Comparison of Experimental Test Results and Analytical Calculations of Window Thermal Performance

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ABSTRACT

This paper presents a comparison of computer-simulated and laboratory-measured thermal characteristics for three commercially available windows. The characteristics—thermal transmittance, U, and shading coefficient, SC—were experimentally derived under a guarded hot box thermal resistance test method and a recently developed solar-simulator-based test method. As a basis of comparison, analytical results were predicted for conditions corresponding to the laboratory test conditions.

Results indicate that simplified computer simulation programs may not adequately predict the thermal characteristics of all window frame configurations. Under certain conditions, a significant deviation in simulated U-values from laboratory results, up to 18%, may occur.

As commercially available glazing units include increasingly complex frame designs and material combinations, such computer programs may result in significant discrepancies. Complex designs and varying construction details due to manufacturing tolerances are accounted for in laboratory measurements. Consequently, to determine specific window characteristics, it is recommended that laboratory testing be undertaken and, if computer results are used, they should be refined and validated against experimental results.

Although the test specimens considered in this study are not representative of all currently available or installed products, this study may then serve as a basis for developing a standard procedure to validate computer modeling intended to determine the thermal performance of glazing units.

INTRODUCTION

In response to the need for energy conservation, the rating and labeling of commercial glazing products have received increased attention. In particular, it has been suggested that thermal performance be included in energy labels for fenestration systems. Thermal performance characteristics include the thermal transmittance, *U*, and the shading coefficient, *SC*. These characteristics are typically measured in test laboratories. However, computer programs are being increasingly used to evaluate the thermal performance of windows, based on analytical analysis and simulation procedures.

Improvements in window design and technologies have resulted in glazing systems that include a variety of materials and complex designs. Heat transmission through total window units, i.e., through glazing, frame, sash, etc., may be complex and difficult to model accurately due to manufacturing tolerances or unknown material properties. Consequently, it may not be possible to account for such construction details in broad-ranging programs, designed to simulate most of the wide range of available glazing systems.

The thermal performance of full-size units can be accurately measured in test laboratories. Guarded hot box thermal resistance test methods (ASTM 1980a,b) or laboratory thermal transmittance test methods (Bowen and Solvason 1987) can be used to measure the winter thermal transmittance. A recently developed test method, based on the use of a solar simulator, produces a "sunlit" thermal transmittance and the *SC* of the test specimens (Dubrous and Harrison 1989). Such test methods produce results that are representative of the design and construction of the total window unit.

However, testing of the entire range of available glazing systems in designated laboratories would be expensive and time consuming and consequently may not be practical. As a result, it is proposed that the evaluation of the thermal performance of glazing systems be based on a combination of test results and computer-simulated calculations. In particular, for windows of a given type, simulation procedures could be used to predict the performance of units of various sizes. These procedures would have to be validated against "real" test results obtained in designated laboratories for specific test specimen sizes and under specified test conditions.

In this study, the thermal characteristics of three commercial windows were obtained from laboratory measurements and compared with computer-simulated values. It should be noted that this sample is not representative of the wide range of available products and that the conclusions of this paper are not meant to represent an average case. Further testing is currently under way, and additional comparisons of analytical with experimental window thermal characteristics are planned.

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TABLE 1
Characteristics of Test Specimens

	specimen type #1	#2	#3
Number of glazing	2	2	3
Window $H_{tw} \times W_{tw}$ (mm)	1600 × 700	1590 × 690	1590 × 690
Glazing $H_{tg} \times W_{tg}$ (mm)	1450 × 560	1450 × 540	1440 × 540
Glass pane thickness (mm)	3	3	3
Interpane gap size (mm)	12.7	12.7	12.7
Gap filled gas	air	air	air
Coating	none	none	soft low-e (inner pane)
Frame	Aluminum & thermal break	wood	wood
Spacer	aluminum	aluminum	aluminum
Sealant	polysulphide	polyurethane	polyurethane & isobutyl

TABLE 2
NRC Winter Nighttime Test Conditions

Test conditions	T_i °C	T_o °C	Outer air film coeff. W/m²·°C	Wind direction
#1	21.0	−7.0	21.80	windward
#2	21.0	−18.0	21.80	windward
#3	21.0	−35.0	21.80	windward

TEST SPECIMEN DESCRIPTION

This paper presents results for two generic types of commercially available windows—two double-glazed, air-filled windows and a triple-glazed window with low-emissivity coating. All windows are vertical sash casement windows without mullions. A description of their design characteristics is given in Table 1. The double-glazed, wooden window and the triple-glazed, wooden window shared the same wood frame during laboratory tests, i.e., casement sections were exchanged.

