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A Validation of the WINDOW4/FRAME3 Linear Interpolation Methodology

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A Validation of the WINDOW4/FRAME3 Linear Interpolation Methodology

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ABSTRACT

The validity of a method to reduce the total number of computer simulations which must be run to determine the U-values of a window product line with multiple glazing options is examined. The accuracy and limits of this method, which uses the WINDOW4 and FRAME simulation programs, is evaluated by comparing the edge, frame, and total window U-values calculated on the basis of single point FRAME simulations to those U-values as calculated on the basis of four point FRAME simulations combined with linear interpolation of frame and edge U-values by WINDOW4. The accuracy of this procedure is examined for two frame types, a low thermal conductivity wood-framed casement and a high thermal conductivity aluminum-framed casement, using both aluminum spacers and insulating spacers over a wide range of glazing types. The effect of center-of-glass U-value, overall glazing thickness and spacer type on frame and edge-of-glass U-values is discussed. It is shown that the agreement between total window U-values as calculated by the single point and four point simulation methods is better than 1% for double and triple-glazed windows with aluminum spacers, better than 1% for double-glazed windows with insulating spacers, and better than 2% for triple-glazed windows with insulating spacers.

INTRODUCTION

When two dimensional computer simulations are used to model the thermal performance of windows, the generally accepted practice is to run a complete simulation for each possible window configuration, as in the NFRC *Standard* 100-91 (NFRC 1991). As manufacturers often offer many different glazing options for each window, the total number of simulations which must be run for a product line can be large. When a range of glazing options is used, there are two reasons why it is necessary to model the frame and edge profiles individually for each option. The first is that while frame U-values are fairly insensitive to center-of-glass U-values, they are affected by overall glazing thickness and spacer type (Carpenter. 1993, EE. 1993, ASHRAE 1993). As the spacer is generally a region of high heat flow in a window, the path length and thermal conductance of the spacer will affect the overall thermal performance of the window. The second reason to model the frame profile separately for each glazing is that the edge-of-glass U-value is a function both spacer type and center-of-glass U-value (Carpenter. 1989).

WINDOW4 (LBL 1992) is a finite difference program which calculates both center-of-glass and total window U-values. FRAME (EE. 1992) is a two-dimensional finite difference frame and edge-of-glass thermal analysis program. By using the advanced features of these programs, the total number of simulations which must be run to model a product line can be significantly reduced. FRAME has an option which allows the user to obtain frame and edge U-values for a given frame over a range of center-of-glass properties, and/or a range of glazing thicknesses. In FRAME, a *two point run* is used when only one of these glazing parameters is changed, while the *four point run* is used when both center-of-glass U-values and glazing thicknesses are being changed. The cases where center-of-glass U-values and overall glazing thicknesses remain constant, as in NFRC 100-91, are known as *single point runs*. We focus on the four point run for simulation of multiple glazing options, as it is the most complex and embodies both types of two point runs.

For a fixed spacer type, the four point simulation requires the user to create only two FRAME files to simulate a given frame profile over a range of glazing thicknesses and center-of-glass U-values, thus avoiding the time-consuming task of creating a new simulation file for each and every possible glazing option (Beck and Arasteh 1993, LBL 1992, EE. 1992). WINDOW4 can then access the FRAME files, determine the frame and edge U-values corresponding to the glazing being modeled through interpolation of the frame and edge U-values contained in the four point FRAME file (Finlayson et al. 1993), and calculate the optical and thermal properties of the whole window according to the glazing specified by the user. This study shows that the results obtained using the time saving four point simulation are essentially equivalent to those obtained using the currently accepted single point simulations.

METHODOLOGY

The accuracy and limits of the WINDOW4/FRAME four point simulation procedure were assessed by comparing the edge, frame, and total window U-values calculated using single point FRAME simulations to those U-values calculated using the four point FRAME simulation combined with linear interpolation of frame and edge U-values by WINDOW4. A wood-framed casement window and a non-thermally broken aluminum-framed casement window were used in the comparison. These windows represent the typical range of frame thermal conductivities encountered in commercially available windows. The frame profiles were held constant except for minor changes made to accommodate different glazing unit thicknesses when necessary. All glazing configurations were modeled with both aluminum spacers and insulating spacers for each frame type in order to represent the possible range of edge-of-glass performance which may be encountered in commercial products. The aluminum spacer was of dual-seal construction, the insulating spacer was composed of pultruded fiberglass with an effective conductivity of 2.08 (Btu.in/h.ft$^{2}\cdot$°F). All simulations were carried out using ASHRAE/NFRC Winter environmental conditions, and all total window U-values are given for AA-size (24 in. x 48 in.) casement windows.

Methodology for Glazing Simulations

A total of 25 double-glazed and 20 triple-glazed configurations were modeled using WINDOW4. The glazings were chosen to represent the range of commercially available insulating glazing unit performance levels. Overall glazing thickness ranged from 0.50 in. to 1.00 in. in 0.125 in. increments. Center-of-glass U-values ranged from 0.57 (Btu/h.ft$^{2}\cdot$°F) to 0.20 (Btu/h.ft$^{2}\cdot$°F) for the double-glazed configurations, and from 0.30 (Btu/h.ft$^{2}\cdot$°F) to 0.12 (Btu/h.ft$^{2}\cdot$°F) for triple-glazed configurations (see Figure 1). Center-of-glass performance points were achieved by using various combinations of low-E coatings and low thermal conductivity gas fills.

Methodology for Single Point Simulations

Single point simulations were carried out in accordance with the NFRC *Standard* 100-91 (NFRC. 1991). This standard specifies that each and every frame, edge, and glazing combination be modeled as a separate simulation. Each of the 45 modeled glazing configurations were incorporated into separate single point FRAME simulation files for both the wood and aluminum frames, and run with both aluminum and insulating spacers to give a total of 180 single point FRAME simulations. The single point FRAME simulation files were then entered into the WINDOW4 Frame Library. The frame and edge U-values were combined on the WINDOW4 Main Screen with the glazings originally specified for those frames in WINDOW4. Total window U-values were calculated using WINDOW4.

Methodology for Four Point Simulations

Simulation of Frame and Edge U-Values

The four point simulations, wherein both the overall glazing system thickness and the center-of-glass U-values may vary over a wide range, were carried out according to the methodology outlined in Beck and Arasteh (1993). For a given frame profile the user creates a FRAME file based upon a primary glazing unit thickness. The user creates a second FRAME file based upon a secondary glazing unit thickness. For each of these frame configurations an alternate primary glazing and an alternate secondary glazing with a different center-of-glass U-values are additionally specified, giving a total of four different glazing configurations for each frame profile. Figure 2 shows the relationships of these four glazing configurations. The four point simulations used in this study took the place of either the 25 double-glazed or 20 triple-glazed configurations used in the single point simulations. The four point simulations were run for all possible combinations of wood or aluminum frames, double-or triple-glazed windows, and aluminum or insulating glazing spacers, making a total of eight four point simulation files. An additional simulation was run for the wood-framed window, combining both double- and triple-glazings into one parametric run to asses the accuracy of such a simulation. The combined simulation was run with insulating spacers only.

