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**Impact on U-factor and SHGC of Differences in
Simulation Styles and Assumptions**

MASTER

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enermodal engineering, inc.

1554 Emerson Street
Denver, CO 80218
(303) 861-2070

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§1.0 Introduction

The thermal performance of a window is currently characterized by the window's thermal transmittance (U-factor) and its solar heat gain coefficient. The National Fenestration Rating Council (NFRC) has established a system for rating the thermal performance of windows. The U-factor is determined through computer simulation and validated with physical tests. The solar heat gain coefficient is determined for homogeneous products through computer simulation. Test methods exist for measuring solar heat gain through more complex products, although there is currently no standard.

Under the NFRC's rating program, a window must be simulated using the Window 4.1 and Frame 3.1 computer programs. There is some debate as to how accurately these computer programs simulate actual windows. This report addresses the differences in simulation styles and assumptions and what impact these differences have on the U-factor and solar heat gain coefficient. Section 2.0 covers center-of-glass modeling, section 3.0 covers spacer modeling, section 4.0 covers frame modeling, and section 5.0 concludes by weighing the relative importance of the assumptions discussed. The focus of this research is on U-factor. For a more detailed study of solar heat gain coefficients refer to Wright (1995).

This report also addresses the efficacy of various techniques, such as increasing glazing gap width or applying low-emittance coatings to interior glazing surfaces, at reducing total window U-factors.

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§2.0 Effects of Center-of-Glass Modeling Assumptions in Window 4.1

The center-of-glass area is defined as the glazed area minus a strip 2.5 inches wide adjacent to the window frame. The center-of-glass area is modelled in Window 4.1. Details that are specified in the model include gap width between layers of glazing, glass thickness, gas fill between glazing layers, and glazing type.

§2.1 Glazing Gap Width

Large glazing gaps are generally associated with reduced U-factors because as the gap width increases, the heat flow path increases, so the resistance to heat flow is increased. At a certain width, however, natural convection becomes stronger and wider gaps actually have decreased resistance to heat flow. This relationship is illustrated in Figure 2.1. For an air-filled gap, the U-factor decreases steeply (by 0.16 Btu/h·ft²·°F between 0.18 and 0.5 inches) as the gap width increases until the gap width is a little more than 0.5 inches, when it begins to increase again. This same relationship occurs with other gas fills at a gap thickness specific to each gas. Wright (1995) has shown that the gap width has a negligible effect on solar heat gain coefficient (SHGC).

Figure 2.1 Effect of gap thickness on U-factor for a 0.125 inch glass, air-filled glazing unit.

For gap widths greater than 1.375 inches, the U-factor results in Window 4.1 are slightly higher than what is expected. It is recommended that for gap widths greater than 1.375 inches that the user model the gap at 1.375 inches in Window 4.1.

§2.2 Glass Thickness

One-dimensional heat transfer through glass may be described by the Fourier conduction equation:

$$Q = [k \cdot A \cdot (T_h - T_c)] / L, \quad (\text{Equation 1})$$

where Q is the rate of heat flow in Btu/h, k is the thermal conductivity in Btu·in/h·ft²·°F, A is the area of the material perpendicular to the direction of heat flow in ft², L is the length of the heat flow path through the material in feet, T_h is the temperature on the hot side of the material in °F, and T_c is the temperature on the cold side of the material in °F. When modeling a glazing unit in Window 4.1, all of the variables in Equation 1 are constant except for the length of the heat flow path (glass thickness). Clearly, the thicker the glass is, the slower the rate of heat transfer, Q . To illustrate this, a glazing unit with a 0.5 inch air gap is simulated with different glass thicknesses and the resulting center-of-glass U-factors are plotted in Figure 2.2. Note that the resulting U-factors only decrease from 0.494 to 0.476 Btu/h·ft²·°F (3.6%) when the glass thickness is increased from 0.088 to 0.32 inches.

Figure 2.2 Effect of glass thickness on U-factor for an air-filled, 0.5 inch gap, insulated glazing unit.

Since glazing optical properties are specific to glass thickness, the SHGC of a glazing system is strongly dependent on glass thickness.

§2.3 Low-Emittance Coatings

Another way of reducing the center-of-glass U-factor is to apply a low-emittance (low-E) coating to one of the glass layers. This reduces the amount of infrared radiation (heat) that is transmitted through the window. A glazing unit with a gap of 0.5 inches is simulated with 100% air and 97% argon for a range of emittances. Whether the coating is on the second or third surface has no effect on U-factor, although placement on the first or fourth surfaces does (see Table 2.1). The resulting U-factors are plotted in Figure 2.3. Note that this is a semi-log plot.

Figure 2.3 Effect of surface emittance on U-factor for a 0.5 inch gap glazing unit.

When modeling low-E coatings in Window 4.1, it is important to locate the coating on the correct surface. A glazing unit with a half inch air gap is modelled with a low-E coating ($e = 0.085$) on different surfaces. The results are presented in Table 2.1. Placing the low-E coating on the wrong surface can create as much as a 55% difference in center-of-glass U-factor, and as much as a 5% difference in solar heat gain coefficient. Low-E coatings should always be modeled on the second or third surfaces of an insulated glazing unit or the full effect of the coating on the U-factor will not be realized. Whether the low-E coating is on the second or the third surface has a negligible effect on U-Factor. However, a glazing unit with the low-E coating on the second surface has a lower solar heat gain coefficient than a glazing unit with the same coating on the third surface.

Table 2.1 Effect of placement of low-emittance coating on U-factor and SHGC.

Glazing Unit Description	Center-of-Glass U-Factor	Solar Heat Gain Coefficient
SG100(1)/AIR/CL	0.4858	0.59
SG100(2)/AIR/CL	0.3126	0.58
CL/AIR/SG100(3)	0.3127	0.64
CL/AIR/SG100(4)	0.3661	0.61

§2.4 Gas Fill

Glazing gaps may be filled with inert gas mixtures having conductivities less than that of air to further reduce the transfer of heat between glazing layers. The most common gas fill is argon. A few manufacturers are also using krypton.

To determine what relationship exists between the percentage of inert gas and the U-factor, a glazing unit with a 0.5 inch gap and a low-emittance coating on one surface is simulated with different percentages of argon. The resulting U-factors are plotted in Figure 2.4. A difference of 10% in argon fill results in about a 2% difference in the center-of-glass U-factor.