EXPERIMENTAL TEST METHODS

Experimental test results were obtained under nighttime, winter conditions at the Institute for Research in Construction (IRC), National Research Council of Canada (NRC), Ottawa (Bowan and Solvason 1987), and under irradiated conditions at the Canadian National Solar Test Facility (NSTF) using a method developed by the Solar Calorimetry Laboratory (SCL) (Dubrous and Harrison 1989).

IRC/NRC Test Method

Testing at the NRC was conducted in an environmental test facility (Bowan and Solvason 1987). To simulate indoor conditions, a guarded hot box was used to maintain constant warm-side temperatures. The weather-side compartment of the facility is refrigerated, and a wind machine is used to produce a rapid air motion on the cold side of the test specimen. During testing, inside surface convective heat transfer is produced by the natural convection of air that develops within the hot box. The testing was conducted at three conditions, including the standard ASHRAE winter rating conditions (Table 2).

Solar-Simulator-Based Test Method

All three windows were also tested using a new, solar-simulator-based test method (Dubrous and Harrison 1989). The unique feature of this method is its capability to simultaneously measure the U-value and *SC* of entire glazing systems under "real life" sunlit conditions.

The window characteristics, i.e., *U* and *SC*, can be derived from unique performance curves established for each test specimen (Harrison and Barakat 1989). With this method, performance is measured based on a simple energy balance over the test specimen. The net heat gain per unit area through the specimen, q_n, is equal to the solar heat gain minus the heat losses through the specimen, i.e.,

$$q_n = SC \cdot F_s \cdot H_t - U \cdot (T_i - T_o) \quad (1)$$

where the losses due to air leakage are accounted for in the U-value. F_s is the standard solar heat gain (ASHRAE 1981), H_t represents the solar irradiance, and $(T_i - T_o)$ is the indoor/outdoor temperature difference. Thermal performance is then simply calculated by:

$$\eta = \frac{q_n}{H_t} = SC \cdot F_s - U \cdot \frac{(T_i - T_o)}{H_t} \quad (2)$$

To establish the performance curves, thermal performance data are measured under a range of steady-state conditions, and the characteristic curves are derived from a linear regression analysis. The *SC* and U-value correspond to, respectively, the slope and y-intercept divided by the F_s of the performance curve.

The National Solar Test Facility (Pullan 1981) ideally simulates "real life" environmental conditions. It allows testing to be performed under controlled climatic and irradiation conditions in a specially equipped environmental chamber. To conduct measurements of window performance at the NSTF, a unique facility, including a calorimeter test cell, has been designed. To simulate "real life" convective heat transfer inside a building room, the cell design allows for natural convection to develop in the enclosure, resulting in a temperature rise from the floor to the bottom of the cell. During testing, the cell is placed in a simulator chamber, as shown conceptually in Figure 1. The simulator supplies the environmental chamber with humidity-controlled air at an adjustable temperature and a uniform velocity and direction, parallel to the floor. The test specimen is then irradiated at regulated levels, ranging from 100 to 1000 W/m², using a single-source arc lamp equipped with a unique reflector system (Camm et al. 1981). A window mounted in the calorimeter cell is shown being exposed during testing in Figure 2. Test conditions for all three windows are listed in Appendix A.

ANALYTICAL PROCEDURES AND SIMULATED U-VALUE CALCULATIONS

The three public domain computer programs used for this study include VISION2, FRAME 1.2, and WINDOW 3.1 (see references). WINDOW 3.1 evaluates both the *SC* and the U-value. A second set of values for the window thermal characteristics was obtained by combining VISION2 and FRAME 1.2.

