values were 4-5% lower than the $U_{\text{window-NFRC}}$ values using CEN surface film coefficients. Therefore, the effect of using different surface film coefficients of both methods does not explain the higher $U_{\text{window-NFRC}}$ values.

From the frame cavity method comparison results above, the $U_{\text{window-NFRC}}$ values of the fiberglass frame combinations were 1% higher than the NFRC values using the CEN frame cavity method. The $U_{\text{window-CEN}}$ values were 1% lower than when using the NFRC frame cavity method. Similarly, the $U_{\text{frame-CEN}}$ frame

cavity method comparison isolated the effect of the different frame cavity methods on the frame by itself, and the results showed that for a triple IGU with a high SHGC, the $U_{\text{window-NFRC}}$ value for the jamb was 3% higher than the $U_{\text{window-CEN}}$ value. Thus, there is a slight difference between the frame cavity methods and this difference does contribute slightly to the higher $U_{\text{window-NFRC}}$ values.

The center-of-glazing approaches of both methods yields results where the $U_{\text{cog-NFRC}}$ values of the IGUs used in this study were found to be 11-22% higher than $U_{\text{cog-CEN}}$ as shown in Table 8. The larger differences were seen for the IGUs with a low SHGC due to the presence of higher conductive low-E coatings. Seeing that the glazing constitutes the majority of the window area and, in addition, is a large component of the thermal transmittance calculations, the thermal transmittance of the glazing is integral and highly influential in the final U_{window} value. The higher $U_{\text{cog-NFRC}}$ values significantly lowers the U_{window} values and thus explains and largely accounts for the higher $U_{\text{window-NFRC}}$ values for the fiberglass frame and IGU combinations. The potential effect of the thermal conductivity differences between both methods will be discussed further.

Table 8: NFRC and CEN U_{cog} Values

IGU	NFRC	CEN	% Change
Double High SHGC	1.627	1.466	11%
Double Low SHGC	1.336	1.071	25%
Triple High SHGC	0.681	0.58	17%
Triple Low SHGC	0.645	0.53	22%

Although the NFRC $U_{\text{cog-NFRC}}$ values for the double and triple IGUs were considerably higher than the CEN values, the higher performing triple IGUs had less of an impact on the U_{window} value than the double IGUs.

Lower performing insulated glazing units influence the thermal transmittance of the frame if the frame is poorly insulated. If the frame is well insulated, it improves U_{window} by impeding the thermal transmittance from the glazing to the frame which could further lower a poorly insulated frame.

4.4.2 $U_{\text{window-NFRC}}$ and $U_{\text{window-CEN}}$ with Various Material Thermal Conductivities

The $U_{\text{window-NFRC}}$ values of the fiberglass, TBSW and SW frames with the double and triple IGUs were compared using the NFRC and CEN thermal conductivity values as shown in Figure 9. All simulations used Spacer C. These results show that harmonizing the fiberglass thermal conductivity values, by utilizing the NFRC value (for example) for both methods, will result in 2-3% lower $U_{\text{window-CEN}}$ values. This drop in values would accentuate the differences in $U_{\text{window-NFRC}}$ and $U_{\text{window-CEN}}$ values seen above. Although using the same material thermal conductivities would accentuate the differences in U_{window} values of both methods, it is important to use the same thermal conductivities for a material and focus on other influential parameters in order to harmonize the two methods. For the solid wood frame, $U_{\text{window-NFRC}}$ values, with the NFRC thermal conductivity for softwood, were 4-6% lower than when using the CEN thermal conductivity. The percentage change is higher than for the TBSW frame due to the larger area of solid wood within the frame. Overall, using thermal conductivities that are 15-25% higher in each method can potentially give 2-6% lower $U_{\text{window-NFRC}}$ values.

Figure 1 $U_{window-NFRC}$ Fiberglass (upper), TBSW (middle) and SW (lower) Frames: NFRC and CEN Thermal Conductivities (TC)

Harmonizing the thermal conductivity values of both methods results in lower $U_{window-NFRC}$ values; whereby the magnitude of the increase is dependent upon the increase in thermal conductivity and the

area of that material within the frame. When identical thermal conductivities are used in both methods, the differences in U_{window} values are analogous for the TBSW and solid wood frames. The differences are less for the TBSW frame due to the less volume of solid wood and the use of lower conductive insulation foam, EPDM and frame cavities, which function as a thermal break between the higher conductive solid wood and aluminum siding. The TBSW frame also does not expose the solid wood to the exterior environment and is thus the other materials mentioned serve as a protective thermal barrier. Seeing that there are lesser differences in the higher performing frames, this supports the possibility of harmonizing the material thermal conductivities of both methods.