The single point labelled 100% argon in Figure 2.4 is the result of a discrepancy in the Window 4.1 program. The program allows the user to specify the mixture of gases, but gives a different answer if 0% air is specified in an air/argon mixture than what is assumed for pure argon. The difference between these two center-of-glass U-factors is about 1%.

Figure 2.3 compares an air-filled window with an argon-filled window while varying the surface emittance. For uncoated glass, the argon reduces the center-of-glass U-Factor by 0.02 Btu/h·ft²·°F. For coated glass with an emittance of 0.01, argon reduces the center-of-glass U-factor by 0.03 Btu/h·ft²·°F. The reduction is greater in low-E windows because conduction through the gas is the dominant mode of heat transfer. In uncoated windows, radiative heat transfer is dominant.

Figure 2.4 Effect of percent argon gas fill on U-factor for a 0.5 inch glazing gap and a low-emittance coating on one surface.

Figure 2.5 Effect of gap thickness on U-factor for a krypton-filled unit with a low-E coating ($e=.1$) on the second surface.

Figure 2.6 Effect of percent krypton gas fill on U-Factor for a unit with an 0.3 inch gap and a low-emittance coating ($e=.1$) on the second surface.

Figures 2.5 and 2.6 show the effect of gap thickness and percent gas fill on U-factor for a krypton-filled unit with a low-E coating on the second surface. The optimum gap width for a krypton-filled window is approximately 0.3 inches.

§2.5 Combined Effects

§2.5.1 Gap Width and Glass Thickness

When modeling a glazing unit of a fixed overall width, the gap width may vary depending on the glass thickness used. For example, a unit which is modelled at two different sizes may require thicker glass for structural reasons in the larger size. To determine what effect this has on the center-of-glass U-factor, glazing units in four overall widths were modelled with varying glass thicknesses and gap widths. The results are presented graphically in Figure 2.7. As long as the gap is greater than about 0.45 inches, the impact of gap width and glass thickness on U-factor is negligible (less than 2%). When the gap is less than 0.45 inches, the difference is as much as 11% for a change in gap thickness of 0.1 inches. The same results are shown in Figure 2.8 as a bar graph.

Figure 2.7 Effect of glass thickness on U-factor for four different overall glazing unit widths.

Figure 2.8 Effect of glass thickness on U-factor for four different overall glazing unit widths.

§2.5.2 Gap Thickness, Gas Fill and Coating Emittance

The effect that gap thickness has on center-of-glass U-factor is dependent on the composition of the gas mixture filling the gap. Figure 2.9 illustrates the differences in U-factor for three different gas mixtures, a low-E coating with an emittance of 0.10, and varying gap thicknesses. The effect gap thickness has on center-of-glass U-factor is also affected by the emittance of the surface coating.

Figure 2.9 Effect of gap thickness on U-factor for three different gas mixtures in a glazing unit with a low emittance coating ($e=0.1$).

Figure 2.10 Effect of gap thickness on U-factor for three different glazing units.

Figure 2.10 illustrates the effect on U-factor of gap thickness, gas fill, and coating emittance in combination. The lower the emittance the greater the effect is from varying the gap thickness. Again, this is because conduction through the gas fill dominates the heat transfer in low-E windows.

§2.6 Use of Spectral Data Files

When modeling glazing units in Window 4.1, files containing the spectral data for each glass type are available and should be used if reporting solar heat gain coefficient. The spectral data has no bearing on center-of-glass U-factors. To determine what effect omission of the spectral data has on the center-of-glass SHGC, several glazing units were simulated with and without the spectral data. Clear, bronze, green, and blue glass were combined with clear glass (Glazing Units 1-4), with SunGate100 Low-E glass (Glazing Units 5-8), with Heat Mirror and clear glass (Glazing Units 9-12), and with Heat Mirror and SunGate100 (Glazing Units 13-16). The results are compared in Table 2.2 and Figure 2.11. The effect of omitting the spectral data is to decrease the solar heat gain coefficient by as much as 23.8 percent.

Figure 2.11 Solar heat gain coefficients with and without spectral data.

Table 2.2 Effect of using spectral data on solar heat gain coefficient (SHGC).

#	Glazing Unit Description	SHGC		% Diff
		without spectral data	with spectral data	
1	CLR/.5" AIR/CLR	0.75	0.76	1.3
2	BRONZE/.5" AIR/CLR	0.62	0.62	0
3	GREEN/.5" AIR/CLR	0.50	0.51	2.0
4	AZURE/.5" AIR/CLR	0.46	0.46	0
5	CLR/.5" AIR/SG100	0.62	0.64	3.2
6	BRONZE/.5" AIR/SG100	0.50	0.51	2.0
7	GREEN/.5" AIR/SG100	0.40	0.43	7.5
8	AZURE/.5" AIR/SG100	0.36	0.40	11.1
9	CLR/.25" AIR/HM66/.25" AIR/CLR	0.36	0.37	2.8
10	BRONZE/.25" AIR/HM66/.25" AIR/CLR	0.30	0.30	0
11	GREEN/.25" AIR/HM66/.25" AIR/CLR	0.25	0.29	16.0
12	AZURE/.25" AIR/HM66/.25" AIR/CLR	0.23	0.28	21.7
13	CLR/.25" AIR/HM66/.25" AIR/SG100	0.32	0.35	9.4
14	BRONZE/.25" AIR/HM66/.25" AIR/SG100	0.27	0.29	7.4
15	GREEN/.25" AIR/HM66/.25" AIR/SG100	0.22	0.27	22.7
16	AZURE/.25" AIR/HM66/.25" AIR/SG100	0.21	0.26	23.8

§3.0 Spacer Effects on Edge-of-Glass and Frame Heat Transfer

The influence of varying the spacer effective conductivity on the heat transfer through the frame and edge-of-glass areas is discussed in this section. The results presented are taken from Reilly (1993) and are specific to fixed frames which have relatively short profiles (short frame height) as compared to other operator types. The influence of the spacer assembly on the heat transfer through the shorter frame is equal to or greater than it would be on a frame with a taller profile. The design of the frame and the position of the insulated glass unit in the frame will also affect the performance, although this is not considered here.