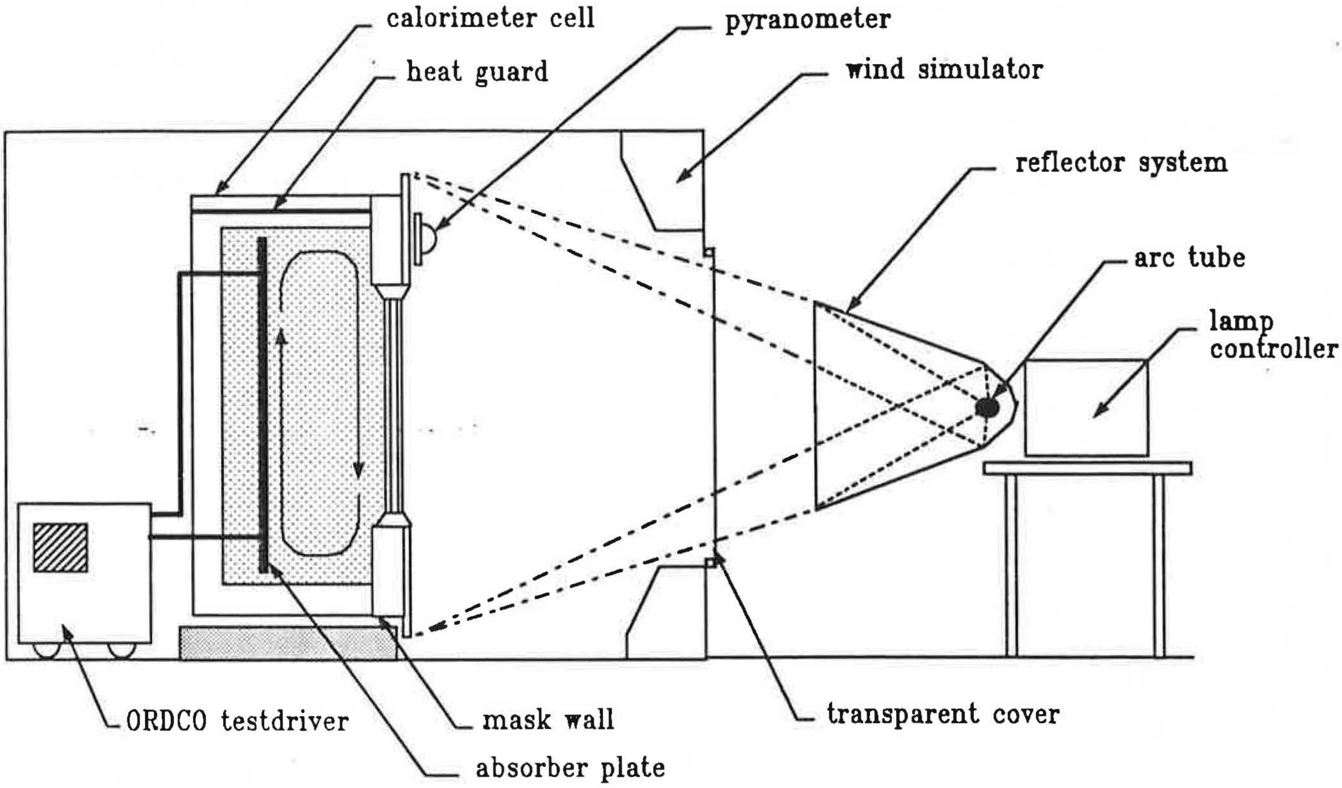

Figure 1 *Schematic diagram of the test cell*

It should be noted that the approach undertaken in this analysis may be typical of that used by designers and architects to evaluate the expected thermal performance of various glazing systems by computer simulation.

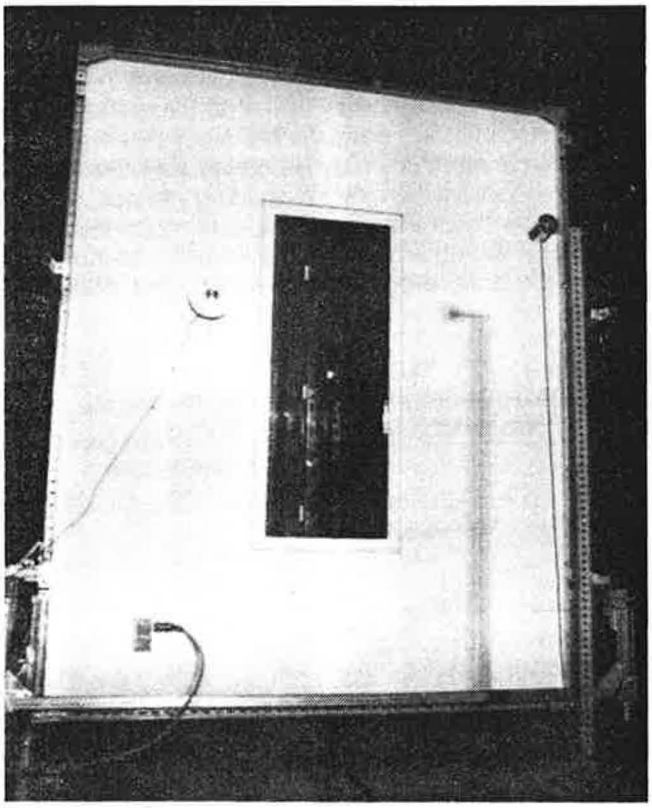

Figure 2 *Test window under irradiated conditions at the NSTF*

Combination of VISION2 and FRAME Output

The *SC* of the center-glazed part of the window, SC_{cg}, is calculated by VISION2 and adjusted to the *SC* of the entire unit using an areabased calculation:

$$SC = \frac{A_{cg}}{A_{tw}} \cdot SC_{cg} \quad (3)$$

where A_{cg} and A_{tw} represent the center glazing and total window area, respectively (Figure 3).

