### Title

Measurement of Single and Double Glazing Thermal Performance under Realistic Conditions Using The Mobile Window Thermal Test (MoWITT) Facility




### Authors

Klems, J.
Keller, H.



### Publication Date

1986-11-01

LBL-22149 c.2

# Lawrence Berkeley Laboratory

UNIVERSITY OF CALIFORNIA

## APPLIED SCIENCE DIVISION



Presented at the ASME Solar Energy Division Conference, Honolulu, HI, March 22–27, 1987, and to be submitted to the Journal of Solar Energy Engineering

**MEASUREMENT OF SINGLE AND DOUBLE GLAZING THERMAL PERFORMANCE UNDER REALISTIC CONDITIONS USING THE MOBILE WINDOW THERMAL TEST (MoWiTT) FACILITY**

J. Klems and H. Keller

November 1986



**APPLIED SCIENCE DIVISION**

Prepared for the U.S. Department of Energy under Contract DE-AC03-76SF00098

LBL-22149
Mo-243

To be presented at 1987 ASME Solar Energy Division Conference, March 22-27, 1987, Honolulu, HI, and to be submitted to the *Journal of Solar Energy Engineering*.

# Measurement of Single and Double Glazing Thermal Performance Under Realistic Conditions Using the Mobile Window Thermal Test (MoWiTT) Facility

J. Klems and H. Keller

Applied Science Division
Lawrence Berkeley Laboratory
University of California
Berkeley, CA 94720

November 1986

This work was supported by the Assistant Secretary for Conservation and Renewable Energy, Office of Buildings and Community Systems, Buildings Systems Division of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

# Measurement of Single and Double Glazing Thermal Performance under Realistic Conditions using the Mobile Window Thermal Test (MoWiTT) Facility

*J. H. Klems and H. Keller*

Windows and Lighting Program
Applied Science Division
Lawrence Berkeley Laboratory
University of California
Berkeley, CA 94720

## ABSTRACT

The thermal performance of single glazing, clear double glazing, and double glazing with a low-emissivity coating was measured in both south-facing and north-facing orientations under realistic field conditions using the new MoWiTT field test facility. The time-dependent net heat flow through each fenestration was found to be consistent with the predictions of the standard simplified heat transfer model, provided that an angle-dependent shading coefficient is used and diffuse solar gain is included in the calculation. Summer-condition average U-values were derived for each glazing type and were found to agree with the expected values for both types of double glazing. The measured U-value for single glazing was lower than predicted.

## NOMENCLATURE

| | |
|---|---|
| $A_B$ | Aperture of window for beam solar radiation ($m^2$) |
| $A_S$ | Aperture of window for diffuse solar radiation ($m^2$) |
| $A_T$ | Thermal aperture of window ($m^2$) |
| $F$ | Solar heat gain coefficient for single glazing |
| $F_D$ | Solar heat gain coefficient for single glazing assuming diffuse solar radiation |
| $h_O$ | Outside surface heat transfer coefficient |
| $I_B$ | Vertical-surface intensity of beam solar radiation ($W/m^2 K$) |
| $I_D$ | Vertical-surface intensity of diffuse solar radiation ($W/m^2 K$) |
| $I_V$ | Total intensity of solar radiation on a vertical surface at the plane of the window ($W/m^2 K$) |
| $Q$ | Net heat passing through the window (Watts) |
| $(SC)$ | Shading coefficient |
| $(SC)_B$ | Angle-dependent shading coefficient for beam solar radiation |
| $(SC)_D$ | Shading coefficient for diffuse solar radiation |
| $t$ | Time (sec) |
| $T_I$ | Indoor air temperature (degrees Celsius) |
| $T_O$ | Outdoor air temperature (degrees Celsius) |
| $U$ | Thermal transmittance ($W/m^2 K$) |
| $(UA)_F$ | Thermal transmittance times area of window frame ($W/K$) |
| $\alpha$ | Solar-optical absorptance |
| $\tau$ | Solar-optical transmittance |

## INTRODUCTION

An understanding of the thermal performance of simple, frameless single-glazed or sealed-insulating-glass window systems is a necessary first step toward a unified approach to fenestration thermal performance. These systems most nearly embody the simplified engineering model of a window as one or more parallel infinite sheets of glazing material. While any practical glazing system is likely to be substantially more complex geometrically, thermally, and optically, the simplified model remains the conceptual basis for the discussion of fenestration heat transfer. The performance of complex systems is reduced to two characteristic parameters, U-value and shading coefficient, which are the thermal and (relative) solar-optical transmittance of an equivalent simplified model.