Arasteh (1989) analyzed the edge-of-glass heat transfer with respect to different spacer types, the position of the spacer relative to the sightline, and center-of-glass U-factors. The results show that as the center-of-glass U-factor decreases, the difference in edge-of-glass U-factors slowly increases between different spacer types. For example, the difference between the edge-of-glass U-factor with a single-seal aluminum spacer and a highly insulating spacer in a double-glazed unit with a center-of-glass U-factor of $0.50 \text{ Btu/h}\cdot\text{ft}^2\cdot^\circ\text{F}$ is $0.10 \text{ Btu/h}\cdot\text{ft}^2\cdot^\circ\text{F}$. In a double-glazed unit with a center-of-glass U-factor of $0.27 \text{ Btu/h}\cdot\text{ft}^2\cdot^\circ\text{F}$, the difference is $0.14 \text{ Btu/h}\cdot\text{ft}^2\cdot^\circ\text{F}$. The relationship between center-of-glass U-factor and edge-of-glass U-factor is not explored any further in this report.

Arasteh (1989) also investigated the impact of dropping the spacer below the sightline. By burying the glazing unit deeper into the sash or using a low-profile spacer, the heat transfer path from the exterior surface of the glass, through the spacer, and to the interior surface of the glass is effectively lengthened. This in turn reduces the heat loss through this area.

Fraser (1993) identified many of the differences between reported material conductivity values. Enermodal Engineering Limited (EEL, 1990) performed a sensitivity study to assess the impact of varying the material conductivities on window heat transfer. The results show that varying the conductivity of the elements which control the heat transfer through a window (the controlling resistance) can result in a difference of up to 25% in total window U-factor. This difference was found with a wood window in which the wood conductivity was varied by 40%. Nearly doubling the thermal conductivity of the thermal break in a thermally-broken aluminum window resulted in only a 4% difference in the combined frame and edge U-factor.

As with frames, the influence of variations in material conductivities on the heat transfer through a spacer assembly also depends on the controlling resistance. Fraser (1993) studied the difference between single-seal aluminum and dual-seal aluminum spacers. The disagreement between experimental and simulation results for single-seal spacers lead to the conclusion that the contact resistance at the glazing/spacer interface significantly reduces the heat loss. This interface is the controlling resistance in single-seal and dual-seal spacers. EEL (1990) took the analysis further and looked at the impacts from varying the spacer materials and dimensions on the edge-of-glass and frame heat transfer. Because the spacer assembly is not the controlling resistance in fenestration products, varying the material conductivities and dimensions over the

range of reported values has little effect on the total heat transfer through the edge-of-glass area and frame. The most significant influence is from varying the primary sealant thickness in dual-seal spacers and is explored further in this study.

Figure 3.1 Simulation model of the aluminum picture frame with a single-block spacer.

Figure 3.2 Simulation model of the vinyl picture frame with a two-block spacer model.

§3.1 Base Models

The base model for the study is a fixed frame with insulated glazing. The glazing system has an overall width of 0.75 inches, two lites of clear, double-strength glass, and a 0.51 inch air gap. Figures 3.1, 3.2, and 3.3 show the aluminum, vinyl, and wood fixed frame models respectively. In the figures, the left represents the outside and the right represents the inside. The fixed frame was chosen because of its relatively short profile (frame height). With a shorter frame profile, the influence of the spacer on the frame and edge-of-glass heat transfer is more pronounced. The aluminum frame has a frame height of 1.3 inches and the vinyl and wood frames have frame heights of 1.8 inches.

Figure 3.3 Simulation model of the wood picture frame with a detailed spacer model.

A spacer assembly consists of the spacer bar with primary and secondary sealants (Figures 3.4 and 3.5). In single-seal spacers, there is no secondary sealant and the primary sealant is behind the spacer bar. Dual seal spacers have a primary sealant between the glass and the spacer bar and the secondary sealant is behind the spacer bar. The difference between the two thermally-broken spacers is the thermal-break size and material. The spacer height is the distance from the bottom to the top of the spacer assembly. For this study, the bottom of the spacer assembly is flush with the bottom of the glass. Table 3.1 lists each of the spacers, the spacer height, the sealants, and the effective thermal conductivity. For more detailed information on the spacer assemblies see Elmahdy (1993), Fraser (1993), and Popular Science (1992).

Three different modeling approaches to the spacer were taken. The spacers were modeled as a single block (Figure 3.1), as two blocks (Figures 3.2 and 3.5), and in detail (Figures 3.3, 3.4, and 3.5). The effective thermal conductivities, k_{eff} , of the spacers for the two-block and single-block models were determined by modeling the spacers in detail separate from the frame assembly. The effective conductivity is equal to the U-factor over a specified surface area multiplied by the overall width of the spacer assembly. The approach is described in detail in EEL (1993).

To account for the influence of the spacers on the heat transfer through the edge-of-glass and the frame areas, the simulation results are presented as U-factors for the edge-of-glass area, U_e , for the frame area, U_f , and for the combined edge-of-glass and frame areas, U_{e+f} (Figures 3.6, 3.7, and 3.8). The U-factor for the combined areas, U_{e+f} , best represents the influence a spacer can have on window heat transfer. Note that the center-of-glass U-factor, U_c , is held constant in this study at $0.49 \text{ Btu/h}\cdot\text{ft}^2\cdot^\circ\text{F}$.

Figure 3.4 Spacer Schematic of the Dual Seal Aluminum and Dual Seal C-Channel Spacers.

Figure 3.5 Spacer Schematic of the Thermally-Broken Spacer and the two-Block model for this spacer. The single-block model would simply be a rectangle the size of the two-block model.

The fixed window frame serves to show the maximum effect a spacer can have on frame and edge-of-glass heat transfer. The total window U-factor is omitted since the center-of-glass heat transfer is typically dominant in a fixed window and the impact of the spacer on total window heat transfer is therefore small. For frames with taller profiles, the influence on the edge-of-glass and frame heat transfer can be expected to be equal to or less than that shown here.