The U-value of the entire unit is calculated using an area-based combination of the center-glass U-value, given by VISION2, and the "frame" U-value, obtained with FRAME 1.2. A user-defined drawing of the cross section of the frame and edge glazing area is input in FRAME 1.2. The program then evaluates the energy transmission through the frame, including the effects of heat transfer through the spacer and sash-edge of the glass, based on a finite difference computational procedure.

Simulated heat loss through the frame and frame/sash, Q_f, is equal to the calculated heat flow per unit length, q_f, multiplied by the total length of the frame. U_{tw} is then evaluated from the thermal transmittance of the center glass, U_{cg}, as calculated with VISION2, and the heat loss through the frame, as follows:

$$U_{tw} = \frac{(U_{cg} \cdot A_{cg}) + \frac{Q_f}{T_i - T_o}}{A_{tw}} \quad (4)$$

where T_i and T_o are, respectively, the indoor and outdoor simulated temperatures. A_{cg} represents the center glazing area and is equal to the total window area minus the frame and sash-frame area.

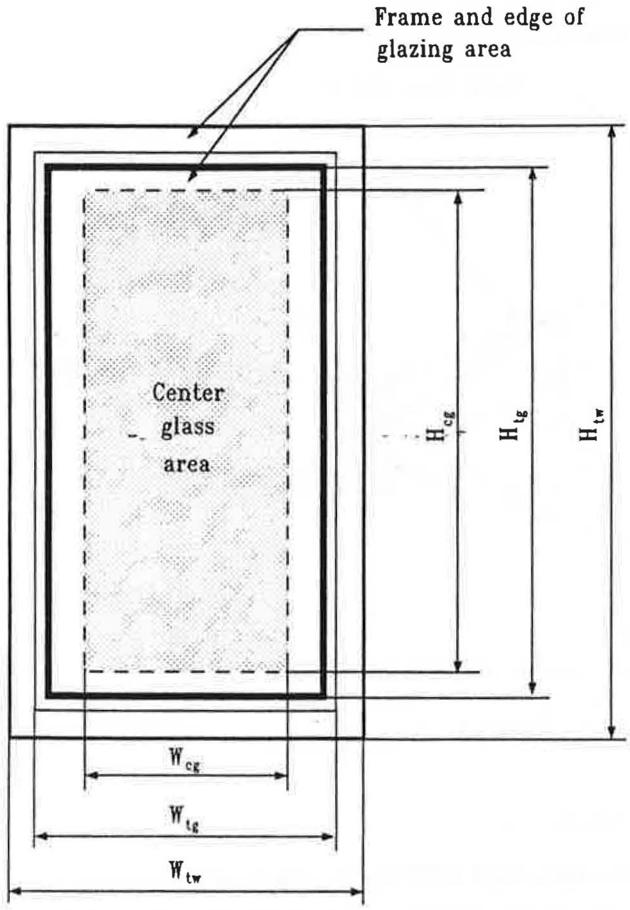

Figure 3 *Window characteristic dimensions for U_{tw} calculation*

Program input was based on experimental test conditions, i.e., indoor and outdoor temperatures, solar irradiation, and wind speed and direction or equivalent air film coefficients. To evaluate more accurately the heat losses through the frame and sash-frame area, the values of the resistance of both the inner and outer film coefficients used for FRAME 1.2 were derived from VISION2:

$$f_o = \frac{Q_{cg,o}}{A_{cg} \cdot (T_{g,o} - T_o)} \qquad (5)$$

where f_o is the outer film coefficient, $Q_{cg,o}$ the heat flux from the outdoor side, and $T_{g,o}$ the outer glass pane temperature. The indoor film coefficient, f_i, is given by:

$$f_i = \frac{Q_{cg,i}}{A_{cg} \cdot (T_i - T_{g,i})} \qquad (6)$$

where $Q_{cg,i}$ is the heat flux to the indoor side and $T_{g,i}$ the inner glass pane temperature. A schematic diagram of this computational procedure is presented in Figure 4.

