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Interim Procedure to Measure the Thermal Performance of Window Systems

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National Bureau of Standards
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U.S. DEPARTMENT OF COMMERCE, Malcolm Baldrige, *Secretary*
NATIONAL BUREAU OF STANDARDS, Ernest Ambler, *Director*

FORWARD

In 1984, the National Bureau of Standards (NBS) began work on preparing an interim test procedure for the Bonneville Power Administration (BPA) for measuring the thermal performance of a class of products known as movable insulations. Those products are used primarily to reduce winter time heat loss through windows. At that time, BPA planned to use the test procedure for developing specifications and certifying compliance with the BPA Residential Weatherization Program which included credits for movable insulation systems for windows. Due to the limited funding available for preparing a draft test method, no testing was to be performed, however the test procedure was to be based on a technical evaluation of test methods described in the literature, visits to testing laboratories and consultation with researchers, testing lab operators and members of standards committees working in similar areas. A letter report describing the rationale upon which the interim test procedure was to be prepared along with an outline for a future program which could increase the scope into a more general procedure that addresses improved accuracy and extended environmental conditions. Dr. Mark McKinstry was named as the BPA Contracting Officer's Technical Representative.

In July 1984, Dr. McKinstry advised NBS that the movable insulation products would not be included in the BPA weatherization program as originally planned, and that a more pressing need was for a recommended thermal test procedure for glazing which could be used in the Model Conservation Standard proposed for adoption by the Northwest Power Planning Council. The proposed standard described maximum allowable U-values for windows, which were to be determined by testing according to either the ASTM C236, ASTM C976 or AAMA 1503.1 Standards. In response to this need, NBS prepared and submitted a revised work statement to BPA.

The revised work statement included the preparation of a report containing the previously proposed technical reviews along with a Draft Standard Test Method describing facilities used for determining window U-values and a Draft Standard Practice describing the calibration procedures, the specific test conditions, the specimen mounting provisions and calculation procedures. Because of the discrepancies between the data obtained using the different test methods and the controversy existing in the testing industry, NBS proposed that the two draft documents be reviewed and ballotted by members of a joint C-16/E-06 task group within ASTM, before making the recommendations to BPA. Progress within the ASTM task group was not as rapid as originally anticipated due to the slowness in obtaining technical data, and the deliberate pace of a consensus standards organization in considering the controversy between the ASTM and AAMA test methods, therefore resulting in the delayed release of this report to BPA.

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1. INTRODUCTION

Transmission heat losses through fenestration system such as window and glass doors represent one of the major energy demands for the heating of residential and smaller size commercial buildings [Kusuda and Collins, 1978]. Prior to the "energy crisis" of the 1970's, the availability of low cost energy led to the widespread use of single glazed windows in most parts of the United States, with double glazed windows being used mainly to increase thermal comfort in the colder regions. Recent research has shown the considerable positive benefits that windows can have on building performance considering passive solar heating and daylighting benefits, provided the thermal transmission heat losses are within reasonable limits.

A range of new window designs and products have appeared on the market or are in advanced stages of development which address the problem of reducing the thermal transmittance (or U-value) of windows [Selkowitz, 1979]. Multiple-glazed windows with sealed double or triple insulating glazing units or single glazed windows with storm sash are available for both new and retrofit buildings. Window assemblies are constructed from a variety of sash and frame materials, including wood, plastic, aluminum and various composites. Recent advances in materials sciences have led to significant improvements in thermal performance of sealed glazing units by introduction of "heat mirror" plastic films [Lampert, 1981] and low-emittance coatings [Grange and Owens, 1984], with the promise of additional improvements through the commercialization of electrochromic coatings, gas fills, evacuated glazings and silica-gel windows [Arasteh et al., 1985]. As a retrofit option for existing buildings, a class of products known as movable insulations, including a wide variety of shutters, shades and curtains [Gibson, 1980; Shurcliff, 1980; Langdon, 1980] are currently available. These products are frequently installed in tandem with existing single glazed windows and usually require manual operation by the building occupant to effect improved thermal performance.

In principle, the thermal performance of a fenestration can be predicted using heat transfer theory and correlations of experimental data involving convective and radiative heat flow, when the air space dimensions and radiative properties of the window are known and the adjacent air space's temperature and flow field are specified [Rubin, 1985; Siegel and Howell, 1981]. The ASHRAE Handbook published by the American Society of Heating, Refrigerating and Air Conditioning Engineers [ASHRAE 1985, p. 27.10] provides thermal transmittance data for a number of widely used fenestrations based on a specific set of design conditions and recommends their use for determining peak energy loads in sizing heating and cooling equipment. However, because the specific design conditions are more severe than those to which the fenestration are exposed to on a continual basis, ASHRAE does not recommend the design data to be used for analysis of annual energy usage.

Sash and frame members present considerable complications in predicting thermal performance of windows due to their multi-dimensional heat transfer characteristics and the uncertainties in thermal contact resistance at the moving joints. The ASHRAE Handbook provides a set of adjustment factors to account for frame and sash effects. These factors vary over a wide range of values, do not account for differences in glass to frame area ratio, and are not available for composite frame materials; therefore the handbook data are not particularly useful for comparing alternative products. The ASHRAE Handbook recommends the use of manufacturer's test results to determine the thermal performance for each specific product.

The purpose of this report is to review the current sources of information on U-values and to describe the state of thermal test methods used for windows in order to provide the Bonneville Power Administration with some general guidelines in the application of thermal test data for use in the Model Conservation Standards (MCS) by the Northwest Power Planning Council. At present, considerable controversy exists in the window industry regarding the thermal testing of windows, therefore no consensus-based standards are available.

After the topics of window heat transfer theory and sources of U-value data for windows are reviewed, the currently available methods for measuring thermal performance of windows and movable insulations will be described and new standards, currently under development, will be presented. Background information on thermal test methods for windows that was obtained by visits to different commercial testing laboratories and research laboratories will also be described along with planned activities related to development of window test standards.

2. U-VALUE DATA FOR WINDOW SYSTEMS

The rate of heat transfer through an idealized, double-glazed window shown in Figure 1 is proportional to the inside-to-outside air temperature difference. The heat transfer process involves the combined effects of conduction, convection and radiation heat transfer. Heat transfer theory relates the steady rate of heat flow per unit area of window, to the air temperature difference, thereby defining the U-value, or thermal transmittance as:

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

where A = heat flow area of glazing, m^2 (ft^2),
Q = steady rate of heat transfer from heated space to cold space, W (Btu/h),
$T_{i,air}$ = temperature of warm space air, C (F),
$T_{o,air}$ = temperature of cold space air, C (F).

The U-value can be computed from a knowledge of the individual factors involved or it can be determined from test data when Q, A, $T_{i,air}$ and $T_{o,air}$ are measured.

It should be noted that in an actual window system, there are usually parallel heat flow paths through the central glazing unit, the edge spacers (not shown), and through the window sash and frame members that support the glazing unit. Thus, the heat transfer process to be described 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 frame and edges.

2.1 HEAT TRANSFER THEORY

Theoretical and experimental work on dynamic heat conduction in opaque building components such as walls and roofs have been used to compute cooling loads for air-conditioned buildings [Stephenson and Mitalas, 1967; Kusuda, 1969]. Less attention has been devoted to surface heat transfer in building components, especially fenestration, which have intrinsically greater sensitivity to surface heat transfer due to their greater thermal conductance and negligible thermal mass. Moreover, studies have shown the difficulty of establishing relationships between surface heat transfer coefficients and the environmental factors on which they depend [Ito et al., 1972].

2.1.1 Surface Heat Transfer

Consider a situation where a double glazed window separates a heated space from the colder outdoors. Air may flow past the outdoor surface at considerable velocity due to the influence of wind; and indoor air may circulate by bouyant forces in which air that is cooled by contact with the cooler glass surface descends and heated air rises. The former is called forced convection and the latter is called free, or natural convection and is dependent on the surface geometry, orientation and the difference in temperature between the surface and the air. In both types of convection, the transfer of heat occurs in a thin layer of air known as a boundary layer, which contacts the surface and has little motion. The thickness of the boundary layer, which is not readily determined, has a profound effect on the flow of heat by convection.

A second heat transfer mechanism is by radiation heat exchange between the surface and its surroundings, which takes place simultaneously with, and independant of, convection heat transfer. Often, the total effect is measured experimentally, and no attempt is made to separate one mode of heat transfer from the other.

In performing heat transfer calculations, surface heat transfer is usually treated approximately, by combining the convective and radiative components into a single, constant surface heat transfer coefficient. Sometimes two values are used; one for winter and one for summer design calculations [ASHRAE 1985, p. 27.10]. Consider the steady rate of heat transfer, Q, which occurs between the room air[1] and the window surface shown in Figure 1. This is normally written as:

$$Q = h_i A(T_{i,air} - T_1) \qquad (2)$$

where T_1 = window indoor surface temperature, ^oC (F)
h_i = combined surface heat transfer coefficient, $W/m^2 \cdot K$ ($Btu/h \cdot ft^2 \cdot F$).

The combined surface coefficient consists of two independent components given by:

$$h_i = h_{ri} + h_{ci} \qquad (3)$$

where h_{ri} = radiative heat transfer coefficient, $W/m^2 \cdot K$ ($Btu/h \cdot ft^2 \cdot F$),
h_{ci} = convective heat transfer coefficient, $W/m^2 \cdot K$ ($Btu/h \cdot ft^2 \cdot F$).

Although Eq. 2 is simple, it does not accurately represent physical reality. Radiative heat transfer, in fact, depends on the difference between the fourth power of the absolute temperature of the radiating surfaces, and is therefore, not nearly proportional to $T_{i,air}-T_1$ and often, the radiating surfaces are at a temperature different than the air temperature. Moreover, the convective coefficient, h_{ci}, is a function of temperature, surface roughness, local air velocity, the direction of heat flow and other factors, and is therefore, not constant.

In considering the transmission of heat through fenestration, different surface coefficients are required for the interior and exterior surfaces. For most building applications, the inside surface convective component falls into the heat transfer regime of free convection. For many years,

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1 - Assuming the room surfaces are at the same temperature as room air.

ASHRAE used a combined inside surface coefficient of 8.3 $w/m^2 \cdot K$ (1.46 $Btu/h \cdot ft^2 \cdot F$) for design purposes. This value has also been widely used in the European community, however the German speaking countries use the slightly lower value of 8.0 $w/m^2 \cdot K$ (1.41 $Btu/h \cdot ft^2 \cdot F$) [Jonsson, 1985].

The average inside surface free convection heat transfer coefficient, h_{ci} is however, a weak function of the temperature difference between the inside surface and the inside air provided air motion is not induced mechanically by fans. This relationship is given by:

$$h_{ci} = C_i \, (T_{i,air} - T_1)^m \tag{4}$$

where C_i = a constant depending on the inside air thermophysical properties,
m = 1/3 or 1/4, depending upon whether the flow is laminar or turbulent.

