WINDOW U-VALUES: RESEARCH NEEDS AND PLANS

W.P. Goss, Ph.D., P.E.
ASHRAE Member

M.E. McCabe, Ph.D.
ASHRAE Member

ABSTRACT

Recently, there has been significant interest in developing a standard test procedure for determining the thermal transmittance (U-value) and thermal conductance (C-value) of window and window treatment products. Currently, several test methods are used to measure these quantities, and the proponents of these methods do not agree on a standard procedure for measurement. As a result, it is difficult to compare the U-values and overall thermal performance of different windows and window treatment products. This paper discusses the specific research needed to address the above problem, as well as a detailed two-phase program to perform that research.

INTRODUCTION

There is no universal laboratory or field method for measuring U-value (overall thermal transmittance) for fenestration products such as windows, glass patio-doors and skylights. Manufacturers have usually tested their products by one of the following laboratory techniques; a) the AAMA test method (AAMA 1980), b) the ASTM C236 Guarded Hot Box method (ASTM 1985a), or c) the ASTM C976 Calibrated Hot Box method (ASTM 1985b). The differences and the similarities between each of these test methods have been described by Goss (1985).

Because of numerous testing methods, the window U-values obtained from different test methods and quoted in manufacturers' product literature are not necessarily consistant, making the information provided to the consumer unreliable. McCabe et al (1986) compared U-value test data for the same window unit from two laboratories; one following the AAMA test method which uses a perpendicular wind direction to simulate wind effects and the other following the ASTM C236 test method which uses a parallel wind direction. The results were in general agreement for test conditions with essentially zero wind speed on the environmental (cold) side of the window units, but there was a large difference in the results at the ASHRAE winter design wind speed of 15 mph (6.7 m/s).

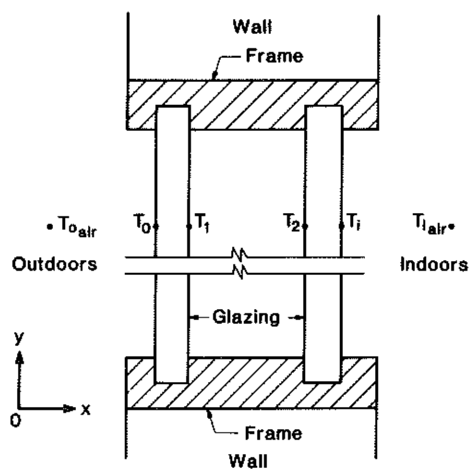
In subsequent testing of the same window unit in a field calorimeter (McCabe et al. (1984), it was observed that measured wind velocities were almost always below 5 mph (3 m/s) and that variable climatic conditions resulted in considerable scatter in the measured night-time U-values, therefore it was concluded that laboratory testing was the preferred method for measuring U-value of window systems. Based on these field and laboratory test results, a test procedure for measuring U-value of fenestration systems was proposed (McCabe 1984). The test procedure requires the laboratory measurement of both the U-value and the surface heat transfer coefficients for a sealed glazing unit over a range of simulated outdoor conditions of wind speed and air temperature. In addition, the test procedure requires measurement of U-value for a window unit consisting of the sealed glazing unit installed in a sash and frame assembly at a single outdoor condition.

William P. Goss is a Professor, Mechanical Engineering Department, University of Massachusetts, Amherst, MA; Michael E. McCabe is a Mechanical Engineer, Center for Building Technology, National Bureau of Standards, Gaithersburg, MD.

ASTM Committees C16 (Thermal Insulation) and E6 (Performance of Building Constructions) formed a joint task group to modify the laboratory test method of measuring window U-values into a consensus-based standard. That task group is currently preparing a standard practice for measuring the thermal performance of windows (ASTM Committee C16.30 1985). The draft describes the use of both ASTM hot box test methods (C236 and C976) for measurement of window thermal performance. In addition to developing this standard practice, the ASTM C16/E6 joint task group has identified a number of research activities that will determine the adequacy of the proposed standard practice. The purpose of this paper is to describe several of the provisions of the proposed test method and to outline a two-phase research program to assist in development of the standard practice.