Table 3.1 Spacer Descriptions

Spacer	Spacer Bar Material	Primary Sealant	Secondary Sealant	Spacer Height (in)	k_{eff} Btu/h·ft ² ·°F
Single-Seal Aluminum	AL	Poly-sulphide	-	0.50	58
Dual Seal Aluminum	AL	PIB	Poly-sulphide	0.50	9.1
Dual Seal Aluminum	AL	PIB	Silicone	0.50	10.6
Low-Profile Dual Seal AL	AL	PIB	Poly-sulphide	0.43	9.8
Corrugated Strip	Butyl / AL	(Air)	-	0.43	4.1
Dual Seal C-Channel	Galv. Steel	PIB	Poly-sulphide	0.43	5.0
Dual Seal C-Channel	Stainless Steel	PIB	Poly-sulphide	0.43	2.3
Foam	Silicone	Urethane	-	0.50	1.4
TB Steel	Galv. Steel	PIB	Poly-sulphide	0.50	3.4
TB Steel	Galv. Steel	Urethane	-	0.50	2.2

KEY: AL=Aluminum; Galv. = Galvanized; k_{eff} = effective thermal conductivity for the single-block model; Spacer Height = distance from top of spacer to bottom of sealant behind the spacer; TB = thermally-broken.

Figure 3.6 Effect of spacer conductivity on U-factor for an aluminum fixed frame.

Figure 3.7 Effect of spacer conductivity on U-factor for a vinyl fixed frame.

Figure 3.8 Effect of spacer conductivity on U-factor for a wood fixed frame.

§3.2 Single- and Two-Block Models Compared to Detailed Model

In comparing U_{e+f} for the three modeling approaches, the single-block, two-block, and detailed models give identical results except for the thermally-broken spacers. For the thermally-broken spacers, the two-block model and the detailed model give the same results. For the vinyl frame only, the single-block model has a U_{e+f} that is 0.01 Btu/h·ft²·°F less than the two-block and detailed models.

§3.3 Variation in Material Properties

The influence of variations in material properties is seen with the dual-seal aluminum spacers and the C-channel spacers. With the dual-seal aluminum spacers, the sealants provide the controlling resistance. The conductivity of polyisobutylene is 1.66 Btu/h·ft²·°F. Figures 3.6, 3.7, and 3.8 show that significant increases in the conductivity of the primary sealant will not have a strong influence on U_{e+f} . However, decreasing the conductivity to 1.0 Btu·in/h·ft²·°F reduces k_{eff} of the dual seal aluminum spacer with a polysulphide secondary sealant to 6.5 Btu·in/h·ft²·°F. This reduces U_{e+f} by 0.01 Btu/h·ft²·°F - see Figures 3.6, 3.7, and 3.8. The conductance of the primary sealant is 83 Btu/h·ft²·°F. By reducing the conductivity to 1.0 Btu·in/h·ft²·°F, a conductance of 50 Btu/h·ft²·°F is obtained. This is equivalent to increasing the thickness of the primary sealant from 0.02 to 0.03 inches.

The difference in the secondary sealants of the two dual seal aluminum spacers - polysulphide has a thermal conductivity of $1.32 \text{ Btu}\cdot\text{in}/\text{h}\cdot\text{ft}^2\cdot^\circ\text{F}$ and silicone has a conductivity of $2.5 \text{ Btu}\cdot\text{in}/\text{h}\cdot\text{ft}^2\cdot^\circ\text{F}$ - results in a relatively small difference in k_{eff} (Table 3.1). Figures 3.6, 3.7, and 3.8 show that this also translates into a difference of $0.01 \text{ Btu}/\text{h}\cdot\text{ft}^2\cdot^\circ\text{F}$. With respect to the spacer bar materials, galvanized steel has a thermal conductivity of $332 \text{ Btu}\cdot\text{in}/\text{h}\cdot\text{ft}^2\cdot^\circ\text{F}$ and stainless steel has a thermal conductivity of $99 \text{ Btu}\cdot\text{in}/\text{h}\cdot\text{ft}^2\cdot^\circ\text{F}$. The difference in $U_{\text{e+f}}$ for the two spacers is $.01 \text{ Btu}/\text{h}\cdot\text{ft}^2\cdot^\circ\text{F}$.

§3.4 Variation in Effective Conductivity

Figures 3.6, 3.7, and 3.8 show the influence of varying the effective conductivity of a single-block model on the U-factors for each of the frame types for spacer heights of 0.50 and 0.43 inches. The figures clearly show that 0.5 inch spacer assemblies with effective conductivities less than $5 \text{ Btu}\cdot\text{in}/\text{h}\cdot\text{ft}^2\cdot^\circ\text{F}$ have the strongest effect on the heat transfer through the frame and edge areas. Over the range of effective conductivities shown in the figures, $U_{\text{e+f}}$ differs by as much as $0.07 \text{ Btu}/\text{h}\cdot\text{ft}^2\cdot^\circ\text{F}$ for the wood and vinyl frames, and $0.04 \text{ Btu}/\text{h}\cdot\text{ft}^2\cdot^\circ\text{F}$ for the aluminum frame.

§4.0 Effects of Modeling Assumptions in Frame 3.1

The National Fenestration Rating Council (NFRC) requires the Frame 3.1 computer program to be used to model the thermal performance of window frames. Because the program uses a simple finite difference method to model window frames, there are some limitations that require special techniques to create an accurate model. These are issues that individual simulators may approach differently and it is important to determine how much impact on U-factors these differences might have. The issues that are addressed in this section are modeling exposed slanted surfaces, air cavities, thermal breaks, and aluminum frames.

NFRC does not require additional Frame 3.1 simulations to calculate solar heat gain coefficients. The solar heat gain coefficient for the frame is proportional to U_{frame} . The frame solar heat gain coefficient has a relatively small influence on the total window solar heat gain coefficient, so variations in U_{frame} are inconsequential. Refer to "Comparison of U.S. and Canadian Thermal Performance Procedures, Standards, and Accreditation and Certification Programs for Fenestration Products," (EEI 1995) for more detail.

§4.1 Exposed Sloped Surfaces

Since sloped surfaces cannot be directly specified in Frame 3.1, sloped sills are modelled using stepped surfaces. The boundary conditions must be modified to account for the resulting increase in outside surface area. The modified film coefficient is calculated according to

$$h_m = h_o(l_o/l_m), \quad \text{(Equation 2)}$$

where h_m is the modified film coefficient, h_o is the default film coefficient, l_m is the modified length (stepped) of exposed surface, and l_o is the true length (sloped) of exposed surface. The default film coefficient (h_o) for the outside surface (15 mph wind and 0°F) is 5.11 Btu/h·ft²·°F.