To some extent h_{ci} varies with window size due to boundary layer thickness variations in the vertical direction. Shorter windows would tend to have larger average convection coefficients than taller windows.

Different methods of calculating the natural convection heat transfer coefficient, h_{ci}, are documented by ASHRAE. For isolated vertical plates, a convection coefficient of 3.24 $w/m^2 \cdot K$ (0.57 $Btu/h \cdot ft^2 \cdot F$) is obtained by subtracting the radiative component from the total surface heat transfer coefficient [ASHRAE 1985, p. 23.3] based on a surface temperature of 21 C (70 F) and a surface to air temperature difference of 5.6 C (10 F). In the same reference, equations are given for temperature-dependent, free-convection laminar and turbulent flow [ASHRAE 1985, p. 3.13]. In yet another chapter of the same reference, combined radiative and convective coefficients for the interior surface of windows are given for laminar free-convection with different values of surface emittance, surface temperature, and surface to air temperature difference [ASHRAE 1985, p. 27.14]. Convective coefficients obtained by these three methods can easily differ by a factor of two. Recent research indicates that the convective correlations obtained for isolated vertical surfaces may not be representative of walls or windows in room enclosures, because of the frictional effects of the other room surfaces [Bauman et al., 1983]. That research developed new correlations which compared favorably with the ASHRAE turbulent heat transfer correlations, although the experimental observations indicated a laminar flow regime.

The radiative component of surface heat transfer for the interior of a glazing surface depends primarily on the relative amounts of glazed and unglazed surfaces seen by the particular surface and on the temperature difference between them. For normal situations in which a window views only the non-glazed surfaces of a heated room that are at approximately room air temperature, the radiation coefficient is of the same order of magnitude as the convection coefficient. If, however, the window views mainly other windows such as in an atrium or sunspace, the radiative component of heat transfer is essentially zero, because the temperature of all the window surfaces are approximately the same. Similarly, the radiant component will be substantially greater than the convective component whenever the window receives radiant energy from surfaces that are much warmer than the room air. This can occur when a window views a radiant heater, an operating fireplace, or a solar storage wall.

The combined heat transfer coefficient for the outside surface, h_o is a function of the air temperature, the effective radiating temperature of the outdoor surfaces and the wind speed. The wind speed and orientation of the building surface relative to the wind direction are important factors in determination of the outside heat transfer coefficient. Wind speed can vary from less than 0.25 m/s (50 ft/min) for calm weather, free convection conditions, to over 11.2 m/s (25 mph) for stormy weather conditions. ASHRAE has used two values; a winter design value of 34.1 $W/m^2 \cdot K$ (6.0 $Btu/h \cdot ft^2 \cdot F$) corresponding to a wind speed of 6.7 m/s (15 mph), and a summer design value of 22.7 $w/m^2 \cdot K$ (4.0 $Btu/hr \cdot ft^2 \cdot F$) corresponding to a wind speed of 3.3 m/s (7.5 mph). In contrast, the European community uses design outside surface coefficient varying from 18 $w/m^2 \cdot K$ (3.17 $Btu/h \cdot ft^2 \cdot F$) in the United Kingdom [CIBS, 1980] to 23 $w/m^2 \cdot K$ (4.1 $Btu/h \cdot ft^2 \cdot F$) in the German speaking nations [Jonsson, 1985].

The simplified representation of surface heat transfer described above, however, is often adequate in many applications, such as heating or cooling load calculations, where the <u>design</u> values represent extreme heat loss conditions and when low-thermal-conductance components (e.g., insulated walls) are considered. In that case, the conductive thermal resistance of the wall itself is large compared with the surface resistances, and even large variations of surface resistance have little affect on the overall heat transfer. However, a more detailed analysis of surface heat transfer is required to improve accuracy when long-term or seasonal energy calculations are performed. In that case, it is incorrect to assume values for the heat transfer coefficients corresponding to extreme weather conditions (e.g., winter design values). This is particularly important when window heat losses are analyzed.

2.1.2 Air Space Conductance

The rate of heat transfer between the inside and outside surfaces of a glazing system in Figure 1 is proportional to the glazing conductance, or C-value, given by:

$$C = \frac{Q}{A(T_1 - T_2)} \qquad (5)$$

where T_1 = average temperature of the window interior surface C (F),
T_2 = average temperature of the window exterior surface C (F), and
C = thermal conductance, $w/m^2 \cdot K$ ($Btu/hr \cdot ft^2 \cdot F$).

The air space thermal conductance, or C-value is an intrinsic property of the fenestration system, while the transmittance or U-value is a function of the C-value and the combined inside and outside surface coefficients that depend on the environmental conditions. The relationship between these two characteristics is given by:

$$U = \frac{1}{\frac{1}{h_o} + \frac{1}{C} + \frac{1}{h_i}} \tag{6}$$

The C-value is useful for comparing insulating properties of alternative glazing systems having prescribed temperatures of the bounding surfaces, while the U-value is useful for computing heat flow when the adjoining space temperatures and air motion is known.

The geometry of many insulating glass units in windows is such that the spacing between the lites of glass is small compared to the height and width of the air space, therefore edge effects can often be ignored and a one-dimensional heat transfer model used to evaluate thermal performance. Often the thickness of the glazing material is small enough to ignore any temperature gradients. With those assumptions, the C-value of an insulating glazing unit depends only on the radiative properties of the glazing surfaces, the glazing geometry and orientation, and the transport properties of the gas in the space.

The rate of radiative transfer between the glass surfaces in Figure 1 is given by

$$Q_{rad} = \frac{A\sigma(T_1^4 - T_2^4)}{1/\varepsilon_1 + 1/\varepsilon_2 - 1} \tag{7}$$

<u>where</u> σ = Stefan-Boltzmann constant = 5.6697 x 10^{-8} $w/m^2 \cdot K^4$ (1.73 x 10^{-8} $Btu/h \cdot ft^2 \cdot R^4$),

$\varepsilon_{1,2}$ = total hemispherical emittance of the indoor and outdoor glass surfaces adjoining the air space, respectively.

Equation 7 is strictly valid for spaces containing a nonabsorbing gas (such as dry air) that does not participate in the radiation exchange by absorbing or emitting radiation, and for surfaces (such as uncoated plate glass) that are both opaque to radiation in the infrared region and whose emittance does not vary appreciably with wavelength. The development of new high-performance windows having non-air gas fills, partially transparent plastic films and/or low emittance coatings might violate any of those assumptions, therefore evaluation of radiative transfer in those products requires additional consideration.

The convective rate of heat transfer across the air space in Figure 1 is given by

$$Q_{conv} = Ah_c(T_1 - T_2) \tag{8}$$

<u>where</u> h_c = convective coefficient of heat transfer between two isothermal parallel surfaces separated by an air space, $W/m^2 \cdot K$ ($Btu/h \cdot ft^2 \cdot F$).

Measurements of air space convective heat transfer were made by NBS [Robinson and Powell, 1954] that have been widely accepted by ASHRAE [1985, p. 23.4] for computing convective heat flow across air spaces. Empirical heat transfer coefficients for air have been generalized for fluids by others [Caton, 1974; Raithby et al., 1977] using dimensionless correlations involving the Nusselt, Raleigh and Prandtl numbers given by:

$$Nu = hL/k \tag{9}$$

$$Ra = g\beta\Delta TL^3/\nu\alpha \tag{10}$$

$$Pr = \nu/\alpha \tag{11}$$

<u>where</u> L = air space width,
k = fluid thermal conductivity,
g = gravitational constant,
β = volumetric expansion coefficient,
ΔT = temperature difference between glazings,
ν = kinematic viscosity,
α = thermal diffusivity.

Recent research [El Sherbiney et al., 1982; Jonsson, 1985] has shown that the convective heat transfer coefficient in a vertical air space is also sensitive to the height-to-width ratio of the air space, which implies that the air space convective conductance measured for a particular window height and space width might not be valid for windows having height-to-width ratios that are significantly different from that measured.

It is convenient to combine the radiative and convective components of heat transfer across an air space into a single value of conductance for use in equation (5). Tabulated values of conductance for vertical air spaces are given by ASHRAE [1985, p. 23.4] as a function of the effective emittance of the confining surfaces and the spacing, the mean temperature, and the temperature difference of the air space.

In applications involving more than a single air space, such as triple or quadruple-glazed windows, or double-glazed windows with interior plastic films, the glazing layer conductive resistance is usually ignored and the individual air space conductances are combined into an overall conductance in a manner similar to combining series resistances in an electrical circuit. This method is adequate for most windows, however care must be exercised whenever any surface in a glazing unit is partially transparent in the infrared spectral region, such as with certain plastic films. In that case the non-contiguous glazing surfaces are radiatively coupled via the transparent intermediate layer, and the radiative and convective components cannot be combined in the simple manner discussed.

2.1.3 <u>Solar Radiation and/or Air Leakage</u>

The heat transfer process in a window system is modified whenever short-wave radiant solar energy strikes the glazing system and/or whenever air leakage occurs which might be due to pressure or temperature difference. In both the solar and air leakage processes, the surface temperature of the various glazing elements may be affected by the process and in turn these modified surface temperatures influence the free convective and the longwave radiative heat transfer coefficients.

Air leakage usually occurs only at the moving joints of operable windows and at the opening in the building wall where the window frame is placed, therefore the heat transfer effect due to air leakage is assumed to be independent of the heat transfer effects due to solar irradiation and window heat transmission. In this report, air leakage considerations on window heat transfer will not be discussed further, although there are potentially significant effects that air leakage has on measured U-values.

To deal with solar irradiated windows, ASHRAE [1985, Chapter 27] uses a simple procedure for predicting the instantaneous rate of net heat transfer through building window systems. That procedure, while originally intended for determining summer design-day heat gains to permit sizing of cooling systems, is also used to characterize fenestration systems used in heating applications. The transfer of heat through a solar irradiated window into a building space can be considered to consist of the following three processes:

1. Direct transmission of radiant solar energy,
2. Convective and radiative transfer of radiant solar energy absorbed by the glazing,
3. Convective and radiative transfer of heat due to outdoor-to-indoor temperature difference.

In the ASHRAE procedure, the two solar-driven processes are combined into a single term, and the net rate of heat transfer into the conditioned space per unit area of glazing is given by:

$$q_{NET} = F\ I_T + U_{day}(T_{o,air} - T_{i,air}) \tag{9}$$

where F = solar heat gain coefficient, dimensionless

I_T = total solar irradiance, w/m^2 ($Btu/h \cdot ft^2$),

U_{day} = overall daytime coefficient of heat transfer, $w/m^2 \cdot K$ ($Btu/hr \cdot ft^2 \cdot F$).