4.4.3 $U_{\text{window-NFRC}}$ and $U_{\text{window-CEN}}$ with NFRC and CEN Surface Film Coefficient Sets

Figures 10 and 11 present all frame and glazing combinations (fiberglass and TBSW) using Spacer C simulated with the $U_{\text{window-NFRC}}$ calculation method using NFRC and CEN surface film coefficients. The same window combinations were simulated with the $U_{\text{window-CEN}}$ calculation method using CEN and NFRC surface film coefficients.

The largest discrepancy for all the window combinations and frame types was for the double IGUs; particularly the double IGU combinations with a high SHGC due to the effect of the different interior and exterior temperature boundary conditions. The trend showed that there are greater differences in the U_{window} values of both methods for the most conductive frame, i.e. solid wood. For the remaining three frames, the deeper the inset of the IGU (i.e. sightline to the bottom of the IGU), and the longer the length between the sightline to the edge of the frame, as well as the conductivity of the frame components all contribute to the lower differences in U_{window} values between both methods.

Overall, the NFRC method’s lower surface film coefficient values result in lower $U_{\text{window-CEN}}$ values. Larger discrepancies were seen in the CEN simulations due to the omissions of the radiation component in the NFRC surface film coefficient sets as stated above.

Figure 10: Fiberglass Frame: NFRC vs CEN Surface Film Coefficients using the NFRC (upper) CEN (lower) Method

Figure 11: TBSW Frame: NFRC vs CEN Surface Film Coefficients using the NFRC (upper) CEN (lower) Method

4.4.4 $U_{\text{window-NFRC}}$ and $U_{\text{window-CEN}}$ using NFRC and CEN Frame Cavity Methods

Using the uPVC frame for context, Figure 12 shows negligible differences between both frame cavity methods when using the either method. This supports the harmonization of the frame cavity procedures of both the NFRC and CEN methods.

Figure 12: U-Window (PVC Frame) Using NFRC Standard (upper) and CEN Standard (lower)

4.5 Harmonization of the CEN and NFRC U_{window} Calculation Methods

Taking into account the percentage changes of all of the frame types and glazing combinations, the overall weighting of the magnitude of the percentage changes for each frame type was determined. Figure 13 compares the NFRC and CEN methods using the NFRC exterior temperature of -18°C . Out of 34 window simulations, the majority of simulations showed a 0-4% difference in NFRC and CEN values for the same window. Only 5 outliers were between a 5 and 6% difference in NFRC and CEN U_{window} values for the same window (i.e. triple IGUs solid wood frame in both methods and the quad TBSW in the CEN method). This finding may support a possible amalgamation between the two methods whereby using the same exterior temperature boundary conditions yields analogous results that primarily lie in a percentage error margin of 0-4%. A 4% lower $U_{\text{window-NFRC}}$ value translates to a 0.05 $\text{W/m}^2\text{K}$ lower difference. The results that lie in the higher 5-6% percentage error margin also support the possibility of amalgamating both methods for it translates to 0.06 $\text{W/m}^2\text{K}$ higher $U_{\text{window-CEN}}$ values in this study. When comparing the percentage errors found by others, where $U_{\text{window-NFRC}}$ values were found to be 14% lower to 18% higher than CEN values, and this study where $U_{\text{window-NFRC}}$ values were 1% lower to 11% higher than CEN values, the proposed amalgamation results have a minimal percentage error margin of 0-6%. Two of the outliers were found with the triple IGUs with the solid wood frame;

this may be attributed to the larger width of the frame that is exposed to the exterior and thus the change in exterior temperature is more pronounced with these frames.

Figure 13: NFRC and CEN U-window Values with NFRC Exterior Temperature Boundary Condition

In addition, this study's findings in comparing NFRC and CEN U_{window} values for the same window unit, have less of a variation than the generalized notion in the building community that NFRC values are approximately 10% higher or lower than CEN values. Generally, considering the triple and quad high performance window combinations with Spacer C, there is a minimal, 0 to 6% difference between the standard NFRC and CEN methods and boundary conditions. For several triple IGU combinations where the $U_{\text{window-NFRC}}$ values are 6% lower than CEN values, this difference translates to a minimal increase in U-window value by 0.067 W/m²K. The impact of this increase upon a building's annual energy intensity use would need further research considering the size and quantity and cardinal direction of the

710 aforementioned triple glazed window units; however the authors' opinion is it would typically be
711 minimal.