Because the simplified model contains parameters, the interior and exterior surface heat transfer coefficients, which are environment- and configuration-dependent, questions have arisen concerning (i) whether the model as currently used correctly describes fenestration behavior, (ii) what values of the surface coefficients to use, and (iii) what laboratory conditions to impose in order to measure the equivalent U-value and shading coefficient for complex systems, and how to extrapolate these measurements to field conditions. Questions (i) and (ii) chiefly concern the standard methodology defined by ASHRAE[1] in which air and radiant temperatures are assumed equal, allowing convective and radiative effects to be lumped together into a single "film coefficient", and wind-driven forced convection is assumed to dominate the exterior coefficient. The research basis for this methodology[2,3] was motivated by problems quite different from those currently being addressed.

This paper begins to address questions (i) and (ii) through a careful measurement under realistic field conditions of fenestrations which approximate the simplified model as nearly as possible. These measurements will then form a basis for the study of more complex fenestration systems.

At Lawrence Berkeley Laboratory we have constructed and calibrated a Mobile Window Thermal Test (MoWiTT) Facility. Consisting of dual, guarded, room-sized calorimeters in a mobile structure, the MoWiTT is capable of simultaneously exposing two fenestration samples, each seeing a room-like interior environment, to ambient outdoor weather conditions and of measuring the net heat flow through each fenestration with good accuracy. This measurement comes from a net heat balance on each calorimeter chamber, performed at short intervals. Measurements here were taken at 15-minute intervals, with each measurement an average over the previous interval. In order to make possible an accurate net heat balance measurement together with control of the interior air temperature during the full diurnal cycle, each calorimeter chamber contains an electric heater, a liquid-to-air heat exchanger with measured flow rate and inlet/outlet temperatures, and a nearly continuous interior skin of large-area heat flow sensors.

The MoWiTT is shown in Figure 1. Its design, theory, and error analysis have been discussed elsewhere [4-6].

Using the dual calorimeters of the MoWiTT, we have made simultaneous net heat flow measurements on (a) clear single-glazed and clear double-glazed sealed insulating glass (SIG) units, and (b) a clear SIG unit and one incorporating a low-emissivity ("low-e") coating, over a several-day period in both south-facing and north-facing orientations. This allows a weather-independent comparison between each pair of units.

It is important to recognize that the difference in nighttime performance between the two fenestrations is not expected to result in a large signal for the comparison between double and low-e double glazing, even under winter conditions. One expects that there would be a difference of approximately 0.97 $W/m^2K$ between the U-values of the two fenestrations. For temperature differences of 20-40 K this implies (for a residential-sized window) differences in heat flow on the order of 20-40 W. This difference must be distinguished from heat flows resulting from thermal storage in the apparatus, envelope conduction, and infiltration. Since these are potentially of larger magnitude, careful attention must be given both to systematic and to random errors [7].

## EXPERIMENTAL ARRANGEMENT

Two commercially fabricated sealed insulating glass units consisting of two lights of clear 4-mm thick glass, with a low-e coating on the number-three surface of one of the two units, were used in the tests. The single-glazing units consisted of 4-mm glass supplied by the same manufacturer. Two units to be simultaneously tested were mounted in identical test frames in the two calorimeter chambers of the MoWiTT. The units were mounted as shown in Figure 2. The MoWiTT was oriented with the sample-holding wall facing due south, the chambers were held at a temperature of approximately 20°C, and data were collected for approximately eight days per test, beginning on May 5, 1986. The MoWiTT was later turned to face due north and the measurements were repeated. Both prior to and after the tests, runs with single glazing in both calorimeters were made to test for systematic errors between the two calorimeter chambers.