It is common practice to reference the solar heat gain coefficient F, for a particular glazing or shading product to a reference glazing consisting of a single sheet of double-strength clear glass. The ratio F/F_{REF} is called Shading Coefficient. Manufacturers of glazing products characterize their products by providing Shading Coefficient data at a selected value of solar irradiance, ambient temperature, and an external heat transfer coefficient corresponding to the ASHRAE summer design condition.

Daytime U-values are in general, different from nighttime U-values due to the affect that solar absorption has on increasing the surface temperature of each glazing layer. The increased temperature of each glazing layer in turn affects the radiative and convective heat transfer coefficient and air space conductances, depending on the total number of glazing layers, the solar absorption coefficient for each layer and the solar radiation intensity. Figure 2 depicts the variation in U-value for single and triple glazings as a function of solar irradiance, for a range of free and forced convection surface coefficients. The U-values are normalized to the winter design conditions and the results display considerable variation between free and forced convection, and winter and summer conditions. The triple-glazed window also shows considerable sensitivity to solar irradiance.

2.2 HISTORICAL REVIEW

As previously mentioned, the determination of the thermal transmittance of windows was necessitated by the desire for heating and ventilating engineers to be able to predict the heating loads for buildings so that they could have a basis for sizing heating systems. ASHRAE and its predecessor, the American Society for Heating and Ventilating Engineers (ASHVE), has been the primary data source for window U-values through their research projects carried out by the ASHVE Research Center in the 1930's and 1940's, by sponsoring research in several universities, and by publication of results in the ASHRAE/ASHVE Transactions, Journals and Handbooks.

The earliest known research on window U-values is attributed to E. Péclet, a French experimenter who measured thermal conductivity for a wide range of materials, including glass, in about 1860. Péclet was apparently among the first to recognize the importance of the surface heat transfer coefficients in relation to the overall transmittance of a given system as given by Equation 6, and he computed U-values for single and double glazed windows based on analytical relationships for the surface coefficients. Péclet's U-values varied with window height and also with the radiative heat flux on the inside surface, depending on whether the window viewed unexposed interior surfaces assumed to be at the average air temperature, or the window viewed exposed window surfaces assumed to be at the same temperature as the window. In that case, no radiative component exists on the inside surface and the resulting U-values are approximately 40 percent lower than with unexposed walls. Reviews of Péclet's data appear in very early ASHVE Transactions [Carpenter, 1907] and tend to confirm his experimental values for thermal conductivity and his calculated U-values for walls and windows.

ASHVE research projects in the early 1930's focused on measuring combined convective and radiative heat transfer coefficients with respect to the effects of wind on the outdoor surface. ASHVE sponsored research at the University of Minnesota by Rowley and coworkers [1930a, 1930b and 1932] measured surface heat transfer coefficients for air flow over a small heated plate located in a confined duct space with flow parallel to the plate, and in an air stream at the discharge of a duct with flow impinging at an angle to the plate, varying between parallel and perpendicular. Laboratory experiments conducted at the ASHVE Laboratory in Pittsburg by Houghton and McDermott [1931] with a small heated plate confirmed the parallel-flow surface coefficients of Rowley. However in field experiments using large, unheated surfaces exposed to parallel winds [Blackshaw and Houghton, 1932], a comparison of velocity gradients between the large unheated panels and the smaller heated panels suggested that the surface heat transfer coefficients observed for the small panels in a confined duct may be somewhat greater than that occurring with larger surfaces in free stream conditions that are representative of windows installed in buildings. Rowley's original data for parallel flow surface heat transfer coefficients appear in Chapter 23 of the current ASHRAE Handbook of Fundamentals as the basis of design heat transfer coefficients for a variety of building materials, including windows.

In the 1940's, Parmelee and coworkers at the ASHVE Laboratory in Cleveland published several papers on surface heat transfer coefficients of relevance for windows. In one paper, experimental studies of turbulent, forced-convection heat transfer for parallel flow were conducted in a well-characterized wind tunnel [Parmelee and Huebscher, 1947a], and generalized relationships were developed using non-dimensional heat transfer and flow parameters. These results and the previously mentioned ASHVE research results were compared and recommendations were made to use the new data, which was about 20 percent lower than the previous results. Field studies of surface heat transfer were also conducted for glazing surfaces in which the significance of the radiative component for both the indoor and outdoor surfaces was mentioned [Parmelee and Aubele, 1949, 1952]. It was concluded that significant variation in the overall heat transfer coefficient for windows would be expected in actual field installations due to the variability of the radiative effects.

Houghten and coworkers [1941] attempted to compare U-values for 50 windows of various descriptions, including size, number of glazings, air spacing and frame types, which were reported between 1916 and 1932 for a variety of test apparatus and conditions of air temperature and velocity. They concluded that the data were inadequate and inconclusive for practical usage and recommended development of a rigid set of test specifications based on the guarded hot box method. Elements to be addressed included test specimen description preparation and placement, heating and cooling equipment description, and specification for measurement of temperature, air velocity and heat flow.

Subsequently, the ASHVE laboratory published an exhaustive compilation of all window heat transfer data to date, comparing both published and unpublished data from a variety of sources extending back 40 years [Parmelee, 1947b]. This work, which is known as ASHVE Research Bulletin Number 1, extended prior ASHVE work by comparing window U-values and surface heat transfer coefficients, examining alternative hot box test methods and commenting on the potential sources of error in hot box tests. They concluded that it was extremely important to characterize the convective and radiative environments to which a test window in a hot box is exposed, if reasonable comparison between measurement and heat transfer theory is to be obtained. Although many papers on window U-values have subsequently appeared in the ASHRAE Transactions, the data and conclusions in ASHVE Research Bulletin Number 1 appear to be still valid, although perhaps forgotten by many contemporary researchers.

2.3 ASHRAE HANDBOOK U-VALUE DATA

U-values for single, double and triple-glazed windows and skylights were published in the ASHVE Guide since the early 1920's, apparently based on 6.7 m/s (15 mph) outdoor conditions and still indoor conditions. Carr and coworkers [1938], commented that no distinction was made in the 1937 Guide regarding window size, method of installation, description of muntins, and glass spacing for multiple-glazed windows, and no means were given to distinguish between different outdoor velocities and temperatures.

Subsequently, Parmelee and Aubele [1950], described the basis of a revised table of U-values which appeared in various editions of the ASHVE Guide and the ASHRAE Handbook between 1950 and 1963. The U-value table consisted of four sections; Section A for flat vertical glass with one to three glazings and variable spacings, Section B for horizontal glazing (skylights with heat flow up), Section C for hollow glass block, and Section D providing multiplication factors that modify that data in parts A and B to account for the effects of sash and frame heat conduction. A range of adjustment factors were given depending on the percent glass, sash material (wood or metal) and number of glass layers (single, double, or single with storm sash). According to Parmelee and Aubele [1950], these factors were derived from the data reported in ASHVE Research Bulletin Number 1 [Parmelee, 1947b] by comparing U-values for unframed glazing panels with U-values for windows based on comparisons between tests performed in the same hot box under identical conditions. The U-value data in parts A and B were calculated at winter design conditions of 6.7 m/s (15 mph), and -18 C (0 F) outdoor temperature, and a separate table was provided to enable conversion of the U-value data between 6.7 m/s (15 mph) conditions and other wind speeds between 0 and 13.3 m/s (30 mph). The origins of that table are unclear, however it appears to be based on calculations involving surface heat transfer coefficients measured under variable outdoor conditions and described by Parmelee and Huebscher [1947a].

The current window system U-values are given in Table 13, Chapter 27 of the 1985 ASHRAE Handbook of Fundamentals [ASHRAE, 1985], which is revised every four years. These design values are used extensively by architects and engineers designing building heating, ventilating, and air-conditioning systems and is the basis for the window thermal analysis in many building energy analysis computer programs. In 1965, the U-value table was changed to its present format containing three parts; part A for vertical panels, part B for horizontal panels, and part C for frame adjustment factors. The table was also expanded to include U-values at summer design conditions. In 1977, U-values for window systems with interior shades appeared in part A for both winter and summer conditions, despite the warning given in the 1972 Handbook not to consider the presence of shades when computing design heating loads. In the 1981 Handbook, part A was further expanded to include glazing U-values with various combinations of storm sash including either acrylic or glass sheets added to the inside, and glass sheets added to the outside. U-values are provided for all combinations of storm sash for both winter and summer conditions, with and without interior shades. At the same time, the part C adjustment factors were expanded to include storm and sash added to multiple-glazed windows, however the factors previously given for different glass fractions were combined into a single range of factors without distinction for size. In the 1985 Handbook, air space conductance data was provided to show the effects of various gas-fill compositions for different glass spacings, and a figure showing the variation in U-value with outdoor temperature was provided to show the effect of various glass spacings, wind speeds, low emittance coatings and glazing layers for winter and summer design conditions.

2.4 CONCERNS OVER CURRENT U-VALUE DATA BASE

In recent years, questions have been raised regarding both the accuracy and the adequacy of the U-value data appearing in the ASHRAE Handbook. This may be partially due to the deletion of much of the rich anecdotal, bibliographical and technical information on the sources of the U-value data provided in earlier versions of the Handbook. Unexplained revisions to the winter design U-values for double and triple glass from the 1955 values appeared in the 1965 and again in the 1977 editions. In addition, the table of U-values has grown significantly in recent years with the addition of summer design conditions, interior shades and interior and exterior storm sash combinations. Meanwhile, newer types of windows are not included; including glazing units with low-emittance coatings and plastic films, and framing materials comprised of composites of wood, metal and plastic. The effects of window size are also not included in the U-value table. Another concern is that ASHRAE Handbook data have been used in various ways by window and window system manufacturers to arrive at U-values used in advertising claims, instead of using test data.

The net result of this situation is that the advertised U-values for windows and window systems are not generally comparable since they do not have a standardized method, either experimental or analytical, for being determined. This is especially true for window treatments where a wide variety of shutters, shades, and curtains, are applied to various types of windows and the resulting range of the advertised U-values can differ by more than 100 percent for the same product. This tends to confuse consumers who are interested in conserving energy in their buildings and would like to have some reliable standardized information on which to base their window system purchase decisions.

There are two general ways that the consumer is provided window system energy conservation information. The first is the manufacturers advertised U-value which is provided for a single set of environmental conditions that are sometimes not specified. The second is the information provided by building energy analysis computer programs which calculate the thermal performance of window systems installed in various types of buildings (residential, commercial, etc.) and then determine the overall heating and cooling season energy and cost savings. Both of these consumer information sources require accurate (and comparable) window system U-value information to be useful. The first requires a single U-value at a standard environmental condition while the second requires a range of U-values for the environmental conditions to which the window system might be exposed.