Simulation of Total Window U-Values

The four point simulation files were then entered into the WINDOW4 Frame Library and combined on the WINDOW4 Main Screen with the range of glazings originally specified in WINDOW4. Total window U-values were calculated using WINDOW4. The four point simulation files contain only the frame and edge U-values corresponding to the maximum and minimum center-of-glass U-values and glazing system thicknesses. WINDOW4 interpolates between these values in order to calculate the frame and edge U-values for glazings other than the ones used in the four point simulation. This process is only valid for glazing systems with glazing system thicknesses and center-of-glass U-values between a 5% tolerance limit (set by WINDOW4) at each end of the range of values used in the four point simulation (see Figure 2). The interpolation methodology of WINDOW4 is linear, based on simulations using WINDOW and FRAME performed at a national laboratory which show that frame and edge U-values tend to change linearly over a wide range of glazing parameters and operator types. As the interpolation is linear, all total window U-values calculated using glazings which are in the range of glazing thickness and center-of-glass U-value defined in the four point simulation will lie on a plane (see Figure 3).

RESULTS

The percentage difference between single point and four point U-value simulations are given by frame, glazing, and spacer category in Table 1. Numerical results and percentage differences between the single point and four point simulations by frame, edge-of-glass and total window U-values are summarized in Tables 2a - 2d. Discussion of the results follows:

Trends in Frame and Edge U-Values With Change in Glazing and Spacer Type

Frame U-values changed linearly with both center-of-glass U-value and overall glazing thickness, while edge-of-glass U-values were seen to be a strong linear function of the center-of-glass U-values only. Variations in frame U-values for frames with aluminum spacers were up to 6% with overall glazing thickness and constant to within 2% over the range of center-of-glass U-values. This is due to the fact that path length is the critical element determining heat transfer in regions of high thermal conductivity, such as aluminum spacers. Variations in overall glazing thickness and center-of-glass U-values played approximately equal roles in affecting the frame U-values of wood frames with insulating spacers, on the order of a 15% change over the range of values for each. Variations in frame U-values for aluminum frames with insulating spacers were up to 8% with overall glazing thickness and constant to within 3% over the range of center-of-glass U-values. Here the path length of the spacer is again the determining element for heat transfer. Edge-of-glass U-values were seen to be linear with change in center-of-glass U-values and constant with overall glazing thickness for all frame and glazing types. Frame and edge-of-glass U-values from the single point simulations are plotted against center-of-glass U-values for all glazing combinations for each of the two frame types, see Figures 4 and 5.

Results for Wood-Framed Casement Windows

Frame U-values for the wood window agreed to within 1.5% for all double- and triple- glazed configurations with aluminum spacers, while the agreement for insulating spacers the agreement was within 2.6% and 1.9%, respectively. Edge U-values for the wood window agreed to within 2% for all double-glazed configurations with both aluminum and insulating spacers, while the agreement for triple-glazed configurations was within 3.4% and 2.9%, respectively. Total window U-values for the wood window agreed to within 0.4% and 0.8% for the double-glazed configurations and within 0.9% and 1.6% for the triple-glazed configurations for aluminum and insulating spacers, respectively. With the four point simulation frame and edge-of-glass U-values were over estimated in 70% of the cases, and total window U-values were overestimated in 90% of the cases. Total window U-values for each of the glazings defined in the four point simulation are expected to be equal to the total window U-values calculated with single point simulations using glazings identical to those in the four point simulation. It was found that round-off errors between the FRAME and WINDOW programs can lead to differences in total window U-values of up to 0.5% between the single point and four point simulations, based on the data for the .RNF file of the wood-framed, triple-glazed, insulating spacer configuration.

Results for Aluminum-Framed Casement Windows

Frame U-values for the aluminum window agreed to within 1.3% for all glazing configurations. Edge U-values for the aluminum window agreed to within 2.8% for all double-glazed configurations with both aluminum and insulating spacers, while the agreement for triple-glazed configurations was within 2.9% and 4.5%, respectively. Total window U-values for the aluminum window agreed to within 0.5% to 0.7% for the double-glazed configurations and within 0.8% to 1.1% for the triple-glazed configurations for aluminum and insulating spacers, respectively. With the four point simulation all frame U-values were overestimated, edge U-values were overestimated in 80% of the cases, and total window U-values were overestimated in 92% of the cases. It was found that round-off errors between the FRAME and WINDOW programs can lead to differences in total window U-values of up to 0.2% between the single point and four point simulations, based on the data for the .RNF file of the aluminum-framed, double-glazed, aluminum spacer configuration.

Limitations of the Simulation Process: Using Both Double- and Triple-Glazings in a Single Simulation

Due to the nature of this type of simulation, there will be many out of range errors when combing double and triple glazings within a four point simulation as compared to doing separate four point simulations for double- and triple-glazed configurations. Out of range errors occur when the window configuration has an overall glazing thickness or center-of-glass U-value outside the 5% WINDOW tolerance level. Four point simulation of the wood-framed casement window, combining both double and triple-glazed configurations with insulating spacers, had 14 out of range errors out of 35 possible glazing configurations, with a maximum error of 1.4% in the total window U-value. The use of both double- and triple-glazed configurations within a single four point simulation is possible, but not recommended. The frame profiles and the spacer types must be identical for this method to yield meaningful results.

CONCLUSIONS

There is excellent agreement between total window U-values calculated using the four point WINDOW4/FRAME3 simulations and those calculated using the single point WINDOW4/FRAME3 simulations for both wood-framed and aluminum-framed casement windows. Significant time savings are possible, as the eight four point simulations replaced 180 single point simulations. Total window U-values were found to be in agreement to better than 1% for double and triple-glazed windows with aluminum spacers, better than 1% for double-glazed windows with insulating spacers, and better than 2% agreement for triple-glazed windows with insulating spacers. The linearity of frame and edge U-value trends with center-of-glass U-values and overall glazing thickness indicate that similar excellent agreement between single and multiple-glazing simulations will hold over a wide range of operator and glazing types. The main conclusions from this study are as follows:

- Linear interpolation of frame and edge U-values based on center-of-glass U-values and overall glazing thickness can be used to calculate total window U-values.
- There is excellent agreement between single point and four point WINDOW4/FRAME3 simulations over a wide range of glazing configurations and frame thermal performances.
- The WINDOW4/FRAME3 four point simulation method is valid when the spacer type and number of glazing layers are held constant within a simulation.
- Simulation programs should use the same rounding procedures when reporting U-values to avoid roundoff errors.