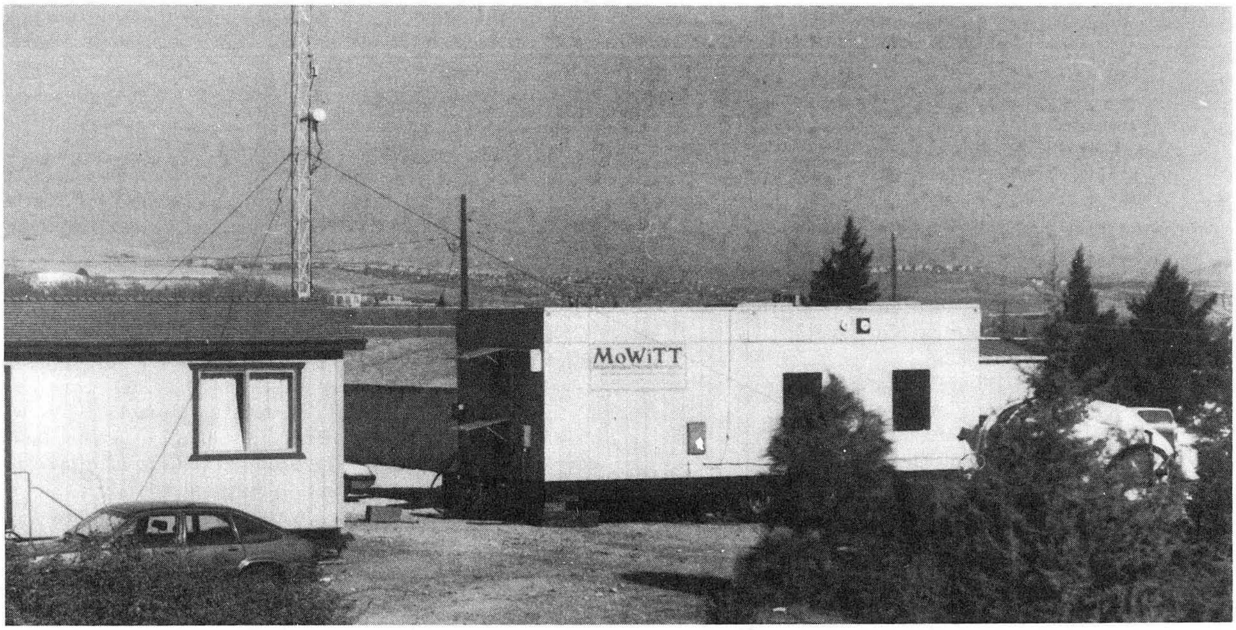


Figure 1. The Mobile Window Thermal Test (MoWiTT) Facility. CBB 860-10756

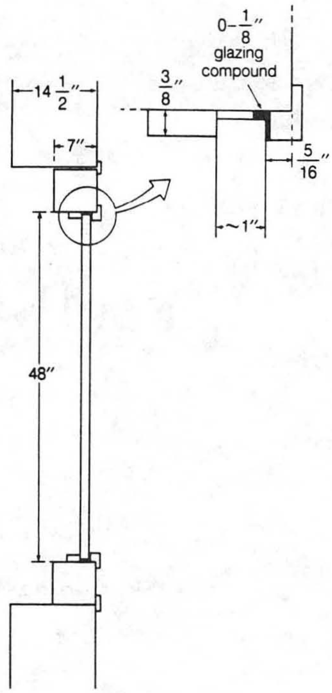


Figure 2. Window mounting section (dimensions approximate).

The tests were made at our field location in Reno, Nevada, in the late spring and early summer. During the early south-facing measurements, however, weather was unusually cold, including an unseasonable snowstorm on the first test day. The data presented here are therefore a mixture of (mild) winter and summer performance. Figure 3 shows the outside air temperature during the north-facing single/double glazing measurements. It was measured with an aspirated RTD sensor located at the top of a 10-m weather tower on the test site and is typical of the magnitudes of temperature swing occuring during all of the tests. Average temperatures were lower during the earlier tests and somewhat higher during the later ones.

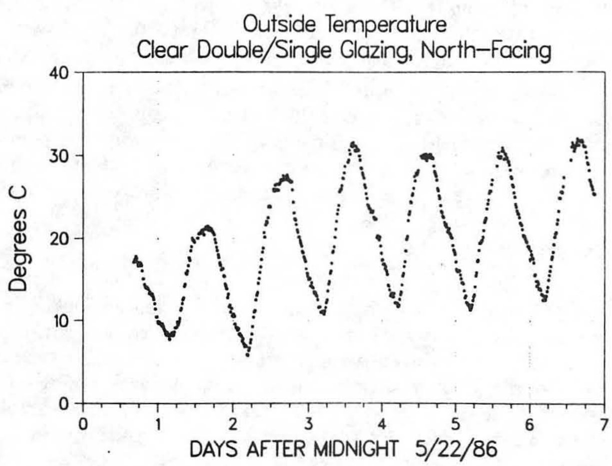


Figure 3.