All of this indicates that there is an urgent need to have a standard procedure for determining the U-value of windows and window systems. The next section reviews the current test methods used in the United States, Canada and in Europe for measuring the U-values of windows. Section 4 will present information on test methods used for measuring thermal performance of movable insulation systems used in conjunction with windows.

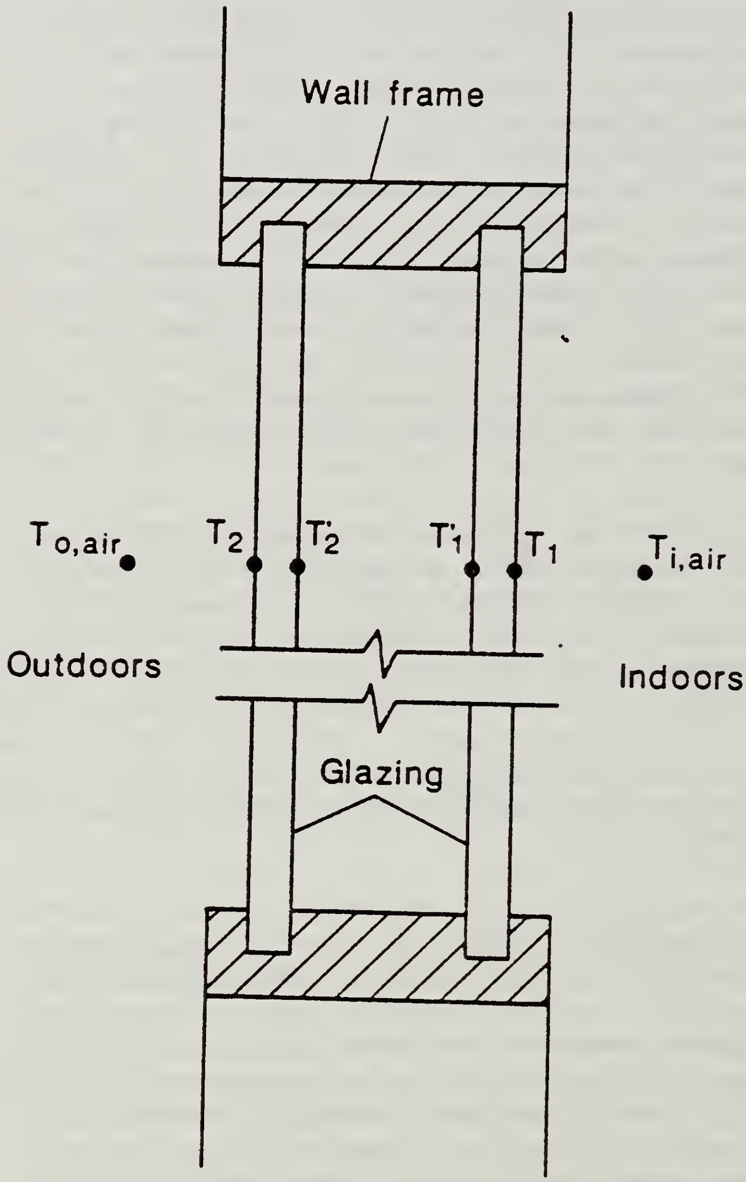
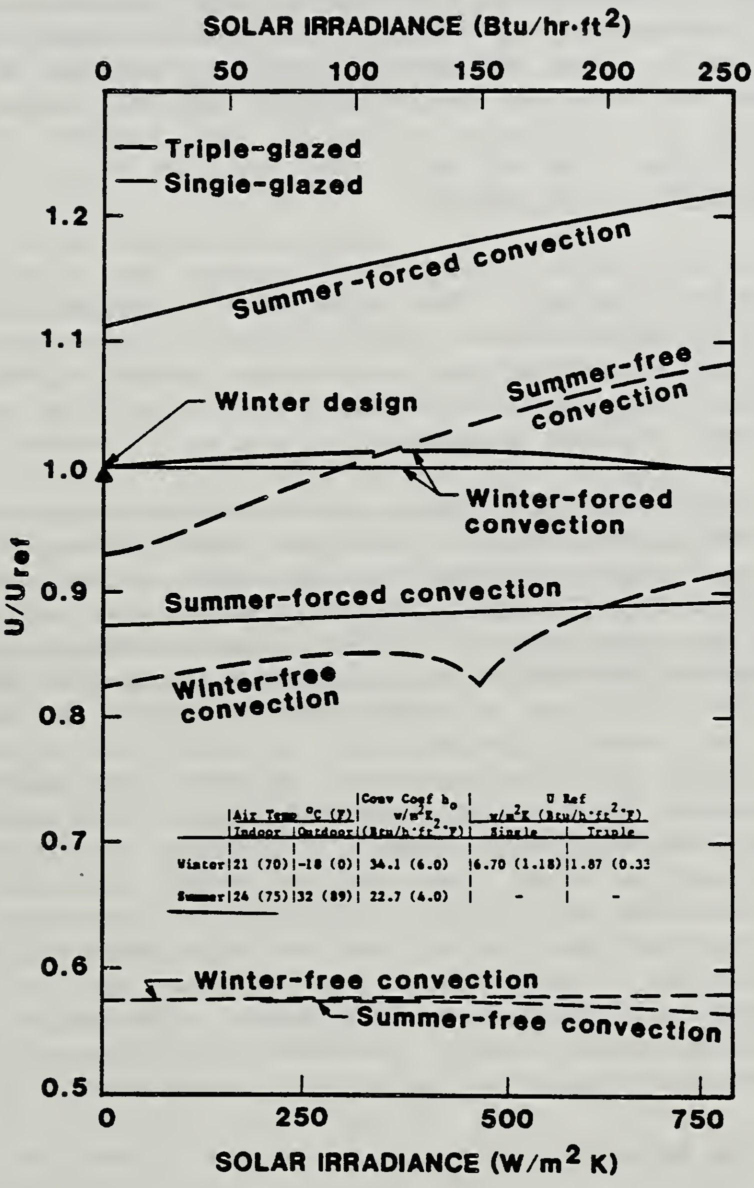


Figure 1. Idealized Drawing of a Double-Glazed Window



	Air Temp °C (F) Indoor	Air Temp °C (F) Outdoor	Conv Coef h_o w/m^2K $(Btu/h \cdot ft^2 \cdot F)$	U Ref w/m^2K $(Btu/h \cdot ft^2 \cdot F)$ Single	U Ref w/m^2K $(Btu/h \cdot ft^2 \cdot F)$ Triple
Winter	21 (70)	-18 (0)	34.1 (6.0)	6.70 (1.18)	1.87 (0.33
Summer	24 (75)	32 (89)	22.7 (4.0)	-	-

Figure 2. U-Values for Solar Irradiated Glazings

3. TEST METHODS FOR MEASURING FENESTRATION U-VALUE

The purpose of this section is to provide an overview of existing standard and non-standard laboratory and field test methods and to discuss their use in measuring U-values for windows. Section 3.1 describes in some detail the hot box test methods most frequently used in the United States for measuring window and skylight U-values under laboratory conditions. Section 3.2 briefly describes the laboratory hot box test methods used in several other nations. Section 3.3 describes site visits to a number of testing laboratories conducted as part of this program and Section 3.4 briefly outlines discussions of U-value test methods at two recent national conferences.

3.1 UNITED STATES PRACTICES (HOT BOXES)

There is no single United States standard test method for measuring window U-value that has been accepted. The majority of the manufacturers of windows and window treatment products use hot boxes to test windows. The reasons why this situation exists are outside the scope of this report, however, a discussion of the laboratory test methods currently used, in the order of their existence, will be presented.

Numerous technical papers and reports deal with experimental measurements of U-value of glazings and various types of windows. As previously mentioned, descriptions of the early apparatus and test procedures are summarized in ASHVE Research Bulletin No. 1 [Parmelee, 1947b]. With a few exceptions, the testing apparatus has been some form of hot box, which still forms the basis for the current laboratory practice. In essence, a hot box is an enclosure made in whole or in part with the material to be tested. One side of the test specimen is heated, usually by exposure to warm air in the adjacent enclosure, and the other side is cooled by exposure to conditioned air either at room temperature or to a refrigerated space. The air on either side of the test specimen may be allowed to circulate by natural thermal action or by forced action using fans. The U-value is computed using Equation 1 from the measured heat source dissipation rate minus any heat flow through surfaces other than that of the test specimen, divided by the product of the projected area of the test specimen in the heat flow direction and the air-to-air temperature difference. The major difference in classification of hot boxes today is based on whether the metering chamber is of the calibrated design or the guarded design.

3.1.1 ASTM C236 Guarded Hot Box

The ANSI/ASTM C236 Standard Test Method for Thermal Conductance and Transmittance of Built-up Sections by Means of the Guarded Hot Box [1985a], which was first approved as an ASTM consensus standard in 1949, has been edited, revised, and reapproved several times. The current edition was issued in 1966 and was reapproved in 1980. It is presently undergoing study for revision by ASTM Committee C16.30.

The ASTM C236 test apparatus shown in Figure 3 consists of a cold box, which simulates winter environmental conditions, a metering box, which simulates the inside conditions of a building, and a guard box, which surrounds the metering box on five sides and is controlled to maintain the same temperature as the metering box. The electrical energy input to the resistance heaters in the metering box is assumed to be equal to the rate of heat transfer through the test specimen that is placed between the cold box and the guard/metering boxes. In using this method for window testing, the window is normally installed in a mask wall constructed from a material of known thermal conductivity. Low thermal conductivity homogeneous walls are preferable, however nonhomogeneous mask walls constructed of wood studs and filled with an insulation product are also used. The metering box covers the window and a portion of the adjoining mask wall, and the net heat transfer rate through the window is calculated by subtracting the heat transfer rate through the mask wall from the total metering box power input.

3.1.2 ASTM C976 Calibrated Hot Box

The ASTM C976 Standard Test Method for Thermal Performance of Building Assemblies by Means of a Calibrated Hot Box [1985b] was approved as an ASTM standard in 1982. There have been calibrated hot boxes in operation since the early part of this century, however it took approximately six years for the present standard to be drafted, revised, and approved. Because it is of more recent vintage, the calibrated hot box standard reflects more of the current developments in hot box operation, instrumentation, and equipment that gradually evolved based on years of hot box operational experience. An updated C236 test method would probably contain a lot of these newer developments, and some individuals have been suggesting that the ASTM C236 and C976 test methods be combined in a manner similar to that being currently described in an International Standard Organization (ISO) Guarded and Calibrated Hot Box Test Procedure.