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Table 1: Percentage agreement between single point and four point simulations

frame	spacer	glazing	Uframe max. (%)	Uframe avg. (%)	Uedge max. (%)	Uedge avg. (%)	Utotal max. (%)	Utotal avg. (%)
wood	aluminum	double	1.5	0.6	2.0	0.5	0.4	0.2
	"	triple	1.5	0.7	3.4	1.4	0.9	0.3
	insulating	double	2.6	0.7	2.0	0.5	0.8	0.2
	"	triple	1.9	0.8	2.9	1.4	1.6	0.4
aluminum	aluminum	double	1.3	0.4	2.8	0.5	0.5	0.2
	"	triple	1.3	0.4	2.9	0.2	0.8	0.3
	insulating	double	1.3	0.4	2.8	0.5	0.7	0.2
	"	triple	1.3	0.4	4.5	1.0	1.1	0.4

Table 2a: Simulation results for wood framed, double glazed window (Btu/hr ft2 F)

		(ALUMINUM SPACER)									(INSULATING SPACER)									
		SINGLE POINT			FOUR POINT			% DIFFERENCE			SINGLE POINT			FOUR POINT			% DIFFERENCE			
Glzsys Thickness (in.)	Ucog	Uframe	Uedge	Utotal	Uframe	Uedge	Utotal	Uframe	Uedge	Utotal	Uframe	Uedge	Utotal	Uframe	Uedge	Utotal	Uframe	Uedge	Utotal	
0.49	0.57	0.49	0.62	0.57	0.49	0.62	0.57	0.2%	-0.2%	0.2%	0.45	0.60	0.55	0.45	0.60	0.55	0.4%	-0.5%	0.0%	.F30
0.61	0.57	0.49	0.62	0.57	0.49	0.62	0.57	-0.4%	0.3%	0.2%	0.43	0.59	0.55	0.44	0.59	0.55	-1.4%	0.5%	0.0%	
0.74	0.57	0.48	0.62	0.57	0.49	0.62	0.57	-1.2%	0.2%	-0.2%	0.42	0.59	0.54	0.42	0.59	0.55	-0.2%	-0.5%	-0.2%	
0.86	0.57	0.48	0.63	0.57	0.48	0.63	0.57	0.6%	-0.2%	0.0%	0.41	0.59	0.55	0.41	0.59	0.55	-0.7%	0.2%	0.0%	
0.99	0.57	0.48	0.63	0.57	0.48	0.63	0.57	0.2%	0.0%	0.2%	0.40	0.59	0.54	0.40	0.59	0.54	-0.8%	-0.3%	0.0%	.W30
0.49	0.50	0.49	0.57	0.52	0.48	0.57	0.52	1.6%	-0.2%	-0.2%	0.45	0.54	0.50	0.45	0.54	0.50	-0.7%	0.7%	0.0%	
0.61	0.50	0.48	0.57	0.51	0.48	0.56	0.51	0.8%	0.9%	0.0%	0.43	0.53	0.49	0.43	0.53	0.49	-0.7%	0.2%	-0.2%	
0.74	0.50	0.48	0.57	0.51	0.48	0.57	0.51	0.0%	-0.7%	-0.4%	0.41	0.53	0.49	0.42	0.53	0.49	-2.2%	-0.4%	-0.4%	
0.86	0.50	0.48	0.57	0.52	0.48	0.57	0.52	-0.2%	0.3%	-0.2%	0.40	0.53	0.49	0.40	0.53	0.49	-0.5%	-0.2%	-0.2%	
0.99	0.50	0.48	0.57	0.51	0.48	0.57	0.51	-0.6%	0.0%	-0.2%	0.39	0.52	0.48	0.39	0.52	0.48	-1.0%	0.4%	-0.2%	
0.49	0.40	0.48	0.49	0.44	0.48	0.49	0.44	0.6%	-0.6%	-0.2%	0.44	0.46	0.42	0.44	0.46	0.42	-0.5%	-0.7%	0.0%	
0.61	0.40	0.48	0.49	0.44	0.48	0.49	0.44	-0.2%	-0.4%	-0.2%	0.42	0.45	0.42	0.42	0.45	0.42	-0.5%	-0.2%	-0.5%	
0.74	0.40	0.48	0.49	0.44	0.48	0.50	0.44	-1.1%	-1.6%	-0.2%	0.40	0.45	0.42	0.41	0.45	0.42	-2.2%	-0.2%	-0.5%	
0.86	0.40	0.47	0.49	0.44	0.47	0.49	0.44	0.6%	-0.4%	-0.2%	0.39	0.44	0.41	0.39	0.44	0.41	-1.0%	-0.5%	-0.5%	
0.99	0.40	0.47	0.49	0.44	0.47	0.50	0.44	0.2%	-1.6%	-0.2%	0.37	0.44	0.41	0.38	0.44	0.41	-1.6%	-0.7%	-0.2%	
0.49	0.30	0.48	0.41	0.36	0.48	0.41	0.36	-0.4%	0.0%	-0.3%	0.43	0.37	0.34	0.43	0.38	0.34	0.0%	-1.6%	-0.3%	
0.61	0.30	0.48	0.41	0.36	0.48	0.41	0.36	-1.1%	1.0%	0.0%	0.41	0.37	0.34	0.41	0.37	0.34	-0.2%	-0.3%	0.0%	
0.74	0.30	0.47	0.41	0.36	0.47	0.42	0.36	0.0%	-1.7%	-0.3%	0.39	0.36	0.33	0.40	0.37	0.34	-2.6%	-1.9%	-0.6%	
0.86	0.30	0.47	0.42	0.37	0.47	0.42	0.37	-0.6%	0.7%	0.3%	0.37	0.37	0.33	0.38	0.36	0.34	-1.6%	1.6%	-0.3%	
0.99	0.30	0.47	0.41	0.36	0.47	0.42	0.36	-0.9%	-1.4%	0.0%	0.36	0.35	0.33	0.36	0.35	0.33	0.6%	0.6%	0.0%	
0.49	0.20	0.47	0.34	0.29	0.47	0.34	0.29	0.8%	-0.3%	0.0%	0.42	0.30	0.27	0.42	0.30	0.27	0.7%	0.0%	0.4%	.RNF
0.61	0.20	0.47	0.34	0.29	0.47	0.34	0.29	0.2%	0.0%	0.3%	0.40	0.29	0.26	0.40	0.29	0.26	0.0%	-1.4%	0.0%	
0.74	0.21	0.47	0.34	0.29	0.47	0.34	0.29	-1.1%	0.3%	-0.3%	0.38	0.29	0.26	0.39	0.29	0.26	-2.1%	-1.4%	-0.8%	
0.86	0.21	0.47	0.35	0.30	0.46	0.35	0.30	1.1%	-0.6%	0.0%	0.37	0.29	0.26	0.37	0.29	0.26	-1.1%	-1.4%	-0.4%	
0.99	0.22	0.46	0.35	0.30	0.46	0.35	0.30	0.4%	1.1%	0.0%	0.35	0.29	0.26	0.35	0.29	0.26	0.8%	-1.0%	0.0%	.RNW