712 It should be noted the lower $U_{\text{window-NFRC}}$ values are slightly beneficial for North American window
713 manufacturer as it gives a slightly higher thermal performance value in the NFRC and CEN calculation
714 methods and thus in both North American and European markets. On the other hand, other factors
715 need to be deliberated upon along with thermal performance. Depending on one's location, a North
716 American window with a $0.05 \text{ W/m}^2\text{K}$ lower U-value may be chosen for a building located in North
717 America which results in financial and environmental savings for the builder as purchasing locally (i.e.
718 within North America) does not incur overseas transportation costs and thus reduces carbon emissions
719 and fossil fuel consumption. Likewise, for a building located in Europe, the same North American
720 window may be competitive within that market when this amalgamation method is used. For example,
721 for a standard NFRC rated window with a $0.96 \text{ W/m}^2\text{K}$ U-value and a CEN rating of $0.91 \text{ W/m}^2\text{K}$, the CEN
722 value would be favoured when selecting for higher thermal performance and achieving specified metrics
723 for primary energy such as that for the Passive House standard. However, the little gain in thermal
724 performance (in a whole building energy simulation) may not justify the transportation costs of
725 importing the European window product into North America. On the other hand, this window may be
726 competitive in the European market for its thermal performance when using the amalgamation method
727 which gives a $U_{\text{window-NFRC}}$ of $0.88 \text{ W/m}^2\text{K}$. Similarly, overseas transportation costs to Europe need to be
728 considered as well.

729 Using the proposed amalgamation method by synchronizing the exterior temperatures according to the
730 standard exterior temperatures, the North American windows used in this study would have a lower
731 U_{window} value using both the NFRC and CEN calculation methods. In terms of thermal performance,
732 simply using the same exterior temperature boundary conditions in computer simulations could
733 potentially support and enable the effort in creating a fairer method in comparing window products.

To evaluate the proposed amalgamation method, a comparison of U_{window} values, according to the NFRC and CEN method, was conducted at an exterior temperature range from -40 to 40°C. The NFRC and CEN U_{window} values were compared in this range for all frame types with double, triple and quad IGUs with a high and low SHGC. Overall, the $U_{\text{window-NFRC}}$ values were 8% lower to 4% higher than $U_{\text{window-CEN}}$ values for all of the exterior temperatures (see Figure 14). The majority of NFRC values were lower than CEN values. 88% of the values each had between a 0-5% difference between both methods. However, 12% of the values were between a 6 and 7% percentage change. By using the same thermal conductivities and tweaking the variations between the center-of-glazing simulations, the percentage change margin could be altered. Foremost, further research is needed to test the proposed amalgamation method to measure its suitability for windows that varying levels of thermal performance.

Figure 14: NFRC and CEN U-window Values Percentage Changes at NFRC (upper) and CEN (lower) Exterior Temperature Boundary Condition (Note: 1- Double High SHGC, 2- Double Low SHGC, 3- Triple High SHGC, 4- Triple Low SHGC, 5- Quad High SHGC)

Frame Cavity Method

For the high performance frames in this study, the difference in the frame cavity methods of both methods is negligible. However, caution needs to be taken for lower performing frames where there is a plethora of cavity regions within the frame. Out of all the frames, the U-PVC frame had the most frame cavities without any insulation materials and the results showed a larger difference of 4% in U-frame values between both methods. The number, size and configuration of the frame cavities impact the frame cavity surface temperatures where the larger the frame cavity and the more thermally conductive the frame materials are, the greater the likelihood of heat transfer to occur through conduction, radiation and convection. Computational Fluid Dynamics (CFD) analysis can specify the impact of heat transferred through increased convection flows within frame cavities; this has been identified by Curcija (2005) and other studies. This study also supports the need for further research into the CFD analysis of high performance frames in order to measure and standardize the impact of CFD of convection flows in frame cavities. Therefore, the difference in frame cavity methods has more of an impact in frames with more frame cavities, and materials that are more thermally conductive seeing that they impact the frame cavity surface temperatures.

Radiation Model

The radiation models of both methods could potentially be synchronized seeing that the NFRC detailed radiation model and the CEN simplified radiation model are the same. The harmonization of several aspects both methods could be achieved where both methods could use the same radiation model and use the same thermal conductivities for all the materials and gases.

U_{frame} Method

When comparing aspects of a whole window unit, the CEN method's procedure in determining U_{frame} is considered to be the most accurate in giving the thermal transmittance of the frame by itself, without the influence of the IGU. Since $U_{\text{frame-NFRC}}$ does not give the thermal transmittance of the frame by itself, the CEN U_{frame} method would be beneficial as an international standard for determining U_{frame} in order for different frames to be fairly compared in the international market. Keeping in mind that the different boundary conditions and calculation methods produce different results, the NFRC boundary conditions could be used. Further research and collaboration between NFRC and CEN experts would be needed to determine an NFRC method of determining U_{frame} with a calibration panel. Foremost, simulation results would need to be compared with physical lab testing to determine the accuracy of this. The NFRC method may potentially adopt the proposed amalgamation method of using the same exterior temperature for the calibration panel where the calibration panel is drawn in THERM and simulated according to the NFRC method; however boundary conditions would need to be altered.