The primary difference between the calibrated hot box and the guarded hot box is the absence of a guard box in the calibrated hot box method. Figure 4 shows a schematic drawing of a calibrated hot box. The absence of the guard box requires that the metering chamber heat transfer rate be accurately known by calibration, which requires determination of the flanking heat transfer rate that occurs through the test specimen frame at the juncture of the metering and cold boxes. The method to accurately perform this calibration procedure is still undergoing development. The advantage of the calibrated hot box is that it can measure the U-value of larger test specimens for a given cold box size since there is no guard box to reduce the specimen heat transfer area. Several calibrated hot box facilities have been constructed or are undergoing modification so that dynamic measurements can also be made for thermally massive building elements such as masonry walls. In these facilities, both the cold sides and hot sides are capable of undergoing variations in temperature, barometric pressure and relative humidity so that the nonsteady effects of heat transfer, air leakage, and moisture transfer can be studied simultaneously. If solar simulation were to be added to the environmental side, then the overall dynamic thermal performance of windows and window systems can be determined in the laboratory. This capability is not yet available, however the activities in dynamic testing should be followed and evaluated from an overall thermal performance viewpoint for window systems.

3.1.3 AAMA 1503.6 Guarded Hot Box

The AAMA 1503.6 Voluntary Standards and Tests of Thermal Performance of Residential Insulating Window and Sliding Glass Doors [1980] was developed by the American Architectural Manufacturers Association as a method to test aluminum framed windows, doors, and curtain walls for overall thermal transmittance (U-value) and also to test multi-paned window systems for resistance to water vapor condensation. Although the AAMA method is essentially a calibrated hot box test method, the original version of this standard was developed from the ASTM guarded hot box method, however more recent versions of the AAMA standard deleted most of the references to ASTM C236. This standard test method differs from the ASTM C236 and C976 hot box test methods in several ways including wind simulation, temperature measurement and calibration. Figure 5 shows a schematic drawing of an AAMA hot box of the calibrated configuration. At least one AAMA hot box has been constructed that is of the guarded type.

As shown in Figure 5, the primary difference between the AAMA and ASTM methods is the direction and magnitude of the simulated outside wind velocity, which is directed normal to the window surface at a speed of 6.7 m/s (15 mph) in the AAMA method. The fans used in the AAMA hot boxes have much larger dimensions and flow capacities than those used in the ASTM hot boxes to achieve as uniform coverage as possible. In order to minimize the possibility of leakage due to air impingement in the AAMA test, the metering side box (warm side) is pressurized to 25.0 pascal (0.10 inches of water) above the ambient pressure to effect a balance with the dynamic pressure on the cold side due to the impinging wind. It should be noted that even though the wind is delivered perpendicular to the window, at the window surface the air in the boundary layer will be tangential due to the turning of the flow caused by the solid window surface.

Another difference between the AAMA and the ASTM test methods in the measurement of the U-value is the number and location of the temperature sensors. In the AAMA method, a single air temperature sensor (usually a radiation shielded thermocouple) is located on the cold side and three air temperature sensors are located on the warm side. Both the ASTM C236 and ASTM C976 test methods specify many more temperature sensors on both the test specimen surfaces and in the air stream adjacent to these surfaces, thus allowing both area weighted thermal transmittance (U-value) and thermal conductance (C-value) to be determined.

A third difference between the AAMA and ASTM test standards is the method of determining the rate of heat transfer through the mask wall in which the test window is installed and the method of measuring the surface heat transfer coefficients during calibration. In the AAMA test method, the surface heat transfer coefficients at the window surfaces are estimated by a calculation procedure using a calibration panel consisting of a double pane window with a 51 mm (2 in) air space. A value of thermal conductance (C-value) for the calibration panel is prescribed, although the rationale for the selected value is not discussed in the AAMA 1503.6 standard. The prescribed C-value of the calibration panel is subtracted from the measured thermal transmittance (U-value) to determine the inside and outside surface heat transfer coefficients. When the prescribed exterior and interior surface coefficients are obtained with the calibration panel installed, the hot boxes are considered to be calibrated to the AAMA 1503.6 standard. This calibration procedure differs from those in other laboratories in which the temperature difference across a known thermal conductance replacement material in the window space is measured along with the air and surface temperatures on each surface. The known-conductance material is usually characterized by testing in an ASTM C177 guarded hot plate or some other absolute thermal conductance device.

3.1.4 Sources of Error in Hot Boxes

As previously mentioned, early hot box investigators concluded that in order to reduce potential sources of error in hot box tests of windows, it was extremely important both to miniminize sensor inaccuracies and to characterize the convective and radiative environments to which a test window is exposed. For most hot box test methods, the accuracy of the basic instrumentation such as temperature sensors (usually thermocouples), electrical energy sensors (watt-hour meters or voltage/current meters), and velocity and pressure sensors affects the computed test results in a similar manner.

3.1.4.1 Temperature Measurement

Most temperatures are measured by thermocouples and it is important that the calibration of the thermocouple wire be known since the emf-temperature relationship varies in commercial thermocouple wire. A possible source of error is introduced when the lead wires are connected in junction boxes to other lead wires extending to the readout device. It is possible for heat conduction to set up thermoelectric voltages at junctions formed between the thermocouple leads and connectors. These voltages tend to cancel but can be a possible source of error. It is good practice to make the extensions of the thermocouples continuous from the thermocouple junction to the switching device or to the meter, both of which should be kept at uniform temperatures. The use of platinum resistance thermometers has some advantages over thermocouples due to improved accuracy, sensitivity and stability, however at greater sensor cost and with the possibility of error resulting from mechanical strain resulting from the handling or supporting of lead wire.

Unshielded thermocouples that measure air temperature also respond to the radiant effects of their surroundings. The relation between the true air temperature and the apparent air temperature depends on the mean radiant temperature of the surroundings and the convective and radiative surface coefficients at the junction of the sensor. Reducing the emittance of the thermocouple junctions by polishing, increasing the air motion or shielding the junction by multiple-concentric shields will reduce this source of error.

The measurement of glass surface temperature is also difficult and subject to considerable error and uncertainty. In many cases the test panels are not homogeneous, but the glass is broken up by muntins or other structural elements of windows. Also, variation in the air temperature from top to bottom affects the surface temperature. A reliable average temperature can be obtained by weighting many temperature measurements.

Surface temperatures are usually obtained by fastening both the thermocouple junction and lead wire to the surface with epoxy or transparent tape. Fine gauge (28 gauge or less) thermocouple lead wire is preferred for obtaining surface temperatures of glass.

3.1.4.2 Electrical Energy

Although it is generally considered that the electrical measurement of the heat source energy input to any test box is probably the most accurate single measurement made, two factors are important. One factor is the range of the readout instrument. For example, an instrument may claim to be accurate within 1/4 of 1 percent. This means 1/4 of 1 percent of the full scale reading of the instrument. Therefore, if an energy input of 20 W (watts) were read on a watt meter which read 100 W at full scale, the percentage of error would be 1-1/4 of 1 percent. The second factor is the waveform of the electrical energy source. Modern temperature controllers usually function by chopping the AC waveform. Watt-hour transducer that are calibrated using sinusoidal waveforms may have significant errors introduced due to distorted waveforms caused by the controllers, therefore calibration of all transducers over the range of operating power is essential for accurate measurement of all electrical sources, including power for heaters and operating fans.

3.1.4.3 Air Motion

Another significant factor affecting the results of tests is the matter of air motion in the test boxes. Measurement of the air velocity at a specified distance from the test surface only partially defines the character of the convection heat transfer. The usual method is to use a hot wire anemometer which has the disadvantage of being subject to radiation effects and of being non-directional. Only when the air stream is uniformly distributed and moves along the test surface in a definite path (a condition which rarely occurs) does the velocity measurement take on significance in comparing different sets of data.

3.1.4.4 Heat Transfer Rate Through Test Window

Measurement of the rate of heat transfer through a test window as in equation 1 to calculate the U-value, is usually accomplished by subtracting heat losses from the metering box surfaces and the mask wall from the measured electrical energy input. In general, those heat transfer rates are minimized by designing high thermal resistance paths, and/or by guarding and then measuring the resulting heat transfer rates by calibration.

For guarded hot boxes specifically, there is a need to measure the metering box heat transfer to the guard box, which although relatively small for conventional high-U-value windows, may be more significant for the lower U-value window systems being marketed or under development. In addition, the guard box must be larger than the window or other fenestration device to be tested. For some guarded hot boxes currently in use, this limits the size of the window that may be tested and eliminates the possibility that larger fenestration products such as glass doors can be studied. Another possible source of error specific to guarded hot boxes is the contact between the guard box and the test wall (or mask) in which the test window is mounted.

Until recently, the thermal transmittance of the nonhomogeneous mask walls used by laboratories with AAMA 1503.6 hot boxes were not calibrated experimentally, but were estimated using standard ASHRAE calculation methods. Since their construction was not specified in the AAMA 1503.6 standard, the heat transfer rate through these mask walls was not well known. For higher U-value windows this may not be a major problem, but for lower U-value window systems, the uncertainty in the mask wall heat transfer rate may cause a significant error in the window system U-value. More recently, an AAMA laboratory constructed improved test walls (wooden stud wall with space completely filled with extruded polystyrene) which should lend to better quantification of the wall heat transfer rate. If these walls were to be calibrated experimentally by filling the window space with a known high R-value insulation product, they would be quite well characterized from a thermal view-point.

3.1.4.5 Simulation of Forced Convection on Exterior Surfaces

A standard practice in existence for many years has been to rate the thermal performance of windows and other building envelope components based on forced-convection conditions on the exterior and free-convection condition on the interior surfaces. For sizing heating equipment, ASHRAE winter design U-values are based on a 6.7 m/s (15 mph) wind, which provides as combined convective and radiative surface coefficient of 34.1 $W/m^2 \cdot K$ (6.0 $Btu/h \cdot ft^2 \cdot F$). This coefficient is traceable to the original work of Rowley [1930b], for parallel flow over a small heated plate, which was previously described in section 2.2.

The simulation of the outside wind condition is one of the primary differences in the test methods used to measure the thermal performance of window and window systems and is a matter of considerable controversy. For the ASTM Guarded Hot Box test method, the external air motion is induced by a fan past the window surface in an upward direction and at a constant speed. Wind speed can vary from natural convection conditions to forced convection conditions depending upon the size and speed of the fan. The direction of the simulated wind is tangential or parallel to the plane of the window. In the ASTM Calibrated Hot Box test method, the simulated wind direction is parallel and may vary from vertical to horizontal. Conclusions cannot be made regarding the "best" speed or direction to simulate outside wind conditions because the actual wind speed and direction are quite variable, depending upon the local weather conditions, the location and surroundings of the building, and the particular exposure of the building surface on which the window is located.

Most often, convective heat transfer research data are obtained from small-scale measurements conducted in carefully controlled wind tunnels with the flow fields fully characterized with respect to velocity and temperature profiles and turbulence intensity [Gray, 1985]. In contrast, thermal performance measurements in hot box test facilities with simulated wind are often conducted on a full-scale test specimen and U-value is measured without any real attempt to either characterize the flow field or measure the convective heat transfer rate on the exterior of the test specimen.