Table 2b: Simulation results for wood framed, triple glazed window (Btu/hr ft2 F)

		(ALUMINUM SPACER)									(INSULATING SPACER)									
		SINGLE POINT			FOUR POINT			% DIFFERENCE			SINGLE POINT			FOUR POINT			% DIFFERENCE			
Glzsys Thickness (in.)	Ucog	Uframe	Uedge	Utotal	Uframe	Uedge	Utotal	Uframe	Uedge	Utotal	Uframe	Uedge	Utotal	Uframe	Uedge	Utotal	Uframe	Uedge	Utotal	
0.49	0.30	0.49	0.41	0.37	n/a*	n/a	n/a	n/a	n/a	n/a	0.43	0.38	0.35	n/a	n/a	n/a	n/a	n/a	n/a	
0.62	0.30	0.48	0.41	0.36	0.48	0.41	0.36	-0.2%	-1.0%	0.0%	0.41	0.36	0.34	0.41	0.36	0.34	-0.2%	0.8%	0.0%	.F30
0.75	0.30	0.47	0.41	0.36	0.48	0.41	0.36	-1.3%	-1.2%	-0.3%	0.39	0.36	0.33	0.39	0.36	0.33	-0.3%	-1.1%	-0.3%	
0.88	0.30	0.47	0.40	0.36	0.47	0.41	0.36	0.0%	-1.7%	-0.3%	0.37	0.35	0.32	0.38	0.35	0.33	-1.9%	-0.3%	-0.6%	
1.00	0.30	0.47	0.41	0.36	0.47	0.41	0.36	0.2%	0.0%	0.0%	0.36	0.35	0.32	0.36	0.35	0.32	0.6%	-0.3%	0.3%	.W30
0.49	0.20	0.48	0.33	0.29	n/a	n/a	n/a	n/a	n/a	n/a	0.42	0.29	0.26	n/a	n/a	n/a	n/a	n/a	n/a	
0.62	0.20	0.48	0.33	0.29	0.48	0.34	0.29	-0.8%	-1.8%	0.0%	0.40	0.29	0.26	0.40	0.29	0.26	0.2%	-1.0%	-0.4%	
0.75	0.20	0.47	0.33	0.29	0.47	0.33	0.29	0.0%	0.0%	-0.4%	0.38	0.28	0.25	0.38	0.28	0.26	0.0%	-1.8%	-0.4%	
0.88	0.20	0.47	0.33	0.28	0.47	0.33	0.28	-0.9%	-0.9%	-0.7%	0.36	0.27	0.25	0.37	0.27	0.25	-1.9%	-1.5%	-0.8%	
1.00	0.20	0.47	0.34	0.29	0.47	0.34	0.29	-0.4%	-0.6%	-0.3%	0.35	0.27	0.25	0.35	0.27	0.25	0.6%	0.4%	0.0%	
0.49	0.17	0.48	0.31	0.27	n/a	n/a	n/a	n/a	n/a	n/a	0.42	0.27	0.25	n/a	n/a	n/a	n/a	n/a	n/a	
0.62	0.15	0.47	0.30	0.25	0.47	0.30	0.25	0.8%	-1.7%	0.0%	0.40	0.25	0.22	0.40	0.25	0.22	-0.8%	-1.6%	0.0%	
0.75	0.15	0.47	0.29	0.25	0.47	0.30	0.25	-0.4%	-2.4%	-0.4%	0.38	0.24	0.22	0.38	0.24	0.22	-1.1%	-1.7%	-0.5%	
0.88	0.15	0.46	0.29	0.25	0.47	0.30	0.25	-1.3%	-3.4%	-0.8%	0.36	0.23	0.21	0.36	0.23	0.21	-0.3%	-1.3%	-1.4%	
1.00	0.15	0.47	0.30	0.25	0.47	0.30	0.25	-0.9%	-1.7%	0.0%	0.35	0.23	0.21	0.35	0.23	0.21	-0.9%	-2.2%	0.0%	
0.49	0.17	0.48	0.31	0.27	n/a	n/a	n/a	n/a	n/a	n/a	0.42	0.27	0.25	n/a	n/a	n/a	n/a	n/a	n/a	
0.62	0.12	0.47	0.27	0.23	0.47	0.27	0.23	0.6%	1.1%	-0.4%	0.40	0.22	0.20	0.39	0.22	0.20	1.3%	0.9%	-0.5%	.RNF
0.75	0.12	0.47	0.27	0.23	0.47	0.28	0.23	-0.6%	-2.6%	-0.4%	0.37	0.21	0.20	0.38	0.22	0.20	-1.6%	-2.8%	-1.0%	
0.88	0.12	0.46	0.27	0.23	0.47	0.27	0.23	-1.5%	-0.4%	-0.9%	0.36	0.20	0.19	0.36	0.21	0.19	-0.8%	-2.9%	-1.6%	
1.00	0.12	0.47	0.27	0.23	0.46	0.27	0.23	1.1%	1.5%	-0.4%	0.35	0.20	0.19	0.34	0.20	0.19	1.4%	1.5%	0.0%	.RNW

*Four point simulations for triple-glazed windows do not include the 0.500" overall thickness glazings, as the lower bound on the center-of-glass U-value (0.12 Btu/hr ft2 F) was not achievable for that overall glazing thickness.