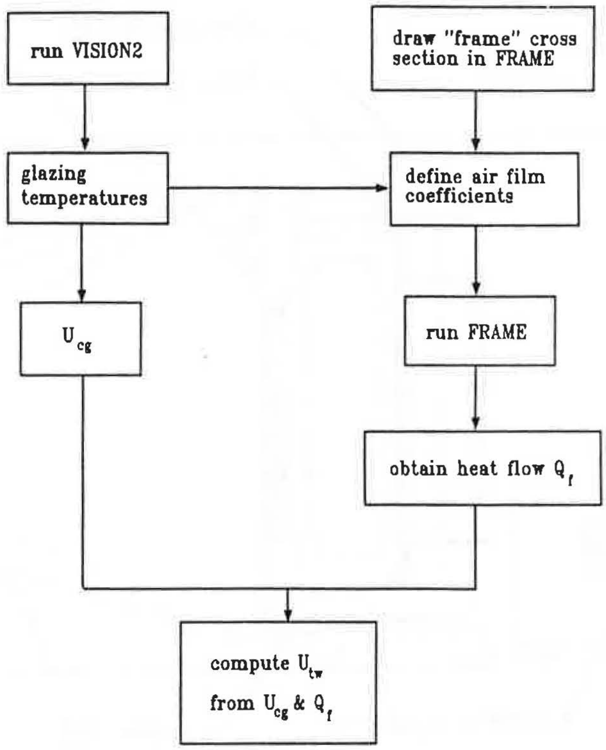

Figure 4 *U_{tw} computation procedure combining output of two computer programs*

WINDOW 3.1 Simulation

U-values and *SC* of the entire glazing systems were also also determined by using WINDOW 3.1. WINDOW 3.1 uses a finite difference method to establish a temperature distribution through the glazing part of the system. Frame and edge-of-glass effects are modeled separately. From the value of SC_{cg} evaluated by WINDOW 3.1, the shading coefficient value of the total unit was derived using Equation 3. Generic glass types were selected to represent the glazing materials of the windows. As detailed information on the frame construction and materials was not available in the program frame library, generic frame types were selected, i.e., wood and aluminum with thermal break. It should be noted that, although the casement windows considered in this study may be adequately described, windows incorporating integral shading devices, e.g., a screen or blinds, or windows of more complex designs, e.g., vertical sliding windows with mullions and muntins, may not be accurately represented by the available options.

TABLE 3
Comparison of Simulated Shading Coefficient Values with NSTF-Measured Values

	Test Specimen #1	#2	#3
Center glass SC_{cg} (calculated)			
VISION2	0.90	0.90	0.66
WINDOW 3.1	0.89	0.89	0.66
Total window *SC*			
NSTF* (measured)	0.64	0.61	0.46
VISION2 (calc.+)	0.65	0.64	0.64
deviation ΔSC (%)	1.6	4.9	2.2
WINDOW 3.1 (calc.+)	0.65	0.64	0.47
deviation ΔSC (%)	1.6	3.3	2.2

*the value of the *SC* is derived from the characteristic performance curve by using Equation 2
+calculated according to Equation 3

TABLE 4
Comparison of NSTF U-Values for Three Windows with NRC-Measured U-Values

Window Type	U_{SCL} sunlit	U_{NRC}	ΔU (%)
Double-glazed, Al frame	3.29	3.33	−1.2
Double-glazed, wood frame	3.00	2.94	+2.0
Triple-glazed, low-E wood frame	1.76	1.79	−1.7

RESULTS AND DISCUSSION

Shading Coefficient

Simulated *SC* values were obtained for each of the three window glazing sections and were adjusted to the total window by using an area-based correction factor, Equation 3. Results are listed in Table 3, along with the measured values. A comparison of these values shows a good agreement of calculated *SC* with measured *SC* values, with deviation ranging from 1.6% to 4.9% from the measured *SC* values.

U-Values

Sunlit U-values obtained with the NSTF solar-simulator-based test method have been compared with NRC measured values. They show good agreement with the NRC values, with deviations ranging from −1.7% to +2.0% (Table 4). Preliminary test results obtained at the NSTF under nighttime conditions are also presented in the Appendix.

The thermal transmittance of the entire unit was simulated, based on WINDOW 3.1 and the VISION2/FRAME 1.2 combined procedure. Simulated results have been plotted vs. measured values for each test specimen (Figure 5). In the case of the aluminum window, significant discrepancies were observed in the simulation of the sunlit U-values. WINDOW 3.1 values resulted in deviations from test values up to 16.6%. Deviations observed with VISION2/FRAME values were comparatively lower, from −0.2% to 7.5%. WINDOW 3.1 results show good agreement with NSTF-measured U-values for test specimen #2. VISION2/FRAME resulted, in this case, in variations up to 10.8%. Significant discrepancies were observed in the case of the triple-glazed window. VISION2/FRAME resulted in up to a −13.1% deviation from NRC-measured values, and WINDOW 3.1 values varied by as much as 17.7% from NSTF-measured values. It should be noted that this comparison does not include NSTF-measured values under nighttime conditions, as further analysis of these experimental data is required.