REVIEW OF HEAT TRANSFER THEORY APPLIED TO GLAZING UNITS

If the effects of air leakage and solar irradiance are not considered, the rate that energy is transferred through the idealized double-glazed window depicted in Figure 1 is proportional to the inside-to-outside air temperature difference. This is a heat transfer process involving the combined effects of radiation, conduction and convection. Consider the winter time condition at night in which heat from the room air $T_{i,air}$ is transferred to the interior window surface at temperature T_i by radiation and convection. This heat is then conducted through the interior glazing layer to the outer surface at temperature T_2 where it is transferred by radiation and natural convection across the air space to the outer glazing surface at T_1. For a triple or quadruple glazed window, this process continues until the exterior glazing surface at temperature T_o is reached where it is radiated and convected to the outdoor air at $T_{o,air}$. It should be noted that in an actual window system, there are usually additional heat conduction paths through the sealed edges of the glazing unit (not shown) and also through the window sash and/or frame members that support the glazing unit. Thus, the radiative/convective/conductive heat transfer process described above applies only to the center portion of the glazing unit and in determining the overall performance of a window unit, additional consideration must be given to heat transfer via the the frame and edges.



Heat transfer theory relates the steady rate of heat flow through a fenestration system by the following, deceptively simple equation:

$$Q = U\, A\, (T_{i,air} - T_{o,air}) \qquad (1)$$

where Q = glazing unit heat transfer rate Btu/h (W),

U = overall thermal transmittance or U-value Btu/hft^{2}F(W/m^2·C),

A = glazing unit heat flow area ft^2 (m^2),

$T_{i,air}$ = indoor average air temperature ^{o}F (^{o}C)

$T_{o,air}$ = outdoor average air temperature ^{o}F (^{o}C).

The expression for overall thermal transmittance can be separated into the surface heat transfer coefficients and the glazing unit surface-to-surface thermal conductance by the following equation:

$$U = \frac{1}{\frac{1}{h_C} + \frac{1}{C} + \frac{1}{h_H}} \qquad (2)$$

<u>where</u> h_C = cold side surface heat transfer coefficient (combined radiation and convection) Btu/hft^{2}F (W/m^2·C),

C = glazing unit thermal conductance Btu/hft^{2}F (W/m^2·C),

h_H = hot side surface heat transfer coefficient (combined radiation and convection) Btu/hft^{2}F (W/m^2·C).

For most glazing systems, the temperature difference across any individual glazing layer is quite small, therefore the thermal conductance can be defined by the following expression:

$$Q = C\,A\,(T_i - T_O) \qquad (3)$$

<u>where</u> T_i = glazing unit average indoor surface temperature ^oF (^oC),

T_O = glazing unit average outdoor surface temperature ^oF (^oC).

To adequately measure the glazing unit U-value, accurate measurements must be made of the heat transfer rate, the glazing surface area and air-to-air temperature difference. Since the glazing unit is usually mounted in a wall that separates the hot and cold chamber in most hot boxes, the heat transfer rate through this wall (called a mask wall) must be known since it is subtracted from the total measured heat transfer rate to obtain the glazing unit heat transfer rate:

$$Q = Q_T - Q_{MW} \qquad (4)$$

<u>where</u> Q_T = total heat transfer rate through glazing unit and mask wall Btu/h (W),

Q_{MW} = mask wall heat transfer rate Btu/h (W).

Ideally, the mask wall heat transfer rate should be small fraction (<10%) of the glazing unit heat transfer rate and its thermal conductance should be well characterized. This usually requires that the mask wall be constructed of a relatively thick, homogeneous insulating material to minimize the mask wall heat transfer rate, and that its thermal conductivity be measured over a range of temperatures in an accurate instrument such as a Guarded Hot Plate (ASTM C177). The mask wall conductance and its surface-to-surface average temperature difference enable approximate calculation of the mask wall heat transfer rate from a one-dimensional conductive heat transfer analysis, or if more accuracy is desired, from a multi-dimensional conductive heat transfer analysis.

