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ABSTRACT

For six windows the U-values measured with the MoWiTT under field conditions are compared with detailed U-value calculations for the same conditions using the programs WINDOW and ANSYS. There is good agreement between measurements and calculations.

INTRODUCTION

The proper specification of window U-values has been a controversial area for many years, and current attempts to incorporate more careful treatment of windows into building standards and utility conservation programs and to define window energy labels has heightened the controversy. The root of this controversy lies in the geometric complexity of windows and the sensitivity of the U-values of ordinary (as opposed to high-performance) windows to the temperatures and surface heat transfer coefficients on their inner and outer surfaces. This makes it difficult to test windows under precisely defined conditions, to interrelate measurements done at different test laboratories, and to apply test laboratory data to determine window U-values under conditions representative of actual use.

In a previous paper (Klems 1979) it was argued that current calculation techniques, as embodied in the computer program WINDOW (Arasteh et al. 1986; Rubin 1982), accurately represented field-measured window U-values, provided frame corrections and surface heat transfer coefficients were correctly estimated, and that in most cases the calculations were also consistent with test laboratory measurements on the same windows. This means that the calculation could serve both as a standard for deriving calculated U-values and as a method of comparing measurements made under different conditions to determine their consistency.

This work has now been extended to form a joint U.S./Canadian collaborative effort to test current computer programs. In this project, U-values for a selected set of windows are to be calculated using either the program WINDOW, with edge and frame corrections calculated with the commercially available program ANSYS® (DeSalvo and Gorman 1987), or the Canadian programs VISION (Wright and Sullivan 1989) and FRAME

(Enermodal 1987). The calculated values are to be compared with laboratory measurements made in Canada and field measurements made with the MoWiTT (Mobile Window Thermal Test) facility in the U.S. This paper is a progress report on the U.S. side of that collaboration and presents MoWiTT measurements on the selected windows in comparison with WINDOW/ANSYS calculations.

WINDOW SAMPLES

The window samples were selected to test the range of situations likely to be encountered in calculating U-values for windows that are now or in the near future are likely to be commonly encountered: central glazing units of varying conductance (single, double, low-E) and a range of frame conductances (aluminum without and with thermal break, wood). In addition, a prototypical "superwindow" supplied by a major manufacturer was also tested as an example of potential windows with much lower conductance glazings. This, in part, compensates for the fact that the low-emissivity window tested had a relatively poor performance coating (emissivity=0.44). All windows were chosen to be well sealed, non-operable models in order to eliminate any possible effects due to air infiltration, which is not included in the calculations and is not intended to be a part of this study.

Details of the windows listed are shown in Table 1, and, with the exception of the superwindow prototype, frame cross sections are shown in Figure 1. A schematic drawing of the superwindow prototype, the exact details of which are proprietary, is shown in Figure 2.

U-VALUE MEASUREMENTS

Measurements were made in Reno, Nevada, during the period 1987-1989. The MoWiTT, which has been described in detail elsewhere (Klems et al. 1982; Klems 1984) consists of two side-by-side, room-sized, guarded calorimeters that measure net heat transfer through two window systems simultaneously exposed in the same orientation to ambient weather conditions. The net heat flow through each window system is determined by a dynamic net heat balance on the calorimeter chamber. During the night, which in these measurements was taken to be the period between midnight and sunrise, the U-value can be determined for each measurement interval by dividing the net heat flow by the sample area and the difference between indoor and outdoor mean air temperatures, which are also measured. A small correction is made for heat flowing through that part of the sample-holding wall that is not accounted for in the net heat balance. Measurements in the MoWiTT are taken rapidly and averaged over a set measurement period, which for these measurements was taken to be 10 minutes.

A window sample is typically studied for about one week. This results in a large set of ten-minute-average U-value measurements. The mean and standard deviation of this set of measurements is taken to be the measured U-value and its measurement error. Defined in this way, the measurement error includes U-value fluctuations due to weather variations as well as those due to random measurement error. Longer-term systematic errors are accounted for by separate calibrations of the critical components of the net heat balance measurement and by periodic redundant "closed-box" tests in which the test sample is replaced by a large heat-flux sensor.