To investigate the effects of the heat flow simulation through the frame on total window simulated U-values, U-values for center glass only, U_{cg}, were calculated using VISION2 and FRAME. Data are presented in the Appendix and U_{cg} values are plotted vs. the mean indoor/outdoor temperature for each test specimen in Figure 6. For all three specimens, simulated results show good agreement for U_{cg} predictions. Therefore, it may be concluded that significant variations in results are due to the frame and spacer and edge of glass simulation.

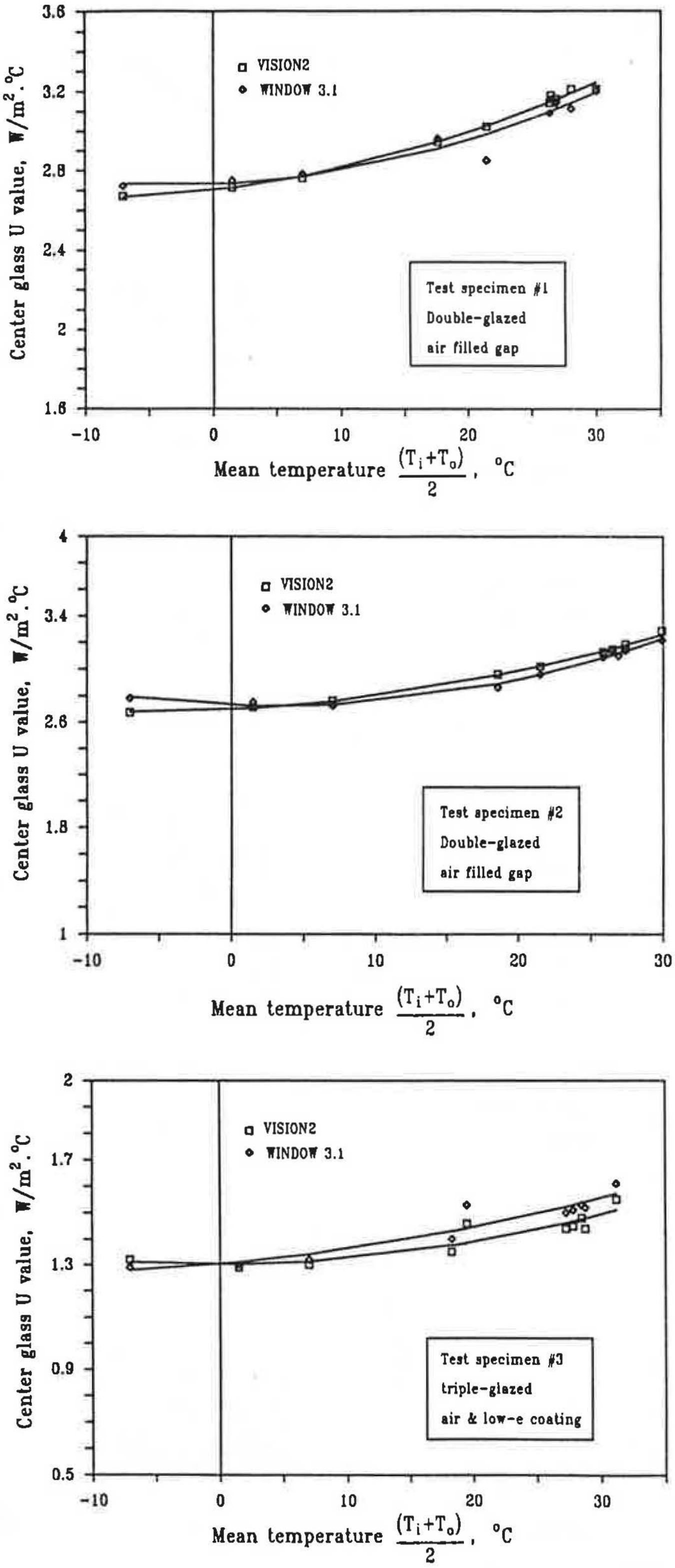

Figure 5 *Plot of analytical U_{tw} values vs. measured values for three different test specimens*

CONCLUSION AND RECOMMENDATIONS

Analytical calculations of the thermal transmittance of three windows were compared with validated experimental test results. Results show that significant deviations in U-