Table 2c: Simulation results for aluminum framed, double glazed window (Btu/hr ft2 F)

Glzsys Thickness (in.)	Ucog	(ALUMINUM SPACER) SINGLE POINT Uframe	Uedge	Utotal	FOUR POINT Uframe	Uedge	Utotal	% DIFFERENCE Uframe	Uedge	Utotal	(INSULATING SPACER) SINGLE POINT Uframe	Uedge	Utotal	FOUR POINT Uframe	Uedge	Utotal	% DIFFERENCE Uframe	Uedge	Utotal	
0.49	0.57	1.63	0.62	0.72	1.63	0.62	0.72	0.0%	0.0%	0.0%	1.60	0.60	0.71	1.60	0.60	0.71	0.0%	0.0%	0.0%	.F30
0.61	0.57	1.61	0.63	0.72	1.61	0.63	0.72	0.0%	0.0%	0.1%	1.57	0.60	0.71	1.57	0.59	0.71	0.0%	1.7%	0.0%	
0.74	0.57	1.57	0.63	0.71	1.59	0.63	0.72	-1.3%	0.0%	-0.3%	1.53	0.59	0.70	1.54	0.59	0.70	-0.7%	0.0%	-0.3%	
0.86	0.57	1.56	0.64	0.72	1.56	0.63	0.72	0.0%	1.6%	-0.1%	1.51	0.59	0.70	1.52	0.59	0.70	-0.7%	0.0%	-0.1%	
0.99	0.57	1.54	0.64	0.72	1.54	0.63	0.71	0.0%	1.6%	0.1%	1.49	0.59	0.69	1.49	0.59	0.69	0.0%	0.0%	0.0%	.W30
0.49	0.50	1.62	0.58	0.67	1.62	0.58	0.67	0.0%	0.0%	-0.1%	1.59	0.55	0.66	1.59	0.55	0.66	0.0%	0.0%	0.0%	
0.61	0.50	1.60	0.57	0.66	1.60	0.57	0.66	0.0%	0.0%	0.0%	1.56	0.54	0.65	1.56	0.54	0.65	0.0%	0.0%	0.0%	
0.74	0.50	1.57	0.57	0.66	1.58	0.58	0.66	-0.6%	-1.8%	-0.5%	1.52	0.53	0.64	1.54	0.54	0.65	-1.3%	-1.9%	-0.5%	
0.86	0.50	1.55	0.58	0.66	1.56	0.58	0.66	-0.6%	0.0%	-0.3%	1.50	0.53	0.64	1.51	0.53	0.64	-0.7%	0.0%	-0.3%	
0.99	0.50	1.54	0.58	0.66	1.54	0.58	0.66	0.0%	0.0%	-0.2%	1.48	0.53	0.64	1.48	0.53	0.64	0.0%	0.0%	-0.2%	
0.49	0.40	1.62	0.50	0.60	1.62	0.50	0.60	0.0%	0.0%	0.0%	1.59	0.47	0.58	1.58	0.47	0.58	0.6%	0.0%	0.0%	
0.61	0.40	1.60	0.50	0.59	1.60	0.50	0.59	0.0%	0.0%	-0.2%	1.55	0.46	0.57	1.56	0.46	0.58	-0.6%	0.0%	-0.2%	
0.74	0.40	1.56	0.50	0.59	1.58	0.51	0.59	-1.3%	-2.0%	-0.5%	1.51	0.46	0.57	1.53	0.46	0.57	-1.3%	0.0%	-0.7%	
0.86	0.40	1.54	0.50	0.58	1.55	0.50	0.59	-0.6%	0.0%	-0.2%	1.49	0.45	0.56	1.50	0.45	0.56	-0.7%	0.0%	-0.5%	
0.99	0.40	1.53	0.51	0.59	1.53	0.51	0.59	0.0%	0.0%	-0.2%	1.47	0.45	0.56	1.47	0.45	0.56	0.0%	0.0%	-0.2%	
0.49	0.30	1.61	0.42	0.52	1.61	0.43	0.52	0.0%	-2.4%	0.0%	1.58	0.39	0.50	1.58	0.39	0.50	0.0%	0.0%	0.0%	
0.61	0.30	1.59	0.42	0.51	1.59	0.42	0.52	0.0%	0.0%	-0.2%	1.55	0.38	0.50	1.55	0.38	0.50	0.0%	0.0%	-0.2%	
0.74	0.30	1.56	0.43	0.51	1.57	0.43	0.51	-0.6%	0.0%	-0.4%	1.50	0.37	0.49	1.52	0.38	0.49	-1.3%	-2.7%	-0.6%	
0.86	0.30	1.54	0.43	0.51	1.55	0.43	0.52	-0.6%	0.0%	-0.4%	1.48	0.37	0.49	1.49	0.37	0.49	-0.7%	0.0%	-0.4%	
0.99	0.30	1.53	0.43	0.51	1.53	0.43	0.51	0.0%	0.0%	-0.2%	1.46	0.36	0.48	1.46	0.36	0.48	0.0%	0.0%	-0.2%	
0.49	0.20	1.61	0.35	0.45	1.61	0.35	0.45	0.0%	0.0%	0.2%	1.57	0.31	0.43	1.57	0.31	0.43	0.0%	0.0%	0.2%	.RNF
0.61	0.20	1.59	0.35	0.44	1.59	0.35	0.44	0.0%	0.0%	0.2%	1.54	0.30	0.42	1.54	0.30	0.42	0.0%	0.0%	0.0%	
0.74	0.21	1.55	0.36	0.44	1.57	0.36	0.44	-1.3%	0.0%	-0.5%	1.49	0.30	0.42	1.51	0.30	0.42	-1.3%	0.0%	-0.7%	
0.86	0.21	1.54	0.36	0.45	1.54	0.37	0.45	0.0%	-2.8%	-0.2%	1.47	0.30	0.42	1.48	0.30	0.42	-0.7%	0.0%	-0.5%	
0.99	0.22	1.52	0.37	0.45	1.52	0.37	0.45	0.0%	0.0%	0.0%	1.45	0.30	0.42	1.45	0.30	0.42	0.0%	0.0%	0.0%	.RNW

Table 2d: Simulation results for aluminum framed, triple glazed window (Btu/hr ft2 F)