Wind speed and direction were measured using conventional cup-and-vane sensors mounted on the same weather tower. Data from these sensors are read rapidly and the perpendicular wind components averaged over the 15-minute recording period to produce a short-term average speed and direction. The resulting wind speed during the north-facing single/double measurements is shown in Figure 4. During this season in Reno wind speeds tended to be high during the day and relatively low at night. The average nighttime wind speed was in the range 2-4 MPH during all of the tests.

The terrain around the test site is quite flat. The environs include both open fields and low-rise urban construction. The elevation is 4490 ft (1370 m). There are 7500 ft (2300 m) mountain peaks 15 mi (25 km) to the east and 8200 ft (2500 m) mountains 7.5 mi (12 km) to the west, resulting in shading at solar altitudes of approximately 5 and 12°, respectively. Incident solar flux was measured with three instruments: a horizontal pyranometer, a tracking pyrheliometer, and a vertically mounted pyranometer located on the sample- holding wall. Total incident flux on a vertical surface, measured by the latter instrument, is shown for the north-facing single/double measurements in Figure 5. On days 2-7, which were clear, sharp morning and evening peaks

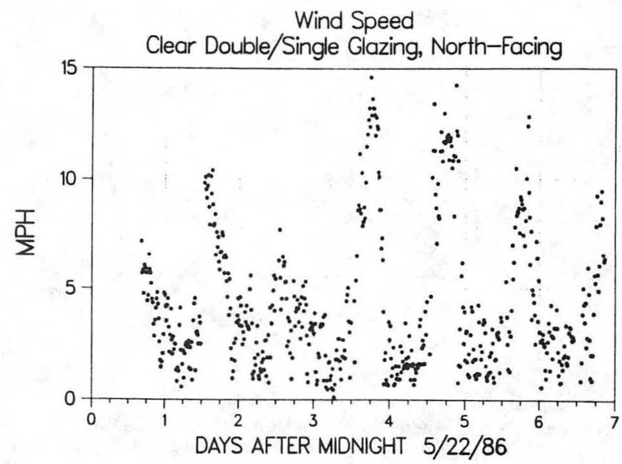


Figure 4.

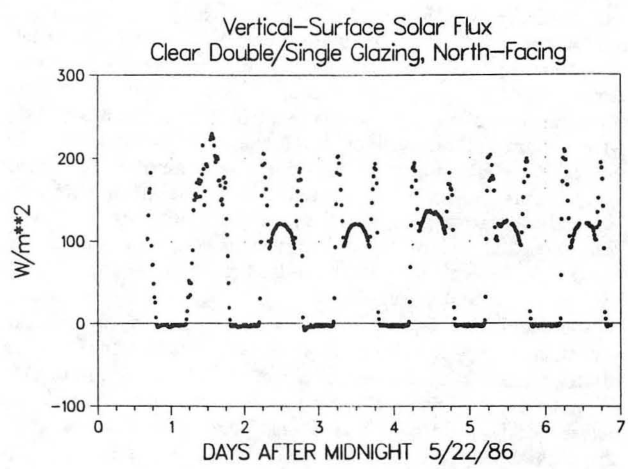


Figure 5.

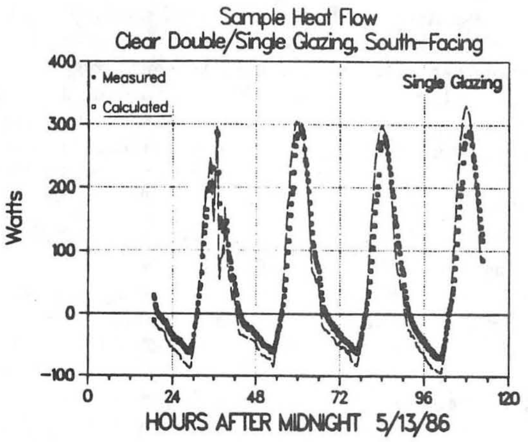


Figure 6.

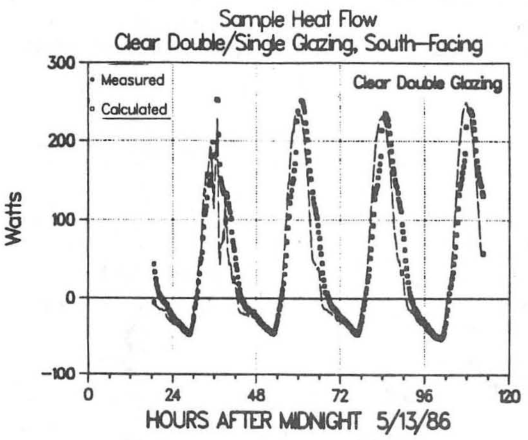


Figure 7.

are apparent where direct sun briefly falls on the sensor; between these peaks the radiation is wholly diffuse. It is interesting to note that the effect of overcast on day 1 is to raise the average solar intensity on the windows.