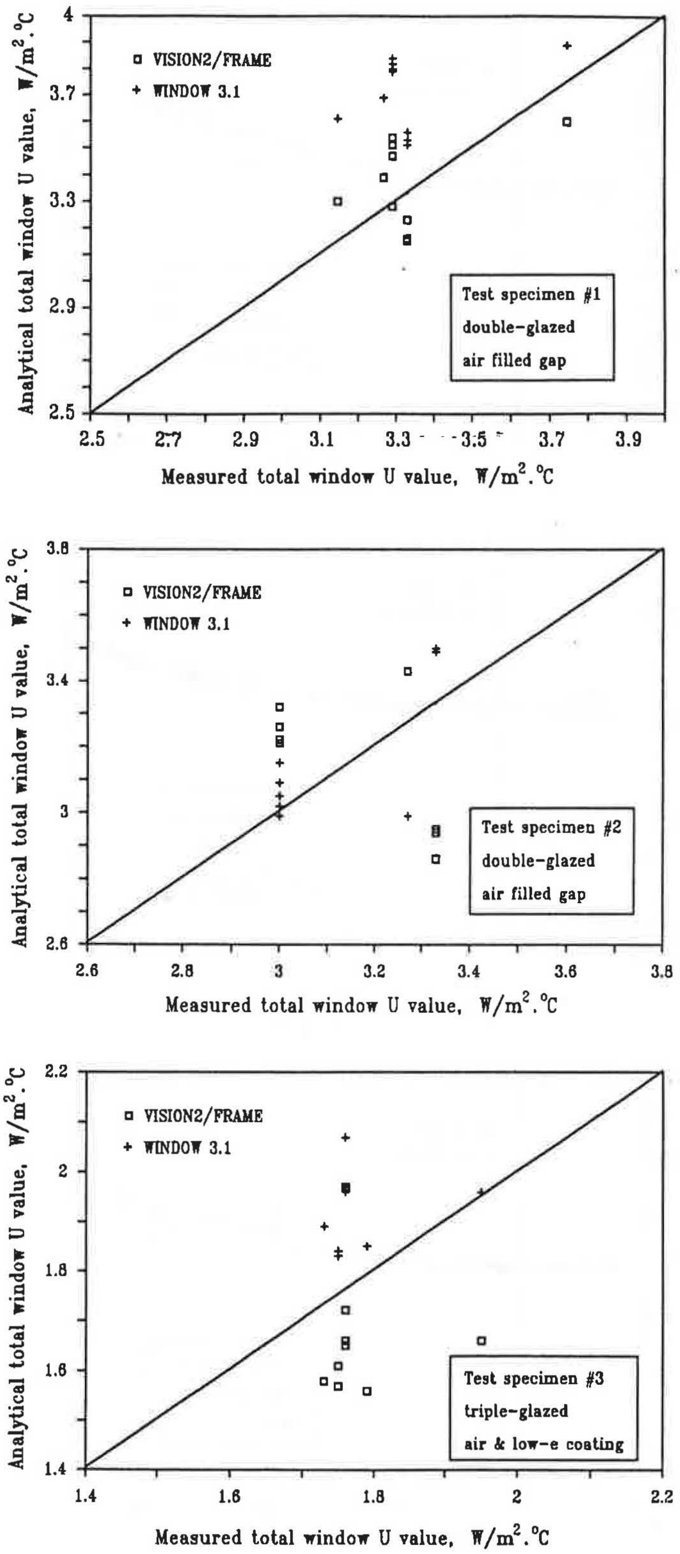

Figure 6 *Plot of analytical U_{cg} values for three test specimens*

values may occur under certain conditions. FRAME 1.2 results are based on a two-dimensional analysis. The extrapolation of FRAME 1.2 output to a three-dimensional U-value and the combination of VISION2/FRAME 1.2 outputs using a non-standard procedure may result in significant variations in U-values. WINDOW 3.1 has a limited frame library, and, therefore, the simulation of heat transfer through complex or new window frames or systems may not be adequate. Consequently, simulated thermal performance of glazing systems should be validated against laboratory-measured values.

As testing of all the available fenestration systems would be expensive and impractical, simulation should be combined with testing to allow for a quick and accurate evaluation of system thermal performances. Test methods, such as the SCL solar-simulator-based test method, would provide the *U* and *SC* characteristics of glazing systems of specific sizes and would be applicable to a new generation of products. The development and validation of such a combined performance evaluation procedure should lead to further research and model validation.

NOMENCLATURE

A	= area, m²
f	= air film coefficient, W/m²·°C
F	= solar heat gain, dimensionless
Ht	= solar irradiance, W/m²
H	= height, m
q	= rate of energy per unit area, W/m²
Q	= energy flow, W
SC	= shading coefficient, dimensionless
U	= thermal transmittance, W/m²·°C
T	= temperature, °C
W	= width, m
η	= thermal performance, dimensionless
ΔT	= temperature difference, °C

Subscripts

cg	= center glazing
cg,i	= center glazing, inner pane
cg,o	= center glazing, outer pane
f	= frame
g,i	= glazing, inner pane
g,o	= glazing, outer pane
n	= net
s	= standard
tg	= total glazing
tw	= total window

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APPENDIX

Simulated Center Glass, Frame, and Total Window U-Values for Three Windows and Comparison with Measured U-Values