The ASTM C236 and C976 test methods currently permit the testing of windows at nearly zero external wind speed and adjusting the results to the ASHRAE winter design wind speed. This adjustment technique is controversial because of the uncertainty of the distribution of surface coefficients with wind speed and direction. The testing of windows at 6.7 m/s (15 mph) is also controversial because field measurements have shown that in many locations, wintertime climatic conditions produce local wind speeds that are very low, therefore a mixed convection regime occurs in which both free and forced convection mechanisms are comparable in magnitude. Under conditions such as those, radiative heat transfer may contribute significantly to the heat transfer rate from a fenestration system.

AAMA Standard 1503.6 prescribes a method for adjusting the air distribution on the cold side of a window to achieve the ASHRAE winter design average surface heat transfer coefficient. The AAMA procedures uses a calibration panel, which consists of an insulating window with a 51 mm (2.0 in.) air space with a number of thermocouples mounted to the warm and cold side glass surfaces, that is installed in the mask wall in place of a test window. The air flow is adjusted until the temperature difference between the warm and cold surfaces is equal to a prescribed fraction of the temperature difference between the cold surface and the cold room air. The technical basis for this method of determining the surface heat transfer coefficients is not well substantiated.

3.1.4.6 Air Leakage

Utilizing fans to provide air motion on either side of a test window increases the possibility of air leakage through the window seals and between the window frame and opening in the mask wall. If the direction of air leakage is from the cold side box into the warm side (metering) box, additional heater energy will be required to heat the cold air and the calculated U-value will be in error. Several mechanisms have been hypothesized for air leakage, depending on the test method.

It has been recognized by several operators of calibrated hot boxes that if a test specimen has any potential sites for air leakage, such as the sliding joint of a window or the unfaced surface of a fibrous insulation board, that breathing may occur. Breathing is a process whereby the cold air and warm air on either side of a test specimen is periodically exchanged. It is believed, but not proven, that this breathing is due to the unsteady nature of the circulating air fans. All fans produce pressure and flow pulsations due to the finite blades "chopping" the air flow. Thus, larger fans have a greater potential for producing air leakage through the window air leakage area. This mass transfer tends to increase the heat transfer rate, and therefore, the overall thermal transmittance. However it has not been established for window testing using the different types of hot boxes. It may be necessary to install infiltration measuring equipment in some of these boxes to ascertain the magnitude of this air leakage for different types of windows.

A greater potential for air leakage between the cold and hot boxes is believed to exist with the AAMA method than the ASTM method due to the perpendicular wind impingement on the cold side of the test window. Although the warm side chamber is pressurized to maintain a static pressure equal to the dynamic pressure in the discharge plenum of the cold side fan, non-uniform pressure distribution within the cold chamber, particularly at the window surface, may result in local pressure differences that contribute to air leakage. Thermal contraction of window seals due to cold side temperatures and mechanical contraction of window surfaces and seals due to pressure forces may also contribute to air leakage.

3.1.5 Future Hot Box Activities

The guarded hot box and the calibrated hot box have been the most widely used test method for measuring the U-value of window systems. Under laboratory conditions, the calibrated hot box has been increasing in popularity as indicated by the number of facilities being built in recent years. With improved calibration procedures and operational experience, calibrated hot boxes may soon attain the maturity of guarded hot boxes. They may be utilized more frequently for research and development work, while the guarded hot box facilities may be used for rapid, repetitive testing applications.

Previous discussion of the AAMA test method should not be construed as criticism of either the AAMA 1503.6 standard or the AAMA hot boxes. Comments were offered to assist the evolution of the AAMA hot boxes as they are starting to reach the maturity of the C236 hot boxes. The ultimate goal should be the development of a standard thermal test method for window systems in which all of the existing hot box test facilities can be modified and/or calibrated to allow them to meet such a standard. None of the boxes should be required to undergo substantial physical modifications, however the test results for the same window or window system should be comparable.

The errors associated with the calibrated hot box instrumentation are similar to those for the guarded hot box. The potential calibration errors are greater, however, with the evolution of more accurate calibration procedures they should be minimized. The errors associated with instrumentation in the AAMA 1503.6 standard, are similar to those discussed for the ASTM C236 hot boxes. The potential errors in calibration have been discussed previously and possible methods to reduce these have been presented. Since the AAMA standard appears to be evolving towards the ASTM C236/C976 test methods, it would be expected that the overall errors will be similar. Since none of the laboratories with an AAMA hot box decided to participate in the recently completed ASTM round-robin test of rigid insulation board, a direct comparison between AAMA and ASTM hot boxes is not available. That is why there is a real need to have an interlaboratory comparison (not a full round-robin) with selected hot boxes (AAMA and ASTM).

Chapter 6 of this report outlines an interlaboratory comparison program that is needed in the near future.

3.2 INTERNATIONAL PRACTICE (HOT BOXES)

Similar to the United States, there is no unique international method for testing windows although individual countries have adopted national standards. The International Standards Organization (ISO), which has been developing an international standard test method for guarded and calibrated hot boxes, recently proposed the addition of an appendix in which the application of this standard to the measurement of window U-values is addressed. Since 1983, the International Energy Agency (IEA) has been working on a research project "Fenestration and Windows," designed to standardize the evaluation of thermal and solar properties of windows and to clarify the interaction between windows and building energy consumption [Van Dijk and Knorr, 1985].

Other European nations and Canada have also been active in research directed toward understanding the basic physics of window heat transfer, in addition to developing standard test methods.

The Scandanavian countries, in particular Norway, Sweden and Denmark, all have national standards for measuring U-values of window systems. In the opinion of the authors, the coordinated national efforts that are funded by the public sector in the European community have resulted in testing facilities for windows and standards that are in an advanced state of maturity. Other countries, especially Canada, Belgium, Switzerland and Germany also have significant national programs aimed at the development of test methods for windows.

In this section, window test methods used in Norway, Sweden, Belgium and Canada are outlined. NBS obtained copies of several national standards for testing windows and for calculating thermal performance. Translations of these standards are provided in Appendix A.

3.2.1 Norwegian Practice

Norwegian building code requires that the U-value of windows for design purposes be less than prescribed values. The U-values are based on testing that is performed at the Norwegian Building Research Institute, located in Trondheim, Norway. In addition, research programs have been conducted at that institute to measure the thermal performance of sealed glazing units with special low-emittance coatings and with gas fills [Breder and Heiersted, 1984].

Appendix A-1 provides a translation of Norwegian Standard NBI-138, 1982 for thermal measurements of sealed glazing units. The standard defines the test method, sample size, temperature sensor placement, and by reference to other standards, the measurement accuracy and calibration procedure. The test results consist of the measured surface-to-surface conductance (C-value), and the U-value is calculated based on addition of prescribed surface resistances corresponding to 8.3 $w/m^2 \cdot K$ (1.45 $Btu/h \cdot ft^2 \cdot F$) inside and 20.0 $w/m^2 \cdot K$ (3.52 $Btu/h \cdot ft^2 \cdot F$) outside surface coefficients.

In the draft standard for window U-values, the measurements are made with a parallel wind on the outside and still air conditions on the inside of the test specimen [Heiersted, 1983]. The prescribed exterior surface heat transfer coefficient is obtained by adjusting the air flow rate, using a calibrated heat flux transducer to measure the surface coefficient. The heat flux transducer is a laminated assembly, consisting of two 4 mm (0.16 in) glass face sheets and a 10 mm (.39 in) extruded polystyrene core, that is the same overall dimensions as the test window.

3.2.2 Swedish Practice

Swedish building codes, which are similar to those in Norway, also require testing of windows in hot boxes under standard conditions. Although Sweden is not a participant in the IEA fenestration research previously mentioned, Sweden recently assumed the secretariat position for preparing the new ISO window U-value test standard.

Appendix A-2 provides a translation of Swedish Standard SS 81 81 29, "Thermal Resistance Test of Windows." The standard defines the test facility, instrumentation, specimen preparation and test procedure. The test results include a composite C-value, based on area weighting of conductances for the glazing unit, sash, and frame members. The C-value is adjusted to a U-value by the addition of standard film resistances, given by the Swedish Building Code.

Researchers at several Swedish universities have made significant contributions to the knowledge of window heat transfer and materials technology. Of particular importance is a treatise "Heat Transfer Through Windows During the Hours of Darkness with the Effect of Infiltration Ignored," by Jonsson [1985] at the Lund Institute of Technology. English language translations of this and other important work are available from the Swedish Council of Building Research, in Stockholm[1]. This report provides a very detailed descriptions of the test method, calibration procedures, test results and a very comprehensive theoretical analysis of all modes of heat transfer in windows, including convection in the air space and conduction through the sash and frame windows.

3.2.3 Belgian Practice

The Building Research Institute in Brussels, Belgium developed a new standard for window U-values based on improved methods for calculating heat transfer through the component parts. The improved calculation method, which is based on substantial laboratory testing and theoretical analyses, is presented in an English language translation in Appendix A-3. This document will be incorporated into a revised version of Belgian Standard NBN

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1 - Address is Sankt Goransgatan 66, S-112 33, Stockholm, Sweden.

B62-002. It is believed that the new ISO standard for windows will be based largely on the Belgian standard.

The basic approach in NBN B62-002 is that the central glazing unit U-value and C-value are calculated based on theoretical considerations, involving the transport properties of the gas fill, radiative properties of the glazing surfaces and the geometrical description of the unit [NBN B62-004, 1986].

The overall U-value for a window is determined by a calculation involving the area weighted U-value of the central glazing unit, the spacer between glazings, the frame, and any opaque panels that may be present. Frame and spacer heat transfer coefficients are provided in the standard for a wide range of materials and configurations, and simplified formulae are presented that permit calculation of the two-dimensional heat conduction effects of glass, spacers and frames. In addition, a proprietary computer program, developed by Standaert in his doctoral studies at the Catholic University of Leuven, Belgium is available to perform the two-dimensional heat transfer analysis of window, spacers and frames [Standaert, 1984].

3.2.4 Canadian Practice

The National Research Council (NRC) in Ottawa, Canada decided to build a new guarded hot box for window testing rather than use the existing guarded hot box previously used for measuring the thermal performance of building wall assemblies (Bowen, 1985). Their new window hot box differs from a typical guarded box by the presence of an isothermal baffle on the warm side and a wind machine on the cold side. The wind machine provides a uniform velocity perpendicular to the window surface using a variable speed fan which directs air through a number of parallel, rotating tubes shown in Figure 6. The isothermal room side baffle enables accurate characterization of the radiant environment and determinant on an effective temperature of the room side surface. By having an accurately-known baffle temperature, the mean window surface temperature is calculated from an energy balance on the room side. This allows determination of both the air-to-air U-value, and the surface-to-surface C-value for a test window.