To quantify the effect of different modeling styles on U-factors, the sloped sill of a vinyl vertical slider is modelled using one, two, and four steps as shown in Figure 4.1.

Figure 4.1 Three styles of modeling a sloped sill.

For each model, the length of exposed surface used to model the sloped section is 2.000 inches. The length of the sloped section is 1.565 inches. Thus the modified film coefficient is 4.00 Btu/h·ft²·°F. The one step model is run using both the default and modified exterior film coefficients to determine the effect of neglecting the correction. The results of the four simulations are shown in Table 4.1.

Table 4.1 Effect on U-factors of number of steps used to model sloped surface in vinyl frame.

Vinyl Model	Conductance [Btu/h·ft ² ·°F]		
	U _{frame, Sill}	U _{edge, Sill}	U _{total, Window}
One Step, h = 5.11	0.4143	0.3061	0.319
One Step	0.4117	0.3060	0.318
Two Steps	0.3990	0.3055	0.318
Four Steps	0.3929	0.3053	0.318

The impact of neglecting to modify the exterior film coefficient is to decrease the frame conductance for the sill cross section by less than 1%. Between the one step and four step models with modified exterior film coefficients, U_{frame} changes almost 12%. When the sill is represented by multiple steps, the large air cavity is broken up into small rectangles. Breaking up air cavities decreases the overall conductance of heat and is discussed further in section 4.2.2. The NFRC guidelines require the effective conductivities of the smaller cavities to be adjusted to that of the equivalent larger rectangle. Also, inspection of the models shown in Figure 4.1 reveals that the models with more steps have a longer heat transfer path to the inside than the one step model. The relative importance of these two effects is established in section 4.2.3. The difference in U_{edge} between the three models is negligible.

Typically the sill is the only member with an exposed, sloped surface. If the sill and its edge-of-glass area account for 10% of the window area, then the modelling assumptions have less than a 1% impact on the total window U-factor.

To determine what effect these same modeling assumptions have on an aluminum window, the vinyl in the above model is replaced with aluminum. The results presented in Table 4.2 demonstrate that correcting the exterior film coefficient has a greater impact (slightly more than 1%) on the aluminum frame because of its greater conductivity, but it is still negligible for the whole window. Changing the number of steps in the sill has no significant impact on U-factors because the heat loss is through the aluminum and the air cavities provide no resistance to the heat flow.

Table 4.2 Effect on U-factors of number of steps used to model sloped surface in aluminum frame.

Aluminum Model	Conductance [Btu/h·ft ² ·°F]		
	U _{frame} (sill)	U _{edge} (sill)	U _{total} (window)
One Step, h = 5.11	1.7186	0.3972	0.709
One Step	1.6988	0.3962	0.708
Two Steps	1.6979	0.3962	0.708
Four Steps	1.6977	0.3960	0.708

§4.2 Air Cavities

§4.2.1 User-defined Air Cavities

The heat transfer through an air cavity in a frame model is estimated using an effective conductivity that accounts for conduction, convection, and radiation. The effective conductivity is calculated by the program using either user-specified temperatures and emittances or default conditions depending only on the emittances of the surfaces abutting the cavity.

To quantify the effects of using default air cavities, the air cavities in a single-hung vinyl window are modelled both using default conditions and specifying the actual cavity temperatures. For example, the five largest air cavities in the original, one step vinyl sill model were modified to use the temperatures calculated by running the model with the default conditions. Table 4.3 presents both the default (DF) and user-defined (UD) temperatures on the cold and warm sides of the five largest cavities, as well as the resulting conductivities. The difference in individual cavity conductivity is as much as 20% for the largest cavity. The effect on smaller cavities is as little as 0%.

Figure 4.2a shows the effective conductivities calculated using the default temperatures. Figure 4.2b shows the temperatures calculated using the default conductivities that were then used to define new effective conductivities. Figure 4.2c shows the resulting effective conductivities. Significant differences in effective conductivities are evident. The conductivities of the large air cavities in the other four cross sections were also redefined to determine the total effect on the window U-factor. Table 4.4 illustrates the effects on the sill and total window U-factors. While the general effect of redefining the air cavity conductivities with more accurate temperatures is to increase the U-factors, the change in total window U-factor is just 1.6%.

Table 4.3 Effect of using default air cavities on temperatures and effective conductivities.

Cavity	Temperature [°F]				K _{eff} [Btu·in/h·ft ² ·°F]		% Diff.
	Cold, DF	Cold, UD	Warm, DF	Warm, UD	DF	UD	
1	12.8	13.1	49.4	49.2	0.48	0.48	0
2	52.6	52.4	66.2	66.0	0.60	0.62	+3.2
3	15.8	16.6	46.5	45.7	1.05	1.18	+11.0
4	14.8	15.1	45.8	45.1	1.49	1.67	+10.8
5	2.5	2.4	14.5	16.0	1.28	1.07	-19.6

Figure 4.2 Modeling air cavities using default (a) and user-defined (b and c) conditions.

Table 4.4 Effect on U-factors of using default conditions for air cavities.

Model	Conductance [Btu/h·ft ² ·°F]			
	U _{edge} (sill)	U _{frame} (sill)	U _{total} (sill)	U _{total} (window)
Default	0.3060	0.4117	0.3669	0.318
User-Defined	0.3062	0.4238	0.3739	0.323

§4.2.2 Breaking Up Large Air Cavities

Modeling sloped sills is discussed in section 4.1. It is noted that using several steps resulted in the air cavity in the sloped section of the sill being broken up into small rectangles. The relative dimensions and overall size of the air cavity dictates the amount of convective heat transfer occurring. In general, smaller air cavities have less convective heat transfer than larger ones and therefore have lower effective conductivities.