TEST SPECIMEN #1 — **Test Conditions**

	NRC			NSTF						
	1	2	3	1	2	3	4	5	6	7
T_o	−7	−18	−35	30.1*	10.0	10.5	10.4	10.1	9.2	9.4
T_i	21	21	21	22.9*	46.1	43.3	42.4	49.9	26.1	33.6
H_t	0	0	0	989	497	225	124	0	0	0
Simulated U_{cg} values										
VISION2 [8]	2.76	2.71	2.67	3.18	3.21	3.16	3.14	3.21	2.94	3.02
WINDOW [10]	2.78	2.75	2.72	3.16	3.11	3.14	3.09	3.20	2.85	2.96
Simulated U_f values										
FRAME [9]	3.48	3.40	3.40	3.63	3.71	3.35	3.69	3.80	3.48	3.57
Total U_{tw} values										
Measured	3.33	3.33	3.33	3.29	3.29	3.29	3.29	3.75	3.15	3.27
Simulated/Calculated										
VISION2/FRAME	3.23	3.16	3.15	3.47	3.54	3.28	3.51	3.60	3.30	3.39
ΔU_{tw} (%)	−3.0	−4.9	−5.3	5.6	7.5	−0.2	6.5	−3.9	4.9	3.7
WINDOW	3.56	3.53	3.51	3.82	3.84	3.80	3.79	3.86	3.61	3.69
ΔU_{tw} (%)	6.8	6.1	5.5	16.2	16.6	15.5	14.9	3.1	14.8	13.0

*simulated summer conditions

TEST SPECIMEN #2 — **Test Conditions**

	NRC			NSTF						
	1	2	3	1	2	3	4	5	6	7
T_o	−7	−18	−35	10.4	9.5	9.2	9.0	10.1	10.2	9.4
T_i	21	21	21	49.4	45.3	43.8	42.7	27.0	43.6	33.6
H_t	0	0	0	982	402	203	125	0	0	0
Simulated U_{cg} values										
VISION2 [8]	2.76	2.71	2.67	3.29	3.19	3.15	3.13	2.96	3.14	3.02
WINDOW [10]	2.78	2.75	2.72	3.22	3.14	3.15	3.09	2.86	3.10	2.96
Simulated U_f values										
FRAME [9]	2.99	3.04	3.09	3.34	3.29	3.26	3.26	3.16	3.25	3.64
Total U_{tw} values										
Measured	2.94	2.86	2.86	3.00	3.00	3.00	3.00	1.99	3.74	3.27
Simulated/Calculated										
VISION2/FRAME	2.91	2.92	2.95	3.32	3.26	3.22	3.21	3.09	3.21	3.43
ΔU_{tw} (%)	−1.1	−2.2	−3.0	10.8	8.5	7.5	7.1	55.4	−14.0	5.0
WINDOW	2.81	2.79	2.77	3.15	3.09	3.02	2.98	2.83	2.99	2.99
ΔU_{tw} (%)	4.4	−2.6	−3.3	4.9	2.9	0.8	1.6	42.0	−20.0	−8.5

TEST SPECIMEN #3 — **Test Conditions**

	NRC			NSTF							
	1	2	3	1	2	3	4	5	6	7	8
T_o	−7	−18	−35	19.6	11.1	10.1	10.1	10.1	9.6	10.1	9.4
T_i	21	21	21	19.4	51.3	46.8	45.5	44.4	47.9	37.1	27.2
H_t	0	0	0	992	989	401	210	128	0	0	0
Simulated U_{cg} values											
VISION2 [8]	1.30	1.29	1.32	1.46	1.55	1.48	1.45	1.44	1.44	1.40	1.35
WINDOW [10]	1.32	1.30	1.29	1.53	1.61	1.53	1.51	1.50	1.52	1.46	1.40
Simulated U_f-values											
FRAME [9]	1.66	1.69	1.73	0.17	1.79	1.74	1.74	1.74	1.75	1.71	1.68
Total U_{tw} values											
Measured	1.79	1.75	1.75	1.76	1.76	1.76	1.76	1.76	1.95	1.27	1.73
Simulated/Calculated											
VISION2/FRAME	1.56	1.57	1.61	0.55	1.72	1.66	1.65	1.65	1.66	1.62	1.58
ΔU_{tw} (%)	−13.1	−10.1	−8.2	68.9	−2.2	−5.4	−6.1	−6.2	−14.9	27.1	−8.7
WINDOW	1.85	1.84	1.83	1.97	2.02	1.97	1.96	1.96	1.96	1.93	1.89
ΔU_{tw} (%)	3.3	5.0	4.6	12.1	17.7	11.9	11.4	11.1	0.6	51.4	9.3