The NRC is an active participant in the ASTM C16/E06 joint task group activities described in Section 5 of this report. The ASTM draft standard practice in Appendix B-3 of this report is based on the NRC window hot box calculation procedure.

3.3 FIELD VISITS TO LABORATORIES

Field trips have been made by the authors of this report to several laboratories which have guarded hot boxes that are operated in accordance with ASTM C236. Laboratories visited in the past several years include Dynatech in Cambridge, Massachusetts, W. R. Grace in Cambridge, Massachusetts, Jim Walter Research in Tampa, Florida, Dynatherm in Blue Lake, Minnesota, Dow Chemical Research Center in Granville, Ohio, and Butler Manufacturing in Kansas City, Missouri. Other guarded hot boxes are located at Wiss, Janey and Fisher in Skokie, Illinois. The guarded hot boxes at W.

R. Grace, Jim Walter Research, and Dow Chemical were manufactured by Wiss, Janey and Fisher. Most of the above boxes have been used for in-house product testing of a wide range of building assemblies such as insulated studded ceilings and roofs, insulated metal building roofs, walls, and windows and doors installed in walls. They have been used to develop and/or verify some of the building assembly transmission coefficients (U-values) given in Tables 4A to 4L, Chapter 23 of the 1985 ASHRAE Handbook of Fundamentals. In addition, most of the laboratories listed above have participated in the recent ASTM round-robin for guarded and calibrated hot boxes so that data on the precision and accuracy for these boxes can be developed in the near future.

Based on visits to these laboratories, the authors have concluded that guarded hot boxes are mature thermal test facilities and are operated by experienced personnel. Through participation on ASTM Committee C16, Thermal Insulation and Vapor Retarders, these laboratories have developed and improved the understanding and use of guarded hot boxes to this mature state.

The authors also visited several of the laboratories with ASTM C976 Calibrated Hot Boxes. The laboratories visited are Owens-Corning Fiberglass Technical Center in Granville, Ohio which has two (vertical and horizontal test specimens) Calibrated Hot Box (CHB) test facilities, Jim Walter Research in Tampa, Florida (its Wiss, Janey and Fisher hot box can operate in either the guarded or calibrated mode), the University of Massachusetts at Amherst, Massachusetts which is based upon the Owens-Corning vertical hot box design, Portland Cement Association Construction Technology Laboratory in Skokie, Illinois, Manville Service Corporation in Denver, Colorado, and the CHB at the National Bureau of Standards in Gaithersburg, Maryland.

The Calibrated Hot Box of the Construction Technology Laboratory, Portland Cement Association has had the capability of operating a dynamic cycle on the environmental side (usually the cold box) for several years and has produced a significant quantity of dynamic cycle data. The Owens Corning Fiberglass horizontal Calibrated Hot Box, the Manville Service Corporation Calibrated Hot Box, and the National Bureau of Standards Calibrated Hot Box all are also capable of operating a dynamic cycle and should start producing dynamic cycle thermal performance data in the near future.

Visits have also been made to two of the laboratories with hot boxes conforming to the AAMA 1503.6 window thermal performance tests. These are Architectural Testing, Inc. of York, Pennsylvania and National Certified Testing Laboratory also of York, Pennsylvania. The third laboratory is Electrical Testing Laboratory (now ETL) of Cortland, New York. The new hot box at Architectural Testing appears to be setting the evolutionary trend for the current AAMA standard now under revision. It has state-of-the-art instrumentation and controls and is fully computerized. It is a true guarded hot box and with minor revisions would probably be able to meet the current ASTM C236 standard test method. The converse may also be true, where the current ASTM C236 and C976 hot boxes with minor revisions might ultimately meet the revised AAMA standards, if some accommodation can be made for the differences in the outside wind speed and direction. It is anticipated that the proposed revisions to ASTM C236 and C976 and the draft standard practice presented in Appendix B of this report will be a first step in this accommodation.

3.4 U-VALUE MEASUREMENT CONFERENCES

In 1985, two important conferences were conducted that are relevant to the discussion of window systems thermal test methods.

3.4.1 Workshop on Laboratory Measurements of "U-Values" of Windows

This workshop was held at NBS in Gaithersburg, MD on February 26-27, 1985 and jointly sponsored by BTECC, ASHRAE, ASTM and DOE. The stated objectives of the meeting were to bring together researchers, manufactuers, architects and others interested in measurement and specification of fenestration system U-values, to permit an exchange of ideas on testing methods, to identify future research efforts and to develop a consensus standard test method.

The agenda consisted of invited papers, short contributions (brief comments) and panel discussions with speakers and participants drawn from a wide range of interests. Published conference proceedings, including peer-reviewed papers and transcriptions of the panel discussions were to be provided by BTECC. Approximately 80 persons participated in the workshop. Table 1 presents the meeting agenda.

Although the final proceedings of this conference have not yet been published, the authors concluded that a large majority of the workshop participants agreed that a standard test method for window U-values was urgently needed. A wide range of debate over the specific details of the proposed test method was a divisive factor in the panel discussions.

3.4.2 Low E Roundtable

The U.S. Department of Energy, Lawrence Berkeley Laboratory and the National Fenestration Council (NFC) jointly sponsored this conference, which was held in Las Vegas, NV, August 28-29, 1985. The objective of this meeting was to review the terminology, heat transfer technology, durability, and energy savings potential of windows with low-emittance coatings. The agenda included overview papers on the various issues and a panel discussion on the need for development of standards.

The conference was attended largely by glass industry representatives. No formal proceedings of the papers presented at the conference was planned, however notes taken by one of the authors (McCabe) lead to the conclusions that the "window industry" strongly desired the development of standards that would uniformly address the performance attributes and design requirements of all fenestration products. The NFC assumed the responsibility of preparing an industry standard for measurement of infrared emittance of the coatings used in the manufacture of "low-E" windows.

TABLE 1

Workshop on Laboratory Measurements of the "U-Values" of Windows

**Laboratory Measurements of the "U-Values" of Windows
at the
National Bureau of Standards, Gaithersburg, MD**

February 26-27 1985

Sponsored by	:	**Building Thermal Envelope Coordinating Council**
Cosponsors	:	**ASHRAE, ASTM, DoE, NBS**
General Chairman	:	**R.P. Tye, Dynatech R/D Company, Cambridge, MA**
Local Chairman	:	**M.C. McCabe, Center Building Technology, NBS**

PROGRAM

Tuesday, February 26, 1985

08:30	Registration - Administration Building, Ground Floor
09:15	Welcome and Opening Remarks
	Dr. J. Gross, Deputy Director - Center of Building Technology, NBS Mr. J. Roehm, Roehm Associates - BTECC Mr. J. Boulin, Conservation and Solar Division, DoE Mr. R.P. Tye, Chairman - ASTM and ASHRAE Mr. M.C. McCabe, Local Chairman - Local Arrangements
09:30 - 10:45	Session I History Current Use of Tests and Primary Audience Chairman: Mr. Jean Boulin, DoE S. Treado : National Bureau of Standards "History of ASHRAE Activities in Measuring Performance of Windows" R. Tye : Dynatech R/D Company "ASTM Test Methods Development for Windows" J. Gurniak : American Architectural Manufacturers Association "AAMA History and Current Use of Laboratory Tests" R. Berg : Veterans Administration "Test Considerations for U Values of Windows" F. Pratt : Bonneville Power Authority "Windows Thermal Performance in BPA Conservation Programs"
10:45	Coffee Break
11:00 - 12:45	Session I (continued) R. Bowen : National Research Council Canada "Thermal Testing of Windows at NRC J. Anderson: Albany International "Laboratory and In-Use Comparison of Insulation Effectiveness of Window Treatments" D. Pellish : Department of Energy "Department of Energy Programs Relating to Window Performance" W. Haynes : New York Landmarks Conservancy "NYC Audiences and Needs in Landmark Buildings"
12:45 - 13:30	Lunch - National Bureau of Standards Dining Area
13:30 - 15:00	Session II Methods Apparatus and Instrumentation Chairman: Dr. George E. Courville - Oak Ridge National Laboratory W. Goss : University of Massachusetts "Test Methods and Instrumentation for the Measurement of U Values of Windows" R. Kinney : Synertech Corporation "Cost Effective Method for Determining the Effective R-values of Insulating Shutters and Similar Window Treatments"

TABLE 1 (continued)

	F. Romesburg	: <u>Dow Chemical, USA</u> "Use of a Heat Flow Meter Unit to Measure Apparent Thermal Conductivity of Window Composites
	R. Dixon	: <u>University of FLorida</u> "Fenestration Configur. on: and Guarded Hot Box Adaptation for Determination of Their U Values"
	H. Taylor	: <u>Architectural Testing Laboratories</u> "Instrumentation for Testing in Accordance with the AAMA Standard"
15:00 - 15:20	Coffee Break	
15:20 - 16:10	Panel Discussion on Session I - Convenor - Jean Boulin	
16:00 - 17:00	Panel Discussion on Session II - Convenor - George Courville	

Wednesday, February 17, 1985

09:00 - 10:30	Session III	<u>Comparability and Relationship of Results</u>
	Chairman:	Dr. Heinz Trechsel - Trechsel Associates
	A. Van Dijk	: <u>Institute of Applied Physics, Delft</u> "Preliminary Comparison between Measured and Calculated U Values of Windows"
	M. McCabe	: <u>National Bureau of Standards</u> "Comparison between Laboratory and Field Measured U Values"
	S. Fullarton	: <u>University of Wisconsin</u> "Testing Window Treatments In-Place"
	G. Page	: <u>United Technologies</u> "Considerations Relating to Thermal Performance of Window Frames"
10:30 - 10:45	Coffee Break	
10:45 - 12:45	Session IV	<u>Other Areas and Future Research</u>
	Chairman:	Mr. D. Pellish, Department of Energy
	J. Klems	: <u>Lawrence Berkeley Laboratory</u> "Towards Accurate Predictions of Comparative Fenestration Performance'
	A. Van Dijk	: <u>Institute of Applied Physics Delft</u>, "Hot Box Measurements in a Proposed Test Facility In The Netherlands"
	T. Cardenas	: <u>Steven Winter Associates</u> "An Assessment of Standards that Measure Thermal Performance of Windows and Their Relevance to The Future of ASHRAE Standard 90"
	W. Putnam	: <u>DSET Laboratories</u> "A Large Multi-Purpose Solar Illuminated Eight Foot Integrating Sphere for Optical Properties Measurements"
12:45 - 13:30	Lunch - National Bureau of Standards Dining Area	
13:30 - 14:10	Panel Discussion on Session III - Convenor - H. Trechsel	
14:10 - 14:45	Panel Discussion on Session IV - Convenor - D. Pellish	
14:45 - 15:00	Concluding Remarks J.M. Roehm / R.P. Tye	
15:00	CLOSE	