Prior to moving the MoWiTT to the field, we carried out a series of tests to determine the accuracy of each chamber. In these tests the sample openings were closed and covered with insulation and additional large-area heat flow sensors. The result was to make each chamber a closed box with redundant measurements of the net heat flow into or out of it. By raising and lowering the chamber and guard temperatures and introducing known amounts of heating into the chamber we were able to check the performance of each component of the net heat balance measurement under the range of physical conditions under which it would operate during the actual measurements. The sole exception to this is the large and spatially inhomogeneous radiative fluxes experienced by the heat flow sensors under direct solar illumination. We have so far been unable to simulate this effect to our satisfaction during calibration; accordingly, the measured daytime heat fluxes may have greater error than the nighttime, where the expected error is on the order of a few watts. Since for these measurements daytime heat fluxes are much larger than nighttime, this does not greatly compromise the accuracy of the data.

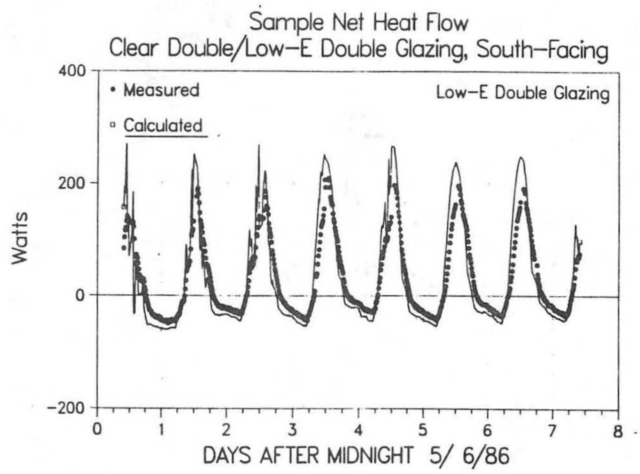


Figure 8.

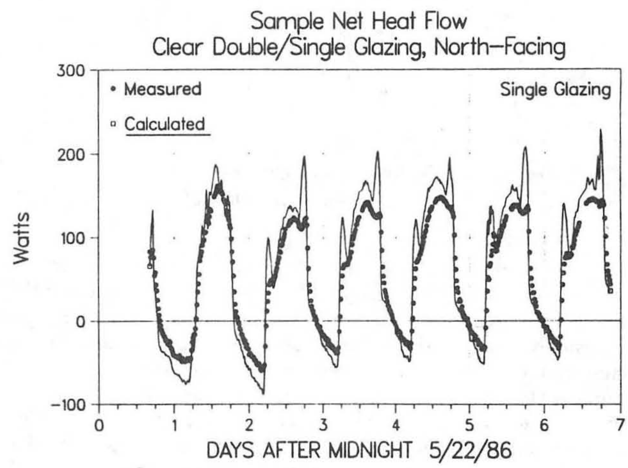


Figure 9.

Tracer-gas measurements were used to establish that the infiltration rates for the two calorimeters were negligible. Since the measurements reported here involve well-sealed, frameless insulating glass units, the important leakage is that of the calorimeter chambers. This leakage would occur between the chambers and the guard. Since the air flows in the guard and the pressure differences between the guard and the calorimeters are much larger than those that would be induced by weather, it was sufficient to measure this leakage prior to the field measurements. Two several-day decay measurements, with approximately one year between measurements, yielded an infiltration air exchange rate of .02 $hr^{-1}$.

## SAMPLE NET HEAT FLOW

Figures 6 through 11 show the measured net (*i.e.*, inward minus outward) heat flowing through the fenestration as a function of time for single glazing, clear double glazing, and double glazing with low-e coating, in south-facing and north-facing orientations. The clear double glazing sample was run simultaneously with both the single glazing and the low-e double glazing sample; for brevity only the data from the runs with single glazing are included. These data are derived from the instantaneous net heat balance of each calorimeter, and constitute the basic measurement produced by the MoWiTT.