Glzsys Thickness (in.)	Ucog	(ALUMINUM SPACER) SINGLE POINT Uframe	Uedge	Utotal	FOUR POINT Uframe	Uedge	Utotal	% DIFFERENCE Uframe	Uedge	Utotal	(INSULATING SPACER) SINGLE POINT Uframe	Uedge	Utotal	FOUR POINT Uframe	Uedge	Utotal	% DIFFERENCE Uframe	Uedge	Utotal	
0.49	0.30	1.61	0.42	0.52	n/a*	n/a	n/a	n/a	n/a	n/a	1.57	0.38	0.51	n/a	n/a	n/a	n/a	n/a	n/a	
0.62	0.30	1.59	0.42	0.51	1.59	0.42	0.51	0.0%	0.0%	-0.2%	1.54	0.37	0.49	1.54	0.37	0.50	0.0%	0.0%	-0.2%	.F30
0.75	0.30	1.56	0.42	0.51	1.57	0.42	0.51	-0.6%	0.0%	-0.4%	1.50	0.36	0.49	1.51	0.37	0.49	-0.7%	-2.8%	-0.6%	
0.88	0.30	1.54	0.42	0.50	1.55	0.42	0.51	-0.6%	0.0%	-0.4%	1.48	0.36	0.48	1.49	0.36	0.48	-0.7%	0.0%	-0.4%	
1.00	0.30	1.53	0.42	0.51	1.53	0.42	0.51	0.0%	0.0%	0.0%	1.46	0.36	0.48	1.46	0.36	0.48	0.0%	0.0%	0.0%	.W30
0.49	0.20	1.61	0.34	0.44	n/a	n/a	n/a	n/a	n/a	n/a	1.56	0.30	0.42	n/a	n/a	n/a	n/a	n/a	n/a	
0.62	0.20	1.59	0.35	0.44	1.59	0.35	0.44	0.0%	0.0%	-0.2%	1.53	0.30	0.42	1.54	0.30	0.42	-0.7%	0.0%	-0.2%	
0.75	0.20	1.55	0.34	0.43	1.56	0.35	0.44	-0.6%	-2.9%	-0.7%	1.49	0.28	0.41	1.51	0.29	0.41	-1.3%	-3.6%	-0.7%	
0.88	0.20	1.53	0.34	0.43	1.54	0.34	0.43	-0.7%	0.0%	-0.5%	1.47	0.28	0.40	1.48	0.28	0.41	-0.7%	0.0%	-0.7%	
1.00	0.20	1.52	0.35	0.44	1.52	0.35	0.44	0.0%	0.0%	0.0%	1.45	0.28	0.41	1.45	0.28	0.41	0.0%	0.0%	-0.2%	
0.49	0.17	1.61	0.32	0.42	n/a	n/a	n/a	n/a	n/a	n/a	1.56	0.28	0.40	n/a	n/a	n/a	n/a	n/a	n/a	
0.62	0.15	1.58	0.31	0.41	1.58	0.31	0.41	0.0%	0.0%	0.0%	1.53	0.26	0.38	1.53	0.26	0.38	0.0%	0.0%	-0.3%	
0.75	0.15	1.55	0.31	0.40	1.56	0.31	0.40	-0.6%	0.0%	-0.5%	1.49	0.25	0.37	1.50	0.25	0.38	-0.7%	0.0%	-1.1%	
0.88	0.15	1.53	0.31	0.40	1.54	0.31	0.40	-0.7%	0.0%	-0.3%	1.46	0.24	0.37	1.47	0.24	0.37	-0.7%	0.0%	-0.5%	
1.00	0.15	1.52	0.31	0.39	1.52	0.31	0.39	0.0%	0.0%	0.0%	1.45	0.24	0.36	1.45	0.24	0.36	0.0%	0.0%	-0.3%	
0.49	0.17	1.61	0.32	0.42	n/a	n/a	n/a	n/a	n/a	n/a	1.56	0.28	0.40	n/a	n/a	n/a	n/a	n/a	n/a	
0.62	0.12	1.58	0.29	0.38	1.58	0.29	0.38	0.0%	0.0%	0.0%	1.53	0.23	0.36	1.53	0.24	0.36	0.0%	-4.3%	0.0%	.RNF
0.75	0.12	1.55	0.29	0.38	1.56	0.29	0.38	-0.6%	0.0%	-0.8%	1.49	0.22	0.35	1.50	0.23	0.36	-0.7%	-4.5%	-1.1%	
0.88	0.12	1.53	0.29	0.37	1.54	0.29	0.38	-0.7%	0.0%	-0.3%	1.46	0.22	0.35	1.47	0.22	0.35	-0.7%	0.0%	-0.6%	
1.00	0.12	1.52	0.29	0.37	1.52	0.29	0.37	0.0%	0.0%	0.0%	1.44	0.21	0.34	1.44	0.21	0.34	0.0%	0.0%	0.0%	.RNW

*Four point simulations for triple-glazed windows do not include the 0.500" overall thickness glazings, as the lower bound on the center-of-glass U-value (0.12 Btu/hr ft2 F) was not achievable for that overall glazing thickness.

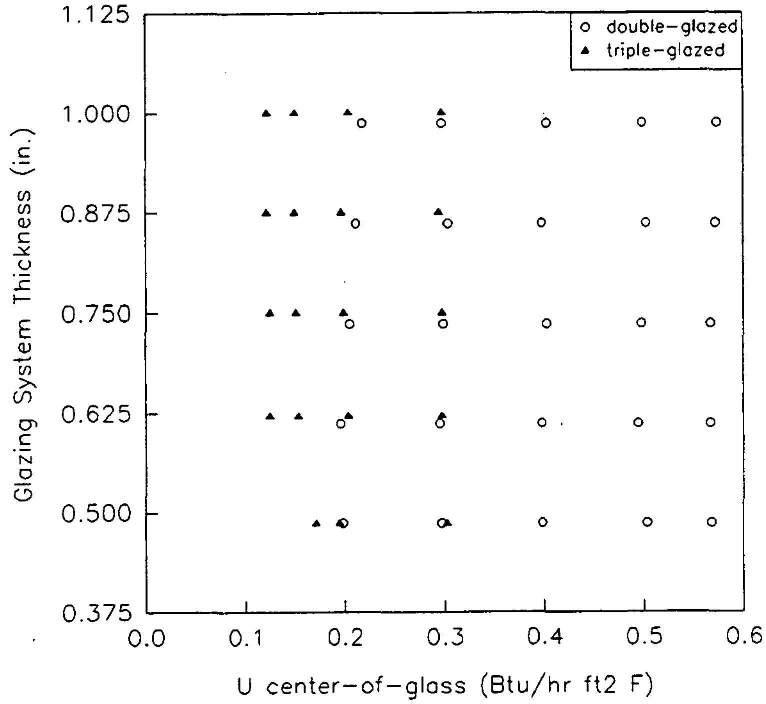

Figure 1. Matrix of simulated glazing configurations. These glazing configurations were chosen to cover the range of commercially available insulating glazing unit gap widths and thermal performance levels.