To quantify the effects of breaking up air cavities, an air cavity is modelled independently (not part of a window frame) as one, two, and three rectangles (see Figure 4.3). The temperature is defined as 10 °F on the cold side and 50 °F on the warm side. The emittance on both sides is taken to be 0.9. The overall dimensions of the cavity are 1.5 inches by 1.2 inches (width by height). The resulting total U-factors are summarized in Table 4.5. The effect of dividing a cavity into smaller rectangles is to reduce the conductance of the air pocket by as much as 57%.

a)	$e = 0.9$ $T = 10^\circ\text{F}$	$K = 1.80$	$e = 0.9$ $T = 50^\circ\text{F}$
b)	$e = 0.9$ $T = 10^\circ\text{F}$	$K = 1.36$ $K = 1.36$	$e = 0.9$ $T = 50^\circ\text{F}$
c)	$e = 0.9$ $T = 10^\circ\text{F}$	$K = 0.77$ $K = 0.77$ $K = 0.77$	$e = 0.9$ $T = 50^\circ\text{F}$

Figure 4.3 Air cavity modelled as one (a), two (b), and three (c) rectangles and resulting effective conductivities.

Table 4.5 Effect on U-factors of breaking up air cavities in the frame model.

Model	U_{total} [Btu/h·ft ² ·°F]	% Difference (from one cavity)
One Cavity (1.5" x 1.2")	1.20	0
Two Cavities (1.5" x 0.6" each)	0.91	24.2
Three Cavities (1.5" x 0.4" each)	0.52	56.7

To see the theoretical maximum effect that breaking up air cavities could have in an actual window simulation, the sloped vinyl sill is modeled with all of the air cavities broken up so that the effective conductivities are close to $0.3 \text{ Btu}\cdot\text{in}/\text{h}\cdot\text{ft}^2\cdot^\circ\text{F}$. The U_{edge} for this model is $0.3045 \text{ Btu}/\text{h}\cdot\text{ft}^2\cdot^\circ\text{F}$ and the U_{frame} is $0.2391 \text{ Btu}/\text{h}\cdot\text{ft}^2\cdot^\circ\text{F}$. This represents a 70% decrease in sill frame U-factor. Extrapolating these results by noting that the frame is 28% of the total window area and assuming a similar difference could be achieved in other cross sections, breaking up large air cavities could have as much as a 20% effect on total window U-factor, although such an extreme case would never actually occur.

The NFRC requires this issue to be addressed in the following manner. An air cavity with a total area equal to the area of the whole cavity and width equal to the width of the whole cavity in the direction of heat flow must first be modelled to determine the correct conductivity. The smaller rectangles comprising the air pocket are assigned the same conductivity. The effect of making this adjustment in an actual sill model is illustrated in Table 4.6. The effective conductivity calculated in the "one step" model ($1.28 \text{ Btu}\cdot\text{in}/\text{h}\cdot\text{ft}^2\cdot^\circ\text{F}$) is used in all of the air cavity rectangles comprising the sill cavity in the two and four step models.

Table 4.6 U-factors in sloped vinyl sill with user-defined conductivity (compare to Table 4.1).

Vinyl Model	Conductance [$\text{Btu}/\text{h}\cdot\text{ft}^2\cdot^\circ\text{F}$]		
	$U_{\text{frame}} (\text{sill})$	$U_{\text{edge}} (\text{sill})$	$U_{\text{total}} (\text{window})$
One Step	0.4117	0.3060	0.318
Two Steps	0.4041	0.3058	0.318
Four Steps	0.4044	0.3056	0.318

If the results in Table 4.6 are compared to those in Table 4.1, it becomes apparent that modeling a sloped sill with four steps produces a U-frame that is within 2% of the U-frame for the one step model if the effective conductivity of the air cavities is corrected. If default effective conductivities are used, the U-frame of the four step model differs from the U-frame of the single step model by up to 5%. Once the effective conductivities have been corrected, the residual difference in U-frame is due to the increased path length for heat flow in the multiple step models.

§4.3 Thermal Breaks

The following discussion of thermal break modeling is partially based on material presented by EEL (1992).

§4.3.1 Thermal Break Width

The controlling resistance in a thermally-broken aluminum window is the width of the thermal break. To determine the relationship between total window U-factor and thermal break width, a casement window with a thermally-broken aluminum frame was modelled with gaps of various widths (see Figure 4.4). The results of the comparison are presented in Table 4.7 and in Figure 4.5. As the thermal break width increases from 0.05 to 0.2 inches (400%), the total window U-factor decreases by nearly 7%. Increasing the width beyond 0.2 inches achieves lower U-factors but the difference for another 0.15 inches is only 4%.

(a) Gap = 0.100 inch

(b) Gap = 0.200 inch

(c) Gap = 0.400 inch

Figure 4.4 Casement window cross section with different thermal break widths.

Figure 4.5 Total window U-factor as a function of thermal break width.

Table 4.7 Effect of thermal break width on U-factors.

Width of Break (inches)	Conductance [Btu/h·ft ² ·°F]			
	U _{edge} (section)	U _{frame} (section)	U _{total} (section)	U _{total} (window)
0.050	0.5844	1.0239	0.7935	0.656
0.100	0.5738	0.9611	0.7581	0.637
0.150	0.5664	0.9150	0.7322	0.623
0.200	0.5605	0.8786	0.7118	0.611
0.250	0.5562	0.8496	0.6958	0.603
0.300	0.5523	0.8234	0.6813	0.595
0.325	0.5505	0.8112	0.6745	0.591
0.350	0.5488	0.8001	0.6683	0.588
0.375	0.5484	0.7935	0.6650	0.586
0.400	0.5458	0.7799	0.6572	0.581
0.450	0.5433	0.7624	0.6475	0.576
0.500	0.5410	0.7463	0.6387	0.571

Figure 4.6 Total window U-factor as a function of thermal break material conductivity.

§4.3.2 Thermal Break Conductivity

Another critical factor in modeling thermal breaks is the conductivity of the thermal break material. Using a gap width of 0.200 inches, the same casement window is modelled using various thermal break materials. The results of the comparison are presented in Table 4.8 and Figure 4.6. Decreasing the conductivity of the thermal break from 3.61 to 0.21 Btu·in/h·ft²·°F decreases the total window U-factor by 17%.

Table 4.8 Effect of thermal break conductivity on U-factors.