To interpret these data, we consider the predicitions of the following simplified model, shown in the figures by the dashed curves:

$$Q(t) = [\, A_T\, U + (UA)_F \,]\,(\, T_O - T_I \,) + A_S\, F\,(SC)\, I_V \, . \qquad (1)$$

In this equation the indoor and outdoor air temperatures, $T_I$ and $T_O$, and the vertical-surface solar intensity $I_V$ are measured quantities. The thermal and solar apertures $A_T$ and $A_S$ are known from the window geometry and are nearly equal. The quantity $(UA)_F$ is a correction for the thermal conductivity of the sample-holding frame, and is calculated to be 0.2 W/K. The quantity $F = \tau + U\,\alpha/h_O$ is the solar heat gain coefficient of single glazing, which under ASHRAE standard conditions is equal to 0.87. The thermal transmittance, U, was taken to be the value under ASHRAE standard summer conditions, as calculated using the program WINDOW 2.0[8,9]. The shading coefficient (SC), defined by equation (1), received more detailed treatment as described below.

Several general features of the plots in Figures 6-11 are apparent. First, all of the calculated curves lead the measured curves by approximately one-half hour in time. This is consistent with observations we have made on the calorimeters during calibration and is believed to be due to the effects of thermal storage in the calorimeters. However, the general shapes of the curves are quite similar and on some partially cloudy days (*e.g.*, day one in figures 6 and 7) sharp spikes in the measured net heat flow, with widths on the order of an hour or less, are visible. This sets an upper limit on the order of an hour on the lag time produced by thermal storage and indicates that the thermal storage effects do not seriously distort the net heat flow. A lag time of approximately one-half hour is consistent with the amount of thermal mass inside the layer of heat flow sensors comprising the boundary of the calorimeter metering volume. We note that a thermal lag time of one-half hour is already small compared to that of any real building space; nevertheless, we plan to investigate this issue further.

Second, the highly transient nature of fenestration heat flows is apparent. During these spring/summer measurements the dominant concern is clearly daytime solar heat gain; however, nighttime heat losses are not negligible, and the diurnally averaged net heat flow is considerably smaller than the average daytime heat gain. This points to the need for an integrated perspective on fenestration thermal performance, to the importance of the thermal mass of the adjacent space, and to the possible opportunities of using diurnal thermal storage to reduce fenestration cooling loads.

## SHADING COEFFICIENT

The simple form of the second term in equation (1) is not really adequate, because at the high solar incidence angles occurring in these runs the shading coefficient is not constant. (We note that the ASHRAE standard conditions correspond to 4 p.m. on August 21 for a west-facing window.) The correct procedure would be to separate the incident solar radiation into beam and diffuse components in equation (1), which is equivalent to replacing the shading coefficient with

$$(SC) = (SC)_B \left[ \frac{A_B}{A_S} \right] \left[ \frac{I_B}{I_V} \right] + (SC)_D \left[ \frac{F_D}{F} \right] \left[ 1 - \frac{I_B}{I_V} \right] , \qquad (2)$$

where the subscripts B and D denote beam and diffuse solar radiation. Unfortunately, during collection of much of this data our pyrheliometer tracking system functioned erratically so that we were unable to measure the ratio $I_B/I_V$. It was therefore necessary to choose an effective shading coefficient and F value. We chose the value at 68° as representative for the south-facing data (for which the solar radiation is primarily beam), and the hemispherical average value for the north-facing data. Glass properties for these two sets of conditions were therefore used as input to WINDOW 2.0, which then calculated the interreflection effects and the thermal effects assuming ASHRAE standard summer conditions. A further complication was that solar-optical data was only available (from the manufacturer) for the low-e glass at normal incidence. We estimated the optical properties at other angles of incidence by scaling the published transmission and absorptance of clear glass[10] by the ratio of those values at normal incidence. This *ad hoc* procedure is clearly flawed,

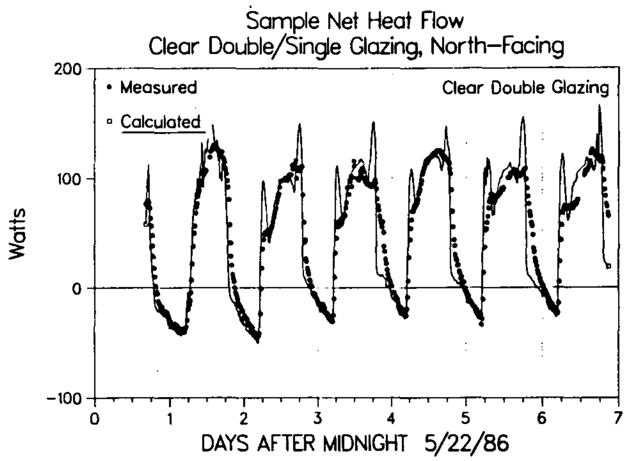


Figure 10.