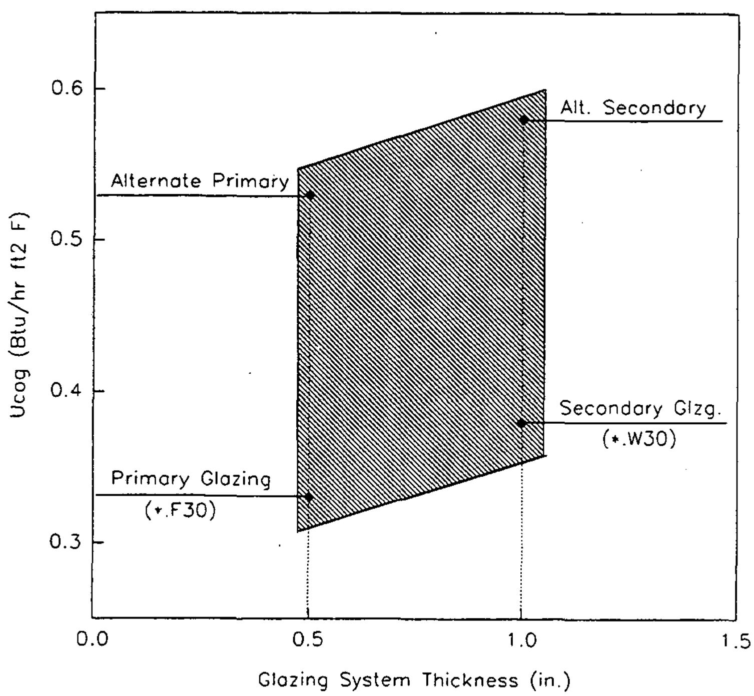

Figure 2. Relationship of the glazing configurations used in a four point simulation. Four glazing configurations are specified for each frame profile in the four point simulation. Once the FRAME simulation has been completed, the simulator can combine this frame profile file with any glazing configuration which falls within the 5% tolerance region set by WINDOW4 (valid within the shaded region).

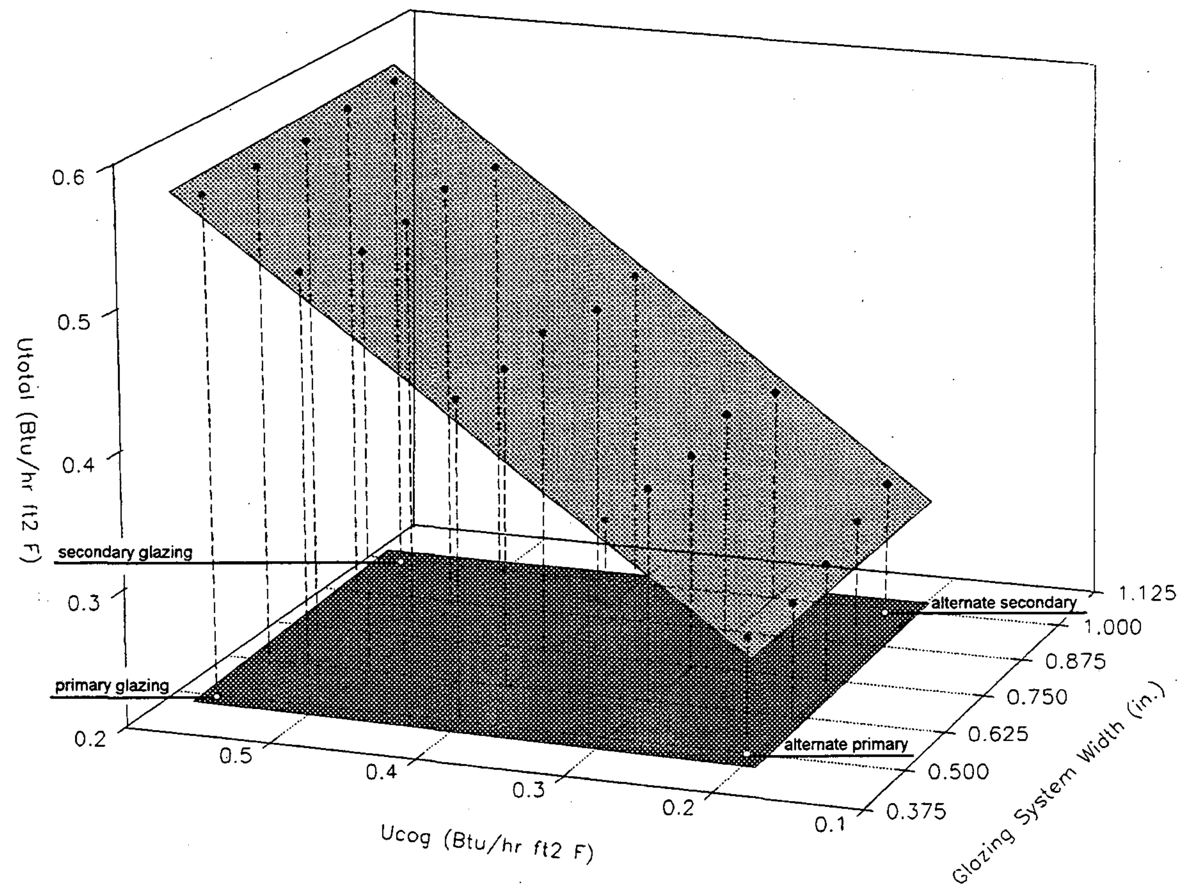

Figure 3. Total window U-value as a function of glazing thickness and center-of-glass U-value. By definition of WINDOW4's linear interpolation, all total window U-values calculated with the four point simulation method and based on valid glazing configurations will lie on the lightly shaded plane of total window U-Values.