The resulting U-value measurement applies to the average conditions of wind, temperature, and surface heat-transfer coefficient the window experiences during the test. In order to compare these measurements with calculations, it is necessary to know the average test conditions. Simultaneously with the U-value measurements, wind speed and direction (at 10 m height on a tower located next to the MoWiTT) and mean radiant temperature (using a vertically mounted pyrgeometer) over the hemisphere viewed by the window are measured; in some cases, the window is paired with a frameless single glazing in the adjacent calorimeter, for which net heat flow, glass temperature, and local wind speed (approximately 10 cm from the glass) are measured. While the wind speed and radiant temperature measurements provide a basis for calculating the average exterior film coefficient, the single glazing and glass temperature measurements provide a direct, simultaneous measurement of both inside and outside film coefficients. Not all window measurements were made with this comparison, however. Where a simultaneous single glazing measurement was not available, the exterior film coefficient was calculated from the wind speed and radiant temperature, using an empirical wind speed-convective film coefficient equation derived from single glazing measurements at other times.

U-value calculations (and laboratory measurements) typically assume that the exterior radiant and air temperatures are the same. This is generally not the case for nighttime winter conditions in Reno. We therefore define an equivalent exterior film coefficient, h_O, from the following equations:

$$\frac{Q_{MEAS}}{A} = h_r(T_G,T_S)\,[\,T_S - T_G\,] + h_c\,[T_O - T_G\,] \qquad (1a)$$

$$h_r(T_G,T_S) = \varepsilon\,\sigma\,[\,T_G^2 + T_S^2\,]\,[\,T_G + T_S\,] \qquad (1b)$$

$$h_O = \frac{h_r(T_G,T_S)\,[\,T_S - T_G\,] + h_c\,[\,T_O - T_G\,]}{T_O - T_G} \quad , \qquad (2)$$

where T_G, T_S, and T_O are the glass, radiant (sky), and outside air temperatures, respectively (in Kelvin); ε is the glass emissivity; σ is the Stefan-Boltzman constant; Q_{MEAS} is the measured net heat flow; and A is the sample area. Equations 1a and 1b are solved iteratively for the unknown glass temperature T_G, and the solution is substituted into Equation (2) to obtain the effective exterior film coefficient.

U-VALUE CALCULATIONS

The window U-values were calculated by putting the measured interior and exterior air temperatures together with the effective exterior film coefficient into WINDOW to obtain a center-of-glazing U-value and an effective gap conductance. An interior film coefficient of 8.29 $W/m^2 \cdot K$ is assumed. A cross section of the frame, including a 5-inch (12.8 cm) section of the glazing unit, is then modeled in ANSYS, assuming that the the gas space in the glazing is filled with a uniformly conducting material with a conductance equal to the overall gap conductance. The boundary conditions of the finite-element model are uniform interior and exterior temperatures and uniform effective interior and exterior film coefficients. Adiabiatic boundary conditions are assumed at the remaining boundaries of the window section.

The finite element calculation produces a two-dimensional heat flow plot, which is divided into three regions (refer to Figure 3): (1) the "center-of-glazing" region, where heat flow is essentially one-dimensional; (2) the "edge" region, consisting of the portion of the glazing unit (2.5 inches [6.4 cm] from the sight line) where the heat flow is not one-dimensional (due to the effect of the spacer); and (3) the "frame" region. The total heat flowing through the boundary surfaces of each region is integrated, and the projected area of the region is used to construct an equivalent U-value for frame and edge. These are then area-weighted and combined with the WINDOW value for the center-of-glazing region to produce an overall U-value for the window under the given conditions of temperature and effective surface heat transfer coefficient.

RESULTS

The results are presented in Tables 2 and 3. In Table 2 the average nighttime conditions of the MoWiTT measurements are presented, together with the effective exterior film coefficient derived from Equation 2. These film coefficients were used in the WINDOW/ANSYS calculations listed in Table 3. As a statistical test of the consistency of the measurements and calculations, we computed the value of chi-squared for each measurement as follows:

$$X^2 = \frac{[\,U_M - U_C\,]^2}{\sigma^2} \quad , \qquad (3)$$

where U_M and U_C are the measured and calculated U-values, respectively, and σ is the experimental uncertainty in the measurement. These values are also listed in Table 3. These values can be added to produce an overall X^2 value of 7.84 for the six independent measurements. There is a 25% probability of statistical fluctuations producing a value of 7.84 or greater for six degrees of freedom; hence, the calculations and measurements are reasonably consistent. In fact, most of the deviation is in the value for window 4, the low-E window. In this case, there is uncertainty in the estimation of the exterior film coefficient that is not included in the experimental uncertainty; therefore, the discrepancy between theory and experiment is probably not as significant as would be indicated by the X^2 value.