The mask wall heat transfer rate should also be experimentally measured by performing a calibration test so the multi-dimensional heat conduction paths that normally exist at the glazing unit/mask wall interface are determined. The method of calibration of the mask wall can be done in several ways. One method is to place different thickness insulation boards having known thermal conductivity in the window opening in the mask wall. This allows the window flanking heat transfer rate (the three-dimensional heat transfer effects in the window mounting opening area) to be measured. A second method is to use heat flux transducer that has the same general dimensions as the window test specimen. The heat flux transducer is calibrated independently and is then used to calibrate the mask wall. It can also be used to determine the surface heat transfer coefficients for different environmental wind speeds and directions. It is anticipated however, that surface heat transfer coefficients determined for the heat flux transducer and similarly dimensioned insulating glass units (IGUS) may not necessarily represent surface coefficients for other size IGUS or for actual window units.

Temperature measurement is another important factor necessary in accurately measuring window U-value. Typical temperature sensors used in hot boxes are thermocouples which are often constructed from relatively large diameter wire (24-gauge). However, for measuring the surface temperature of window glazings, smaller diameter wire (30 or even 36-gauge) is often used in European laboratories to minimize the effect that the wire might have on the surface convection heat transfer coefficients. As an alternative, NRC/Canada researchers have recommended that the average temperatures of the glazing surfaces be calculated by performing an energy balance on the enclosures on both sides of the test window. This requires that the surface temperatures and emittances of all test chamber surfaces capable of radiant exchange with the test window be accurately measured.

As a final point on temperature measurement, thermocouples are reasonably accurate when used to measure temperature differences. For situations where the absolute temperature rather that temperature difference is desired, thermocouples are less accurate. This can be improved by accurately calibrating the thermocouple/data acquisition system or by substituting more accurate RTD temperature sensors.

RESEARCH PROGRAM FOR DEVELOPING WINDOW TESTING STANDARDS

The first phase of a two-phase program specifically designed to address the above cited research needs for developing window testing standards is currently underway at the thermal measurements laboratory at the University of Massachusetts at Amherst using the calibrated hot box (hereafter called the Research Calibrated Hot Box - RCHB). This phase focuses on measuring the U-values of IGUS for a range of environmental conditions. The following sections present some primary features of Phase 1 research.

Phase 1 Research

Test Facility Modifications. The RCHB will be modified so that both parallel and perpendicular wind directions can be simulated. By using variable speed fans, wind speeds varying between low velocities typical of natural convection up to the ASHRAE winter design conditions of 15 mph (6.7 m/s) will be simulated. With a single test facility providing both parallel and perpendicular wind directions, a direct comparison can be made of the effect of wind direction on the window U-value.

The mask wall used for supporting the test window and for separating the hot and cold chambers is constructed of 6 in (152 mm) extruded polystyrene and covered with 1/4 in (6 mm) plywood faces. The mask wall has a centered opening where the IGUS will be mounted flush with the environmental side surface.

Heat Flux Transducer. The 40 x 40 in (1016 x 1016 mm) heat flux transducer (HFT) used for the Phase 1 research program will be similar in design to the HFT used by NRC/Canada. It consists of a 1/2 in (13 mm) layer of expanded polystyrene and two sheets of glass. Type T thermocouple wire in a thermopile configuration is installed between the glass sheets and the polystyrene. The thermal conductivity of the polystyrene is accurately measured using the ASTM C177 Guarded Hot Plate method. This value, along with the measured temperature difference, is used to determine the heat flux through the HFT. A second heat flux transducer will also be designed and fabricated. This HFT will be more sophisticated in design than the first and will be capable of obtaining heat flux distributions.