Conductivity of Thermal Break [Btu·in/h·ft ² ·°F]	Conductance [Btu/h·ft ² ·°F]			
	U _{edge} (section)	U _{frame} (section)	U _{total} (section)	U _{total} (window)
0.21 (polyurethane foam)	0.5217	0.6011	0.5595	0.528
1.18 (rigid vinyl)	0.5480	0.7902	0.6632	0.585
1.60 (fiberglass-reinforced nylon)	0.5547	0.8360	0.6885	0.599
2.15 (urethane)	0.5615	0.8809	0.7135	0.612
3.61 (high density polyethylene)	0.5730	0.9533	0.7539	0.634

§4.4 Interior Film Coefficients in Non Thermally-Broken Aluminum Frames

The controlling resistance in a non thermally-broken aluminum frame is the exposed surface area on the inside. The amount of heat transfer occurring at this surface is dictated by the surface area and the interior film coefficient. The interior film coefficient is calculated in Frame 3.1 using the following equation from the 1993 ASHRAE Fundamentals on page 27.4:

$$h_i = 0.27 \cdot (T_i - T_s)^{0.25} + [e_s \cdot \sigma \cdot (T_i^4 - T_s^4)] / (T_i - T_s), \quad (\text{Equation 3})$$

where h_i is the interior film coefficient in Btu/h·ft²·°F, T_i is the inside air temperature (70°F), T_s is the inside surface temperature, e_s is the inside surface emittance, and σ is the Stefan-Boltzmann constant (1.712E-9 Btu/h·ft²·°R⁴). The temperatures in the second part of the equation must be in degrees Rankine. An assumption must be made for the temperature and the emittance of the inside surface of the frame.

Frame 3.1 assumes a surface emittance of 0.84 and a surface temperature of 20 °F for an aluminum frame. To examine how accurate this assumption is and what effect it has on the total window U-factor, a single-hung window is modelled with four different values of emittance.

Since Frame 3.1 allows you only to specify the surface film coefficient and the air temperature at the boundary (70 °F), the emittance must be adjusted indirectly. An interior film coefficient is guessed, the Frame 3.1 model is run, and the resulting temperatures on the interior surface are examined. Another iteration is performed with a new interior film coefficient and the resulting temperatures are compared to the temperatures that would be required to produce the desired emittance. For example, to achieve a surface emittance of 0.84 (Frame's default emittance), the boundary is first given a film coefficient of 1.461 Btu/h·ft²·°F. After running Frame, the local temperature feature is used to find the temperature of the inside surface of the aluminum frame (34 °F). Putting this temperature and emittance into the above equation yields a film coefficient of 1.433 Btu/h·ft²·°F. Using a film coefficient of 1.433 Btu/h·ft²·°F resulted in convergence on the inside surface temperature. This same process was used to determine what emittance and surface temperature would be required to produce a film coefficient of 1.461 Btu/h·ft²·°F for this window. To determine what impact the assumption of surface emittance has on the total window U-factor, emittances of 0.5 and 0.2 were also simulated. The relationship between surface temperature and film coefficient is illustrated in Figure 4.7 for three values of emittance. Increasing the inside surface temperature by 50 °F decreases the film coefficient by 15%. The impact of emittance on total window U-factor is shown in Table 4.9 and Figure 4.8. Increasing the frame emittance from 0.2 to 0.87 increases the total window U-factor by 15%.

Figure 4.7 Relationship between inside surface temperature and inside film coefficient for three different surface emittances.

Table 4.9 Impact of frame emittance on total window U-factor.

Emittance of Aluminum	Interior Surface Temperature [°F]	Interior Film Coefficient [Btu/h·ft ² ·°F]	Total Window U-factor [Btu/h·ft ² ·°F]
[0.84]	[20]	1.461	0.7533
0.84	30	1.433	0.7491
0.87	34	1.461	0.7533
0.5	30	1.134	0.7018
0.2	27	0.8718	0.6554

[] indicates Frame default values. These values do not correlate with the given film coefficient for this window.

Figure 4.8 Total window U-factor as a function of frame emittance.

§4.5 Wide Glazing Cavities

Windows with storm panels can have a gap width of greater than one inch between the primary glazing unit and the storm panel. There are three potential mistakes that could be made in the simulations:

- 1) The gap width is greater than 1.375 inches and is modelled as so in Window 4.1. Any gap widths greater than 1.375 inches should be modelled at 1.375 inches as discussed in section 2.1.

For example, a window with a glazing gap of 3.83 inches, correctly modeled as 1.375 inches, has a center-of-glass U-factor of 0.51 Btu/(h•ft²•°F). If it is modeled with an air gap of 3.83 inches, it has a center-of-glass U-factor of 0.53 Btu/(h•ft²•°F). This is almost a 4% difference.

2) The gap is wider than it is tall and a correction is not made in the Frame 3.1 model. In the NFRC glazing cavity option, Frame 3.1 assumes that the direction of heat flow is parallel to the shortest side of the rectangle. This is not true when the glazing cavity is wider than it is tall, so the simulator must calculate the effective conductivity of the cavity and input it as a user-defined conductivity in the Frame 3.1 model. The effective conductivity is calculated as

$$k_{\text{eff}} = U_{\text{cog}} \cdot (T_{\text{out}} - T_{\text{in}}) \cdot \text{gap width} / (T_{\text{cold}} - T_{\text{warm}}) \quad (\text{Equation 4})$$

where U_{cog} is the center-of-glass U-factor from Window 4.1, T_{out} is the outside air temperature, T_{in} is the room air temperature, T_{cold} is the temperature of the cold-side surface bounding the gap, and T_{warm} is the temperature of the warm-side surface bounding the gap.

3) The pocket of air beneath the glazing cavity is modelled as a frame air cavity. It should be modelled as a glazing cavity since there is no physical separation.

To illustrate points 2 and 3 above, an aluminum horizontal slider with a storm panel separated from the primary glazing by 3.83 inches (see Figure 4.9) is modeled in six ways. First, Equation 4 is used to calculate an effective conductivity of 3.74 Btu•in/h•ft²•°F. This value is used to define rectangle 1 in models KEUD, KEFF, KENF, and KEAC. It is also used to define rectangles 2,3,4, and 5 in model KEFF. In model KEUD, rectangles 2,3,4, and 5 are defined using the "user-defined glazing cavity" option in Frame 3.1. The temperatures and center-of-glass U-factor from Window 4.1 are used and since the user specifies the direction of heat flow, the problem of inverting dimensions in a wide glazing cavity is avoided. This is the approach recommended in the NFRC Simulation Laboratory Workbook (NFRC, 1993). In model KENF, rectangles 2,3,4, and 5 are defined using the NFRC glazing cavity option in Frame 3.1, thus incurring the error discussed in point 2 above. In model KEAC, rectangles 2,3,4, and 5 are defined using the NFRC frame air cavity option in Frame 3.1, thus incurring the error discussed in point 3 above.