We note that the measurements for windows 1, 2, and 5 have been published previously (Klems 1989). In that publication the measured U-values were found to be consistent with U-value calculations for which the frame correction had been estimated from a simplified analytic calculation. It is reassuring to see that these measurements are also consistent with a more careful ANSYS calculation.

The magnitude of the frame and edge corrections can best be seen from Table 4. In this table the frame and edge effects are listed as corrections to the approximation that the entire window has a U value corresponding to the center of glass value. The entries in this table list the individual terms in the equation

$$U = U_{CTR} + (U_E - U_{CTR})\frac{A_E}{A_T} + (U_F - U_{CTR})\frac{A_F}{A_T} \quad , \qquad (4)$$

together with the values of the central, edge, and frame U-values, U_{CTR}, U_E, and U_F, respectively, and the edge and frame projected areas, A_E and A_F. The total area A_T is 1.104 m^2 for all the windows. It can be seen from the table that for all windows except No. 5 (the superwindow), the edge correction is not larger than 4% and the frame correction is less than 20%. For the superwindow, the frame correction rises to 30%, but even here the edge correction is no bigger than 6%. Since for windows 1, 2, and 4 the quoted experimental uncertainty is around 10% (due to calibration problems during those particular measurements), the experimental constraint placed on the frame calculation is not a very stringent one in those cases. Frame effects are visible, however, as is readily apparent if one compares the experimental uncertainty for the measurement of windows 3, 4, and 6 with the magnitude of the frame corrections for those windows listed in Table 4. For the best measurements the experimental error is around 4%. Thus, none of the measurements is capable of distinguishing the effects of the edge calculation.

The frame correction is about the same magnitude as the variations in U-value caused by the range of differing exterior film coefficients observed during the course of the MoWiTT measurements of the conventional windows. This illustrates the importance of adequate knowledge of the exterior (and interior) film coefficients if one hopes to verify the frame calculations; conversely, a U-value calculation of adequate accuracy only requires a frame calculation of modest accuracy. For the superwindow, the effect of the film coefficient is much smaller, as is the experimental uncertainty; this reperesents the most stringent test of the frame calculation.

CONCLUSIONS

Measured U-values using the MoWiTT are found to be in good agreement with the values calculated using WINDOW/ANSYS for a variety of windows ranging from single glazing through a prototypical superwindow. The comparison primarily tests the central glazing calculation; for the conventional windows, frame corrections are comparable to the effects of exterior film coefficient, and experimental uncertainties do not allow a stringent test of the frame calculations. However, frame effects are experimentally visible and a large error in the calculation would be detected. The experiments are insensitive to the edge correction for all of the windows tested.

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TABLE 1
Description of the Window Samples

Window	Glazings	Fill Gas	Low-E Coatings	Frame Material	Frame Detail	Thermal Break
1	1	Air	No	Aluminum	D	No
2	2	Air	No	Aluminum	C	No
3	2	Air	No	Aluminum	B	Yes
4	2	Air	1	Aluminum	B	Yes
5	2	Air	No	Wood	E	No
6	3	Small Gap: Krypton; Large Gap: Air	2	Wood	Fig. 2	No

TABLE 2

MoWiTT Measurement Conditions

Window Number	Orientation	Measurement Date	Interior Air Temp. º C	Exterior Air Temp. º C	Exterior Radiant Temp. º C	Exterior Film Coefficient W/(m^2 K)
1	East	May-87	22.11	8.39	5.28	15.09
2	West	May-87	21.61	12.61	9.28	21.95
3	West	Dec-88	20.17	-16.18	-16.78	17.60
4	North	Mar-87	21.00	0.72	-1.72	13.89
5	South	Jan-87	19.89	3.39	-2.50	26.22
6	North	Feb-89				14.06

TABLE 3

Comparison of MoWiTT Measurements with WINDOW/ANSYS Calculations

Window Number	MoWiTT Measurement U-Value W/(m^2 K)	WINDOW/ANSYS Calculation U-Value W/(m^2 K)	Chi-Squared
1	4.94 ± 0.51	5.34	0.62
2	3.63 ± 0.34	3.38	0.54
3	3.24 ± 0.17	3.18	0.12
4	3.01 ± 0.17	2.66	4.24
5	2.61 ± 0.34	2.86	0.54
6	1.48 ± 0.06	1.40	1.78