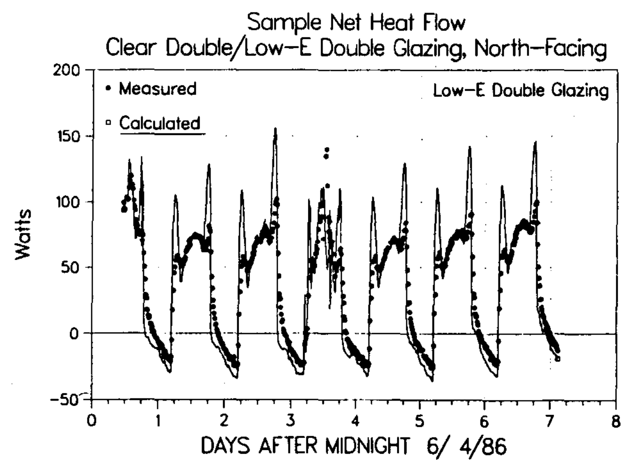


Figure 11.

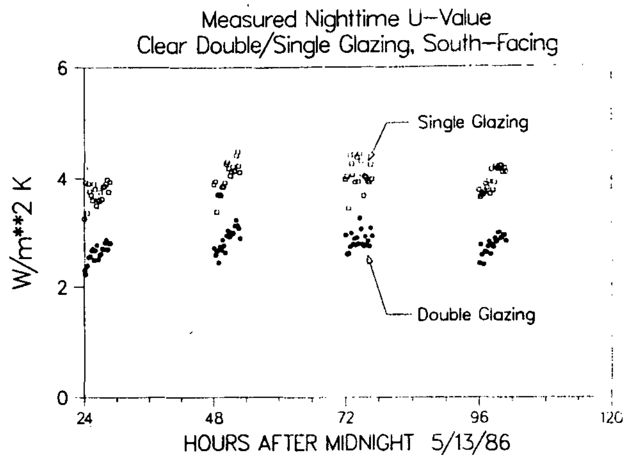


Figure 12.

but proved adequate for our purposes. It resulted in an F value of 0.67 for single glazing with shading coefficients of 0.60 and 0.60 for south-facing double and double/low-e glazing, respectively, and an F value of 0.77 with shading coefficients of 0.72 and 0.60 for north-facing. As can be seen from the figures, these values result in reasonably good fits to the measured curve. The shading coefficient value used for south-facing low-e is probably somewhat high.

## U-VALUES

One feature of the data in figures 6-11 is the poor match between the calculated and measured curves at night, indicating that the U-value for ASHRAE standard summer conditions assumed in the calculation does not well represent the actual heat transfer. The most probable reason for this is that the measured nighttime wind speeds were much lower than those assumed for ASHRAE summer conditions.

Since both the net heat flow and the temperature difference are measured in the MoWiTT, it is possible to construct the instantaneous measured nighttime U-value, as shown in Figure 12. These measurements show considerable scatter, which is due in part to the small temperature differences which sometimes occurred, and in part to thermal storage effects in the calorimeters. Only data taken after midnight was used in order to eliminate the latter effect; however, depending on the magnitude of the solar gain the previous day and the nighttime temperature, this measure did not always succeed.

Table 1. Measured and Expected Nighttime U-values

| Sample | South-Facing | North-Facing | Expected |
|---|---|---|---|
| Single Glazing | 3.93±.27 | 3.56±.48 | 5.11 |
| Clear Double Glazing | 2.76±.19 | 2.30±.75 | 2.69 |
| | 2.83±.18 | 2.94±.33 | |
| Low-e Double Glazing | 1.68±.19 | 1.48±.37 | 1.65 |

The data obtained in this way were averaged for each data run, and are shown in Table 1. The expected errors were computed from the RMS deviations of the individual measurements, and will therefore include the effects of the above biases. Also appearing in the table are the expected U-values, which were computed using WINDOW 2.0 assuming 2 MPH wind speed. As can be seen, all of the calculated values agree reasonably well with the experimental except for single glazing, where the experimental value is about 20% low. We are reluctant to attach too much significance to this at present, because of the low temperature difference at which these measurements were made.