Temperature Measurements. Small diameter (30-gauge) calibrated thermocouples will be used to measure the IGU surface temperatures and the air temperature near the IGU surfaces. In addition, the RCHB baffle wall temperatures will be measured so that the IGU surface temperatures can be determined by calculation. Results of this research will provide a technical data base for thermal performance standards for windows, including both calculation and measurement procedures for determination of U-value for a variety of applications. In addition, the IGU will be well characterized and should be quite valuable in the subsequent Phase 2 research program.

Test Specimens. During the Phase 1 program, testing will be performed on the following 40 x 40 in (1016 x 1016 mm) insulated glazing units (IGUS).

1. Standard double glazed unit:

   1/4 in (6 mm) glass - 1/2 in (13 mm) airspace - 1/4 in (6 mm) uncoated glass.

2. Low emittance double glazed unit:

   1/4 in (6 mm) glass - 1/2 in (13 mm) air space - 1/4 in (6 mm) glass with low emittance coating on inner surface.

3. Triple glazed spectrally selective unit:

1/4 in (6 mm) glass - 1/2 in (13 mm) airspace - spectrally selective, low emittance plastic film - 1/2 in (13 mm) airspace - 1/4 in (6 mm) glass.

Test Conditions. The following matrix of test condition was selected to obtain data relating the sensitivity of IGU test specimens to the environmental conditions:

1. Temperature outside/inside F (^{o}C)

winter:	18/68	(-8/20)
summer:	95/75	(35/24)
fall/spring:	38/68	(3/20)

2. Wind speeds mph (m/s)

free convection	0	(0)
summer design	7.5	(3.4)
winter design	15.	(6.8)

3. Wind direction

parallel
perpendicular

4. Position of outside of test specimen (relative to environment side of mask wall)

flush
recessed

Phase 2 Research

Specific details for the Phase 2 research program will depend on the outcome of the Phase 1 research program. A broad-based testing and analysis program is envisioned for Phase 2, including continuation of the RCHB testing initiated in Phase 1 and extension of the testing program to include both commercial hot box testing in laboratories and field testing in outdoor facilities.

Research Laboratory Testing and Analysis. The insulating glazing units tested in the RCHB facility in Phase 1 will be further tested in order to enlarge the technical data base from which the thermal performance standards will be developed. In Phase 2, several of the standard 40 x 40 in (1016 x 1016 mm) IGUS will be fabricated into windows by adding sash and frame members composed of wood, aluminum, and PVC plastic. These windows will be tested in the RCHB according to the draft standard practice (ASTM Committee C16.30 1985). Heat transfer models will also be prepared for each window, and analytical predictions will be made for thermal performance. The model predictions and the test results for the IGUS and IGUS with sashes will be compared, and empirical frame adjustment factors established for the different frame materials. This research will assist in development of standard calculation procedures for estimating frame and sash adjustment factors from IGU test results.

The effect of both test specimen size and of slope angle (deviation from vertical) on the U-value will also be determined. Several IGUS differing in size but having the same generic configuration as those tested in Phase 1 will be tested. The IGUs will have nominal dimensions of 24 x 24 in (610 x 610 mm) and 48 x 80 in (1219 x 2032 mm), corresponding to a small window and a large patio door respectively. This testing, which includes window specimens with and without edge framing, will establish 1) sizing effects of the IGU, and 2) sizing effects of the IGUS plus frame on the U-value. In addition, several 40 x 40 in (1016 x 1016 mm) standard glazing units from Phase 1 will be tested at various orientation angles between vertical and horizontal, with heat flow in both the up and down directions. Determination of size and slope adjustment factors are essential in establishing whether or not testing is required for each unique window size and whether or not nonvertical glazing systems, such as those used in artria and sunspace applications, require special testing.

In addition to measurement of window U-Value in an RCHB facility, a certain level of wind tunnel testing appears to be appropriate in order to determine exterior surface convective heat transfer coefficients. Scale model testing will be performed in a wind tunnel for several window/building configurations to determine the distribution of surface heat transfer coefficients with wind speed and wind direction for windows that are either flush mounted or are set back from adjacent building walls. Flow visualization techniques and methods for measuring convective heat transfer coefficients are available for small scale wind tunnel experiments; however, they need modification for full-scale window geometry and typical wind speeds used in hot box testing.