TABLE 4

Magnitude of Edge and Frame Corrections in the Calculation of U-Value

Window	Region	Area m^2	U-Value $W/(m^2\ K)$	Term in Eqn. 4 $W/(m^2\ K)$	Percent of Total U %
1	Center	0.745	5.26	5.26	98.5
	Edge	0.239	5.21	-0.01	-0.2
	Frame	0.120	6.12	0.09	1.7
	Total	1.104	5.34		
2	Center	0.745	2.90	2.90	86
	Edge	0.239	3.21	0.07	2
	Frame	0.120	6.67	0.41	12
	Total	1.104	3.38		
3	Center	0.742	2.69	2.69	84
	Edge	0.238	3.06	0.08	3
	Frame	0.124	6.38	0.41	13
	Total	1.104	3.18		
4	Center	0.742	2.13	2.13	80
	Edge	0.238	2.57	0.09	3
	Frame	0.124	5.97	0.43	17
	Total	1.104	2.66		
5	Center	0.593	2.89	2.89	101
	Edge	0.215	3.39	0.10	3
	Frame	0.296	2.42	-0.13	-4
	Total	1.104	2.86		
6	Center	0.608	0.94	0.94	65
	Edge	0.218	1.32	0.08	5
	Frame	0.278	2.66	0.43	30
	Total	1.104	1.45		