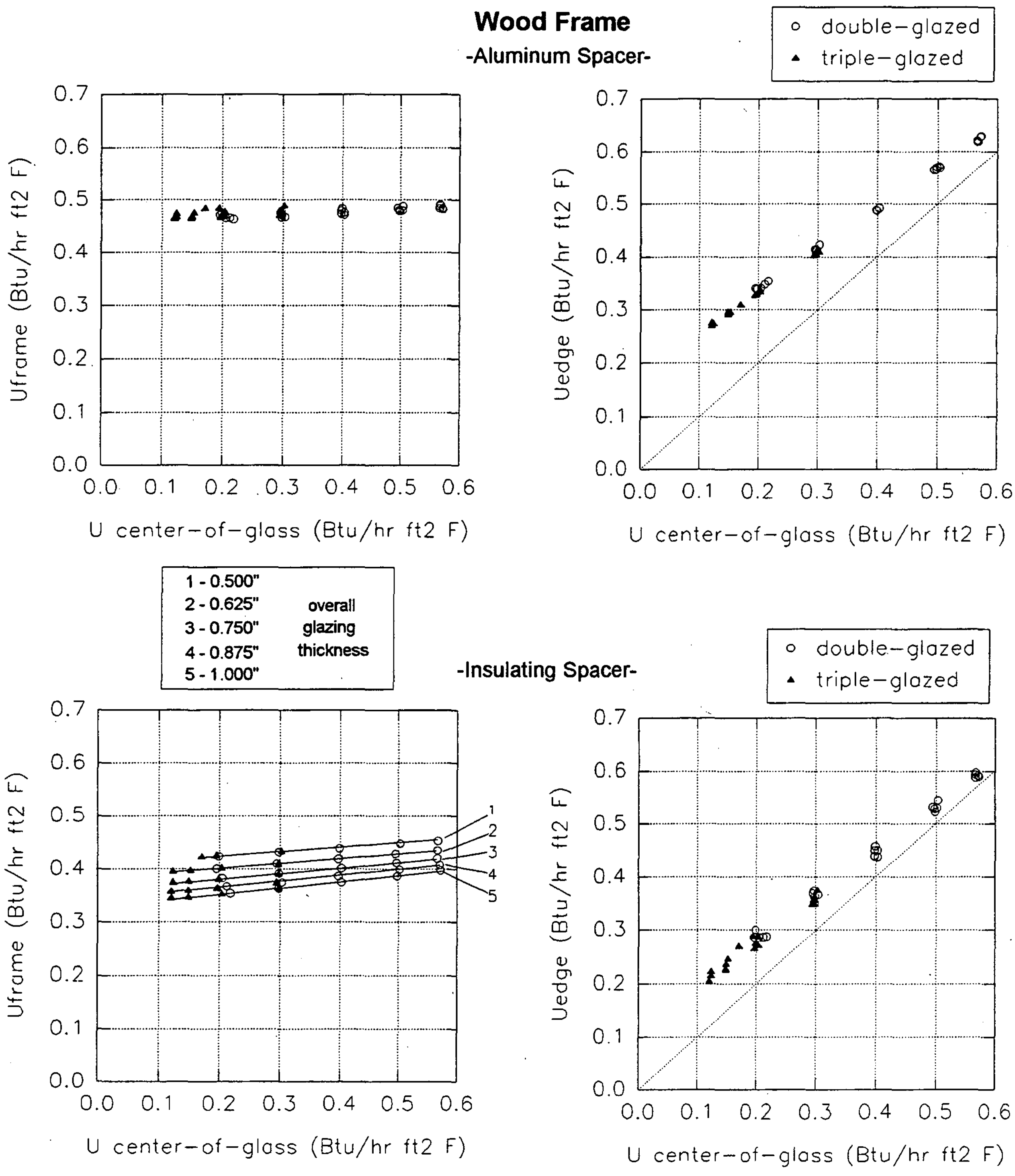

Figure 4. Change in frame and edge U-values with center-of-glass U-values based on single point simulation of a wood-frames casement window. Data is shown for all glazing thicknesses modeled.

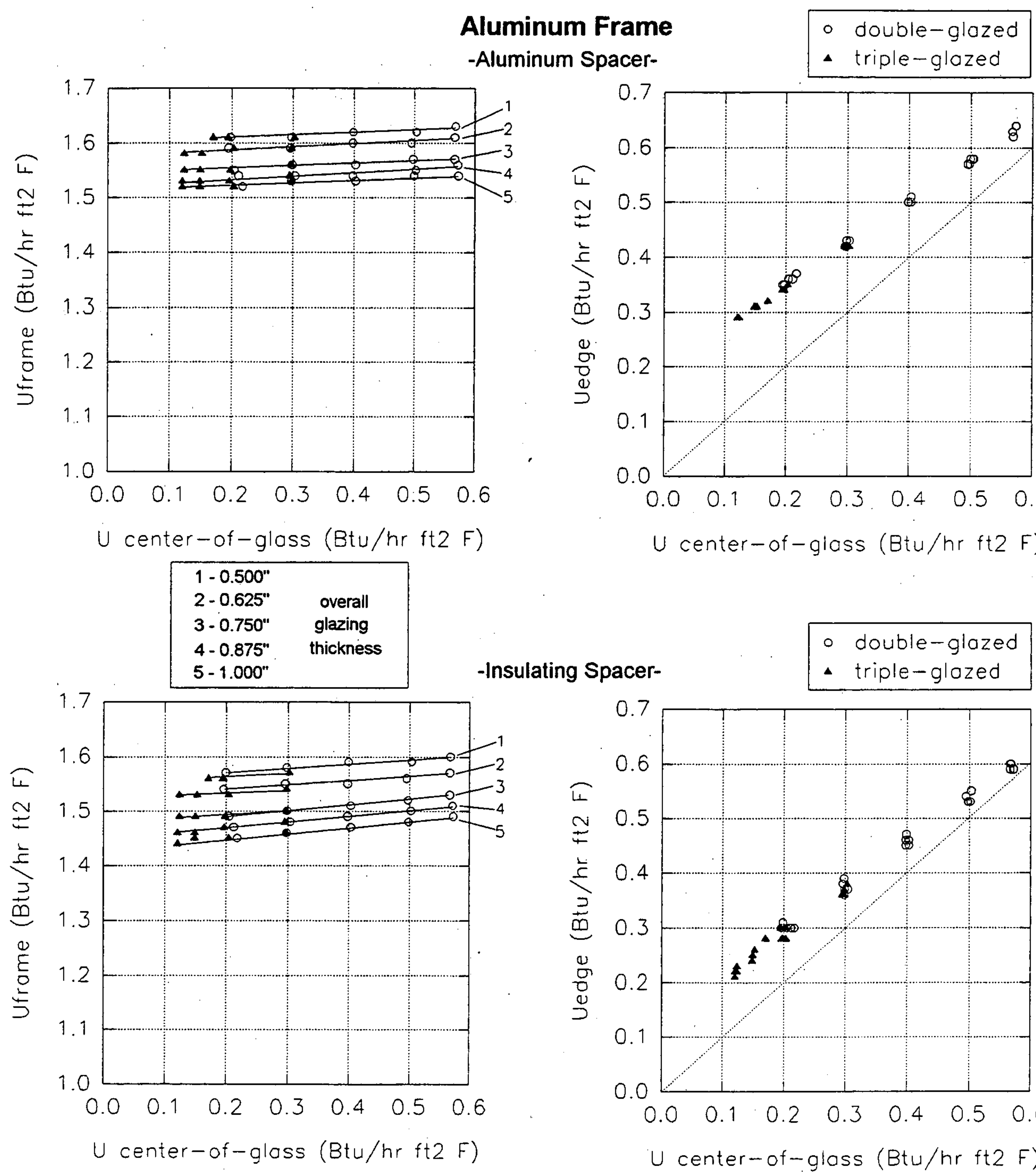

Figure 5. Change in frame and edge U-values with center-of-glass U-values based on single point simulation of a non-thermally broken aluminum-framed casement window. Data is shown for all glazing thicknesses modeled.