Commercial Laboratory Hot Box Testing. A coordinated research effort, aimed at obtaining operating experience for the new window testing standards in commercial laboratories, is desired for measuring the consistancy between differing test facilities. Previous research (McCabe 1986) indicates that for different laboratory test methods there are substantial discrepancies in U-value measurement for windows. These discrepancies are attributed to different methods of simulating wind and are possibly due to air leakage. To avoid ambiguities in window testing, steps must be taken by the window-testing laboratories to reduce possible air leakage and to verify that the residual levels of leakage are within a tolerable range. In addition, a standard method for calibration of the mask wall and a technique for measurement of surface heat transfer coefficients must be developed. These are considered key elements in the draft standard practice for testing windows and doors. A number of commercial testing laboratories will participate in a round-robin evaluation of the new testing standard for windows, using the IGU specimens from Phase 1. At least two testing laboratories for each type of hot box testing facility will participate, including facilities designed according to the ASTM C236, ASTM C976, and the AAMA test methods.

Field Testing. Several field testing facilities have been constructed, each having different capabilities to measure the thermal performance of full-sized fenestration systems. Performance is measured under carefully controlled indoor conditions with prevailing outdoor conditions of air temperature, wind velocity and solar radiation. The performance data produced by this method of testing are more realistic than those produced by simulating outdoor environments in laboratory facilities. However, outdoor testing inherently results in limited productivity, since relatively long test periods are often required for each test specimen to obtain sufficient test data and time when testing is possible is limited by local climatic conditions. Extrapolation of the test results to other times of year, weather patterns or to other climatic regions is also required.

The IGU test specimens from Phase 1 will be installed in the participating outdoor testing laboratories and tested during both winter-time and summer-time testing seasons. The field test results will be compared with the laboratory test results and the simulation models. Due to complexities in characterizing the exterior thermal boundary conditions in field testing, it is apparent that additional air temperature, air flow and radiant heat flux measurements will be required, which may require new sensors and measuring techniques.

CONCLUSION AND RECOMMENDATIONS

The research plans described in this paper should provide many answers to some of the research needed to provide a basis for window U-value measurements. Once there is a standard method for accurately measuring the thermal performance of window and door systems with no air leakage and solar effects, then several possible uses of the data provided are possible. One use is for comparing the performance of different window and door products for consumer use. A second use is to have well characterized window and door systems for validation of analytical models of fenestration systems. These may be single window models or the window portion of large building energy analysis computer programs.

Once this research is completed and a standard practice is approved, the results should be combined with those studies concerning air leakage and solar transmission. This might be carried out analytically, or it may result in an overall window thermal performance test method and rating system similar to what has been developed for solar collector systems.

REFERENCES

AAMA 1503.1 1980. "Voluntary test method for thermal transmittance of windows, doors and glazed wall sections". American Architectural Manufacturers Association.

ASTM C236 1985a. "Steady-state thermal performance of building assemblies by means of a guarded hot box". Annual Book of ASTM Standards, Vol. 0406.

ASTM C976 1985b. "Thermal performance of building assemblies by means of a calibrated hot box". Annual Book of ASTM Standards, Vol. 0406.

ASTM Committee C16.30 1985. "Standard practice for determining the thermal performance of window and door systems". Working Draft 3, December.

Goss, W. P. 1985. "Test methods used for measurements of window U-values". BTECC Workshop on Laboratory Measurements of the "U-Values" of Windows, Gaithersburg, MD.

McCabe, M., Ducas, W., Cholvibul, R., and Wormser, P. 1986. "U-value measurements for windows and movable insulations from hot box tests in two commercial laboratories". ASHRAE Transactions, Vol. 92, Part 1.

McCabe, M. E., Hancock, C. E., and Van Migum, M. 1984. "Thermal performance testing of passive solar components in the NBS calorimeter". NBSIR 84-2920.