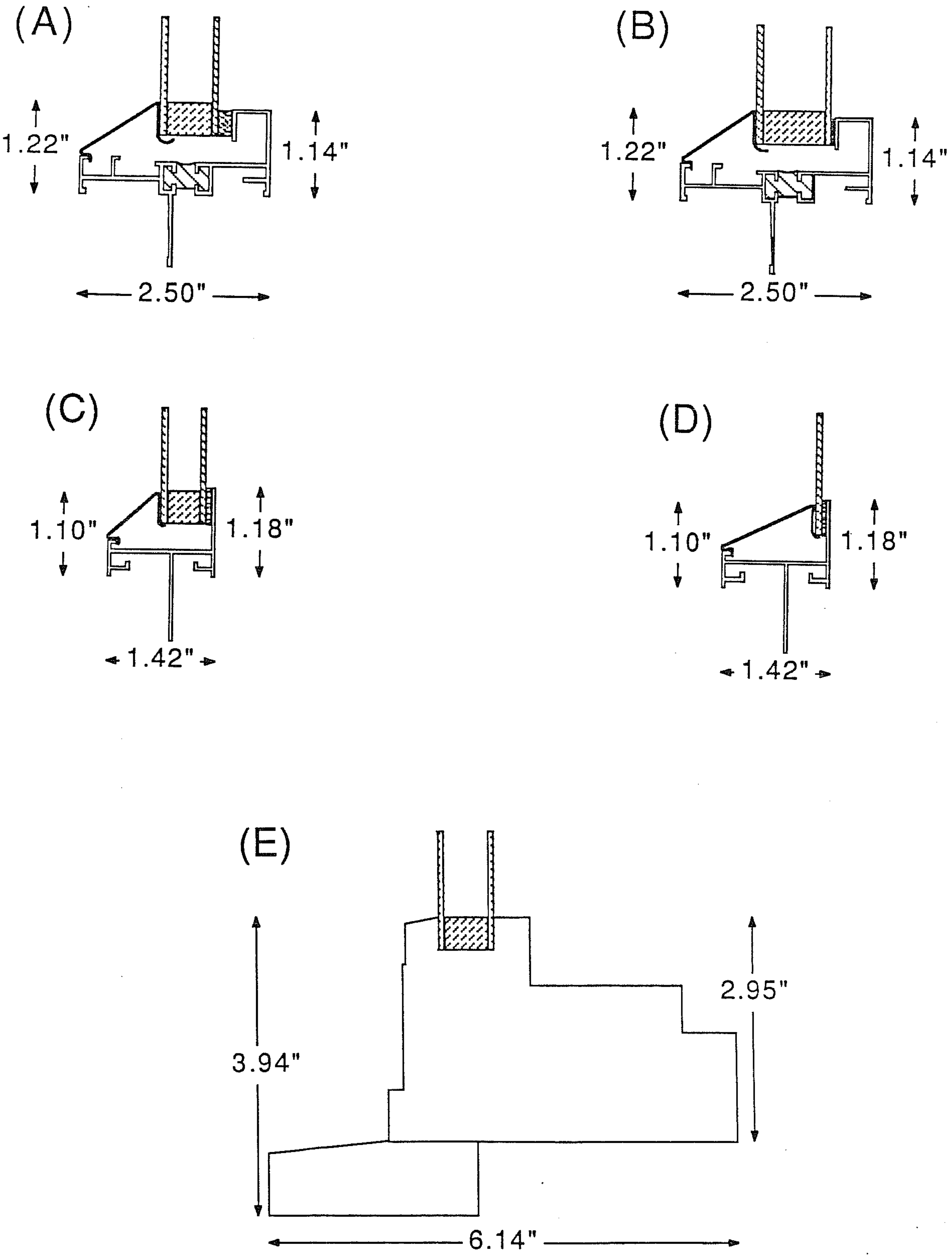

Figure 1. Cross sections of the frames of the commercial windows tested.

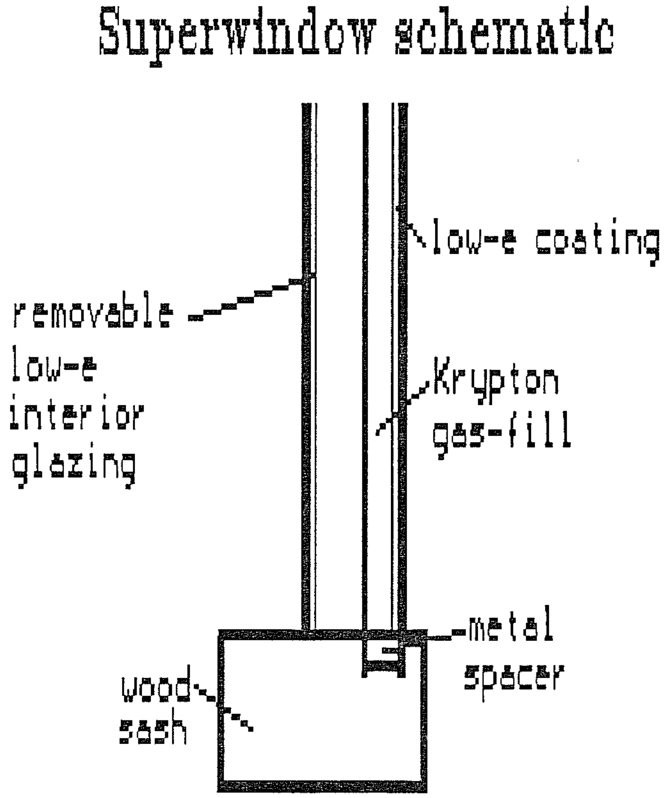

Figure 2. Schematic cross section of the prototype superwindow.

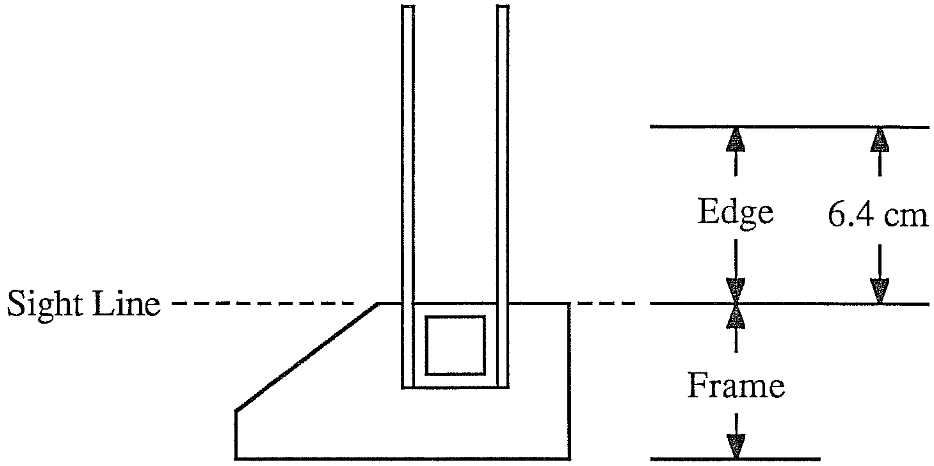

Figure 3. Definition of edge and frame regions in the U-value calculation.