Other Harmonizing Strategies and Areas that need Improvement

A clearer labeling system of glazing products is needed where the SHGC is specified for an individual glazing product (glazing only) and window product (with the frame) separately. Although each method for determining the SHGC of the glazing by itself are similar to each other, using the same boundary conditions and thermal conductivities would aid in synchronizing SHGC values. Similarly, adopting the same thermal conductivities of gas infill mixtures and the same U_{cog} procedure would be beneficial for comparing individual glazing products. Due to the trends found in this study, where U_{cog} values largely influenced the differences in U-values of both methods, the harmonization of the U_{cog} procedure of both methods needs further research. Likewise, harmonized surface film coefficient sets and summer and winter boundary conditions for an international standard needs further research.

The NFRC and CEN methods each have inherent strengths, however, elements of both could be viable in the international market. This study supports the findings identified by others where the CEN method is found to be more accurate in comparing individual window components. The NFRC method is considered to be more accurate in determining thermal transmittance, SHGC and center-of-glass values of the actual window product at specified product dimensions as identified by the NFRC standard.

In consideration of the results of this study, the CEN method is considered to be the preferred method of calculating the whole window U-value (i.e. $U_{W-ITN'L}$). However, a whole window U-value, for each climate zone in North America and Europe, would be ideal for each window product using the annual average exterior temperatures. A unified material and gas thermal conductivity list is necessary for a fairer comparison of products. The NFRC interior surface film coefficients are considered to be more accurate as they are specified according to the type of frame material; the interior reduced radiation sections may be omitted seeing that using one interior surface film coefficient simplifies the simulation process. Physical lab testing is needed to test the applicability and accuracy of this method.

Foremost, physical lab testing of an array of current high performance window products would also help identify which method is more accurate in calculating thermal transmittance. In addition, further testing using computer simulations could be performed to narrow the scope of physical lab testing that would be necessary, thereby reducing costs. Using 3D software may highlight the heat transfer characteristics in a more detailed manner, particularly in the IGU; this is beyond the scope of this study, however, physical lab testing would need to be rigorous. Finally, exploring the impact of various window sizes in continued research would add robustness to and future harmonization recommendations.

5 Conclusions

This study has shown the critical importance and intricacies of the calculation methods and procedures used in determining the thermal transmittance of window products. A comparative evaluation of the

NFRC and CEN U-value calculation methods was conducted for several North American residential high performance window products. An evaluation of the several parameters that are most influential in determining the whole window U-value for high performance windows in eight representative climate zones was also performed.

The differences that were found between both calculation methods showed that each window product configuration and material property react distinctively to the assumptions and boundary conditions of each method. The results of this study aid in identifying and explaining the percentage change between both methods, as well as, determining how each method defines and utilizes various parameters. The trend showed that the higher the performance of the IGU, the lesser the differences in U_{window} between the NFRC and CEN methods. The variances are accrued to the effect of the different exterior and interior temperature differences, surface film coefficients, frame cavity methods, U_{frame} methods, U_{cog} methods, material thermal conductivities and different U_{window} calculations. Lower performing windows would exhibit larger differences between both methods due to the greater influence of the exterior temperature on the gas infill in the lower insulative IGU. This is due to the heat transfer effects of the IGU transferring to the lower performing frame. The significant weighting of the U_{cog} in the U_{window} calculation results in a lower U_{window} value. Different calculations, assumptions and boundary conditions highlight the uniqueness of the NFRC and CEN standard thermal transmittance methods and therefore each method should be treated as such.

Considering the differences in the U-values of each method were generally smaller for high performance windows, the varying values of boundary conditions had less influence than on lower performing windows, as seen in previous studies. Altogether, this leads to the harmonization of both methods. Some of the parameters that could be harmonized include the exterior and interior temperatures, surface film coefficients, frame cavity methods, SHGC of the IGU without the frame and the U_{frame} method. Ideally, a single ISO international window calculation procedure for determining thermal

transmittance would allow for an equitable and fair comparison of window products in the international market. In working towards this, using the same exterior temperature, as shown in this study, could aid in harmonizing the NFRC and CEN methods, until an international standardized method is conceived. A harmonized international thermal transmittance calculation method would be highly beneficial for the window and high performance building industry in creating a fair market and more accurate performance metrics for energy models.

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