In model UDGC, all of the rectangles are defined using the "user-defined glazing cavity" option in Frame 3.1 with temperatures and center-of-glass U-factor from Window 4.1. In model NFRC, all of the rectangles are defined using the NFRC glazing cavity option in Frame 3.1, thus incurring the error discussed in point 2 above. The total window U-factors obtained by running these six models are presented in Table 4.10. Assuming model KEUD to be the most accurate, the percent difference of each other model from KEUD is calculated.

Study of the results presented in Table 4.10 suggest that there are three methods that are acceptable for modelling wide glazing gaps, represented by models KEUD, KEFF, and UDGC. These results reflect the fact that the errors described in points 1, 2, and 3 above are avoided in

Figure 4.9 Aluminum window with storm panel located 3.83 inches from primary glazing.

Table 4.10 Effect of defining wide glazing cavities in different ways on U-factor in aluminum window with storm panel 3.83 inches from primary glazing.

Model Name	Model Description	$U_{total} \text{ (window)}$ Btu/h·ft ² ·°F	% Diff.
KEUD	$K_{eff} = 3.74 \text{ Btu}\cdot\text{in}/\text{h}\cdot\text{ft}^2\cdot^\circ\text{F}$ in rectangle 1/ user-defined glazing cavities in rectangles 2,3,4,5	0.5252	0
KEFF	$K_{eff} = 3.74 \text{ Btu}\cdot\text{in}/\text{h}\cdot\text{ft}^2\cdot^\circ\text{F}$ in all rectangles	0.5349	+1.8
KENF	$K_{eff} = 3.74 \text{ Btu}\cdot\text{in}/\text{h}\cdot\text{ft}^2\cdot^\circ\text{F}$ in rectangle 1/ NFRC glazing cavities in rectangles 2,3,4, and 5	0.4803	-8.5
KEAC	$K_{eff} = 3.74 \text{ Btu}\cdot\text{in}/\text{h}\cdot\text{ft}^2\cdot^\circ\text{F}$ in rectangle 1/ frame standard air cavities in rectangles 2,3,4, and 5	0.4831	-8.0
UDGC	User-defined glazing cavities in all rectangles using Window 4.1 temperatures	0.5223	-0.6
NFRC	NFRC glazing cavities in all rectangles using Window 4.1 temperatures and center-of-glass U-factor	0.4492	-14.5

these three approaches. Another words, wide glazing gaps could be modeled equivalently using either a user-calculated effective conductivity (Equation 4) or the temperatures and center-of-glass U-factor determined in Window 4.1. If one of these three approaches is not used, errors in total window U-factor of up to 14.5% could be realized.

§5.0 Conclusions

The intent of this report is to quantify and clarify the importance of differences in simulation styles and assumptions in using the Window 4.1 and Frame 3.1 computer programs to determine U-factors and solar heat gain coefficients of windows. The report addresses center-of-glass, spacer, and frame modeling in separate sections. The modeling differences discussed in this report include issues that must be decided by the simulator (using engineering judgement) due to lack of information or limitations of the computer program and mistakes due to user carelessness or errors in the computer program. The efficacy of various techniques at reducing total window U-factors is also addressed.

In most windows, the center-of-glass area accounts for an average of 50% of the window area. Therefore, differences in center-of-glass modelling potentially have the greatest impact on total window U-factors. Luckily, the center-of-glass area is more straight-forward to model than the frame and edge-of-glass areas.

The largest errors in center-of-glass U-factor occur at gap widths less than 0.438 inches and with misplacement of a low-emittance coating on an exposed glass surface. Placing the low-E coating on the wrong surface can create as much as a 55% difference in center-of-glass U-factor. For solar heat gain coefficient, the largest errors occur by not using spectral data files and misplacing coatings. Omitting the spectral data can decrease the solar heat gain coefficient by up to 23.8%. Placing the low-E coating on the wrong surface can create as much as a 5% difference in solar heat gain coefficient. Effects of gap width and gas fill are negligible on solar heat gain coefficients.

Although spacers are not the controlling resistance in fenestration products, they can have a significant impact on the total window U-factor. The greatest variation in combined edge and frame U-factor (U_{e+f}) is $0.07 \text{ Btu/h}\cdot\text{ft}^2\cdot^\circ\text{F}$ and occurs with a change in spacer effective conductivity. The effect of variation in effective conductivity on total window U-factors is between 0.0 and $0.05 \text{ Btu/h}\cdot\text{ft}^2\cdot^\circ\text{F}$, depending on the spacer type. Spacers with effective conductivities of less than $5 \text{ Btu}\cdot\text{in/h}\cdot\text{ft}^2\cdot^\circ\text{F}$ have the most significant impact on the heat transfer. Simplifying the spacer in the simulation model of the frame section will give the same U-factor as the detailed model. A difference of $0.01 \text{ Btu/h}\cdot\text{ft}^2\cdot^\circ\text{F}$ is found with the single-block model of the thermally-broken spacers. The uncertainty in material properties can result in variations in U_{e+f} of $0.01 \text{ Btu/h}\cdot\text{ft}^2\cdot^\circ\text{F}$. It is important to clearly identify the materials used in a spacer assembly because the performance can vary significantly, as seen with steel products. Differences in the performance of the material providing the controlling resistance have the strongest influence.

The frame area generally accounts for less than thirty percent of the window area, but some of the trickiest aspects of window modeling occur in the frame. Theoretically, breaking up large air cavities could have as much as a 20% effect on total window U-factor. Although such a case is extreme, it illustrates the importance of redefining the effective conductivities of broken-up air

cavities, especially in vinyl windows. A mistake in specifying the conductivity of the thermal break material could change the total window U-factor by as much as 17%. Modeling an aluminum window using default interior film coefficients could make a difference in total window U-factor of 15% if the window had a low-emittance surface on the inside. A wide glazing gap incorrectly modeled with NFRC glazing cavities could incur an error in total window U-factor of up to 14.5%. A mistake in modeling the thermal break width could produce a total window U-factor difference of nearly 7%. Other modeling issues discussed in the body of the report have less than a 5% impact on total window U-factors.

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