There is another method by which U-values might be derived from the data in Figures 6-11. This is by separating out the nighttime heat flows in these figures and doing a linear regression between the heat flow per unit glazing area and the inside-outside temperature difference. The slope obtained is then the average U-value. We also used this method and found that one obtains (i) systematically higher U-values and (ii) positive intercepts which vary from data run to data run (and sometimes from night to night). Some of these intercepts were clearly inconsistent with our calibration measurements, which restrict residual heat errors to a few watts.

We believe this method gives erroneous U-values for the following reason. In Figure 12 one can see that there is approximately 10% scatter in the (short-time-scale) measured U-values. While this may be due to variations in the film coefficients, on several of the nights there appears to be a systematic trend toward larger U-values later in the night. This may well be the residual of thermal storage effects: if the data before midnight are plotted a clear set of decaying exponentials is observed (usually, but not always, under conditions of small temperature difference, becoming negligible by midnight). Since over the same time period the outside temperature is falling, this upward slope will appear as a correlation between the heat flow and the inside-outside temperature difference if the time information is removed. This would then result in both a non-zero intercept and a higher U-value. For this reason, we considered the method unreliable.

We note also that this effect is by no means confined to calorimeters such as ours which make daytime as well as nighttime measurements. Dropping outside temperatures will cause changing inside surface temperatures in the calorimeter due to radiative coupling to the window. If the calorimeter has any thermal mass at all, similar transient effects will occur even if there has been no solar gain, and these may be significant. Similar biases may be induced by changes in heat transfer coefficients if the changes happen to be correlated with outdoor temperature (*e.g.*, through systematic changes in wind speed between sundown and sunrise).

## CONCLUSIONS

We conclude that a simplified model of window heat transfer adequately reproduces the measurements of sealed insulating glass, provided that one recognizes that (i) the shading coefficient may be angle- independent, (ii) diffuse solar radiation is not always negligible, and (iii) U-values depend upon wind speed and temperature. Measured U-values for single glazing were significantly lower than calculated values for low wind speed.

## ACKNOWLEDGEMENT

This work was supported by the Assistant Secretary for Conservation and Renewable Energy, Office of Buildings and Community Systems, Building Systems Division of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

## REFERENCES

1. ASHRAE, *ASHRAE Fundamentals*, American Society of Heating, Refrigerating and Air Conditioning Engineers, Atlanta, GA, 1985.

2. Parmelee, George V. and Aubele, Warren W., "Overall Coefficients for Flat Glass Determined under Natural Weather Conditions", *ASHRAE Transactions 55*, 1949, p.39.

3. Rowley, F.B., Algren, A.B., and Blackshaw, J.L., "Surface Conductances as Affected by Air Velocity, Temperature, and Character of Surface", *ASHRAE Transactions 36*, 1930, p. 429.

4. Klems, Joseph H.; Selkowitz, Stephen; and Horowitz, Sy., "A Mobile Facility for Measuring Net Energy Performance of Windows and Skylights," An Foras Forbartha, *Energy Conservation in the Built Environment (Proceedings of CIB W67 Third International Symposium),* Vol III, p. 3.1, Dublin, Ireland, 1982.

5. Klems, J. H., "Measurement of Fenestration Performance under Realistic Conditions", *Windows in Building Design and Maintenance,* Gothenburg, Sweden, 1984.

6. Klems, J. H., "Measurement of Fenestration Net Energy Performance: Considerations Leading to Development of the Mobile Window Thermal Test (MoWiTT) Facility", Presented at the American Society of Mechanical Engineers Winter Annual Meeting, New Orleans, LA, December 9-14; Meeting paper no. 84-WA/Sol-7, 1984.

7. Klems, J. H., "Error Analysis of In-situ Field Tests of Fenestration Net Energy Performance", *Energy and Buildings,* Vol 8, no. 3, 1985, pp 165-173.

8. Rubin, M., "Calculating Heat Transfer Through Windows", *International Journal of Energy Research,* Vol 6, No. 4, 1982.

9. Arasteh, D., *Window 2.0 User Reference Guide,* to be published, 1986.

10. Rubin, M. "Optical Constants and Bulk Optical Properties of Soda Lime Silica Glasses for Windows", *Solar Energy Materials 12*, 1985, p. 275.