All sessions will be held in Lecture Room B, Administration Building

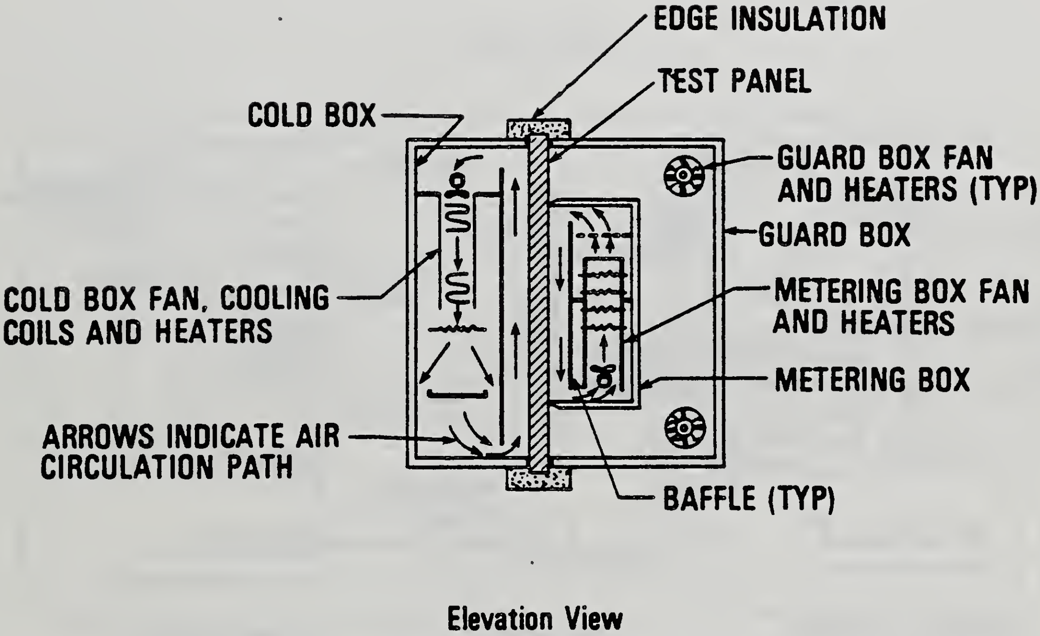

Figure 3. ASTM C236 Guarded Hot Box

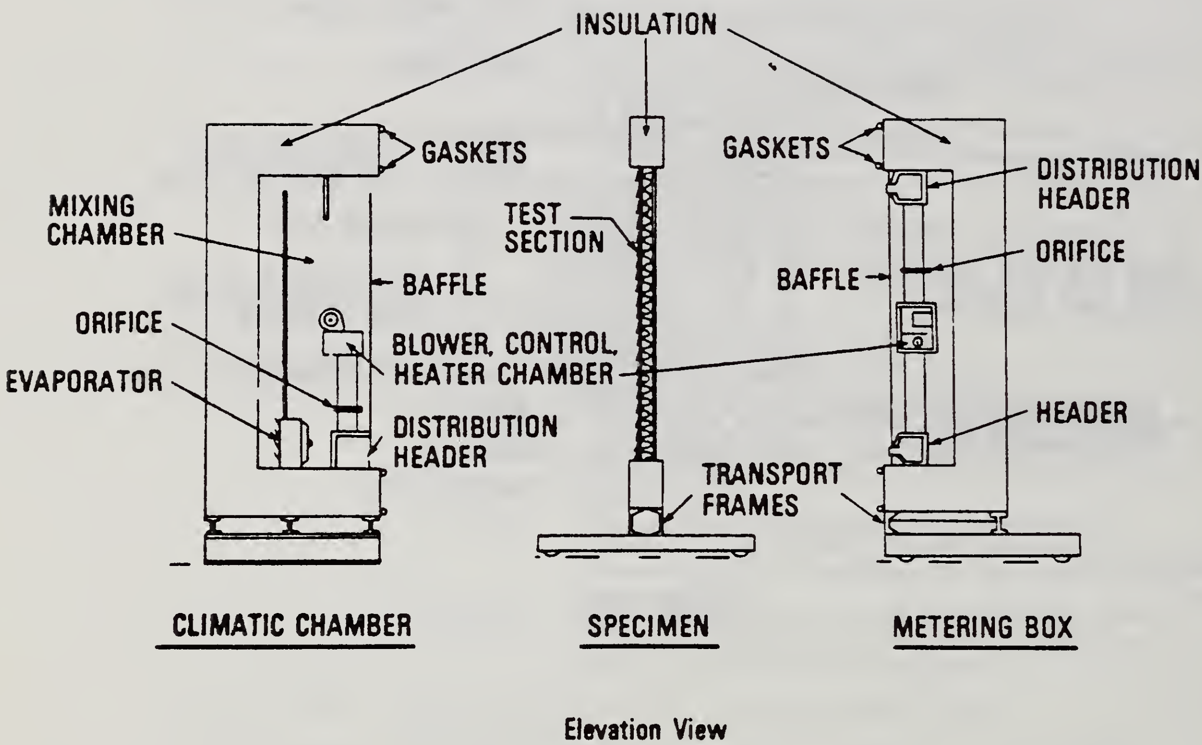

Figure 4. ASTM C976 Calibrated Hot Box

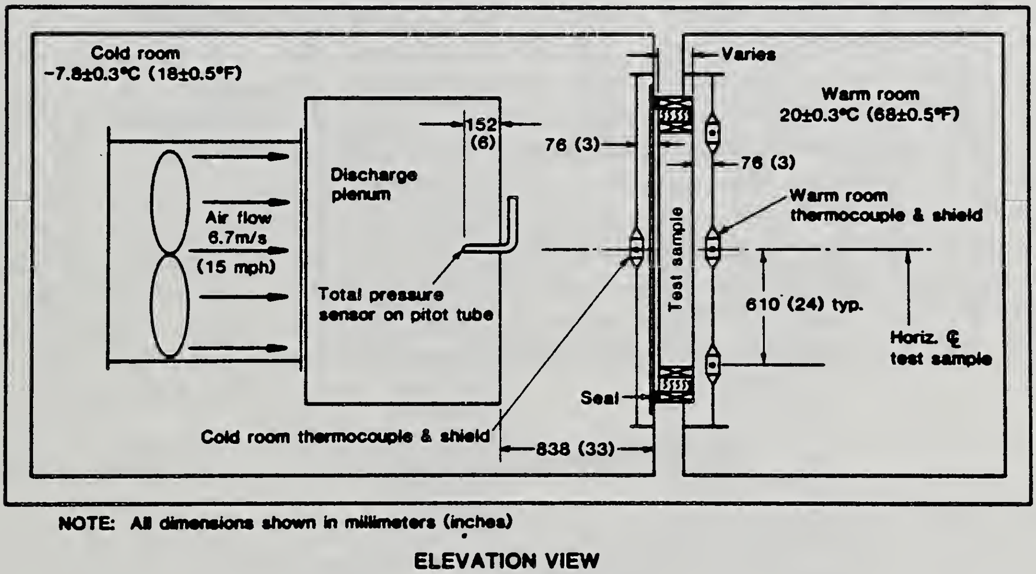

Figure 5. AAMA 1503.6 Hot Box

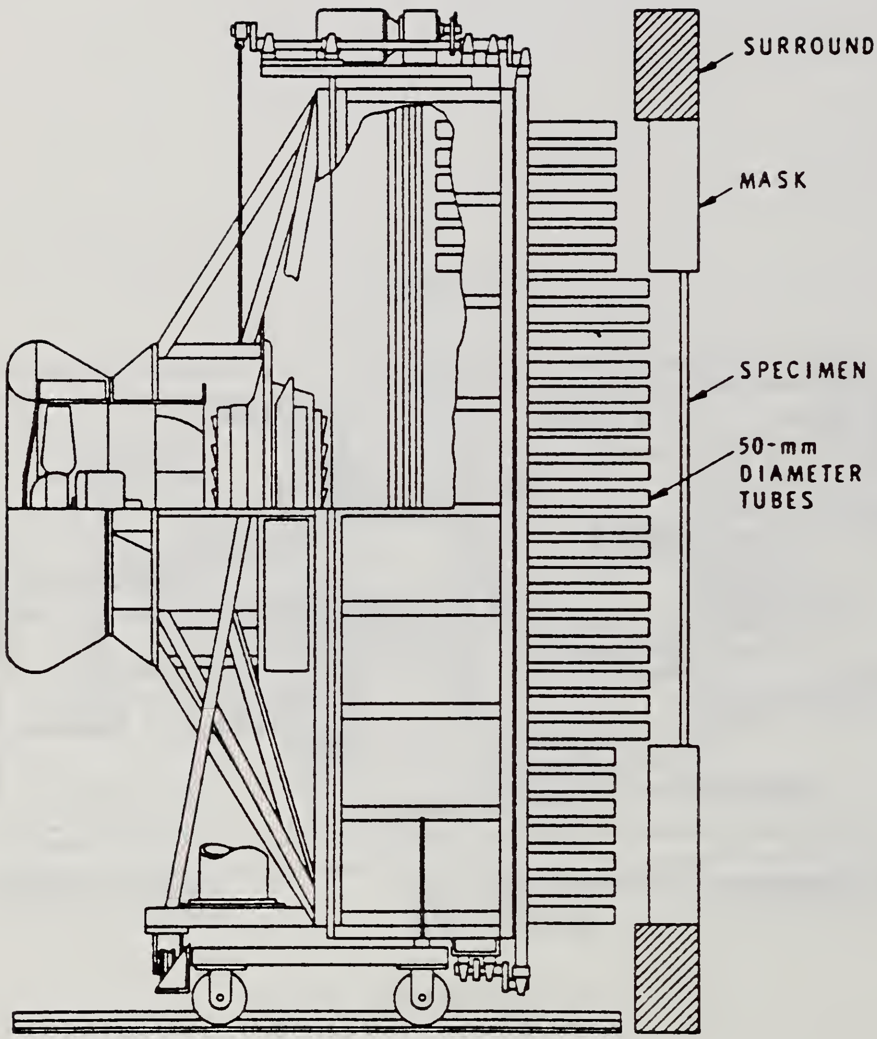

Figure 6. NRC Canada Wind Simulation Machine

4. THERMAL PERFORMANCE TESTING OF MOVABLE INSULATION SYSTEMS FOR FENESTRATION

The development of movable insulation systems for windows was stimulated largely by the needs of builders and owners of passive solar residential buildings to reduce the nightime heat loss through relatively large areas of south-facing glazing, and thereby provide increased thermal performance and comfort for the occupants [Balcomb, 1982]. The generic term, movable insulation, refers to materials and components that are installed with conventional windows, glass doors and skylights that have at least two operating modes to modify and control the transfer of radiant solar energy and conductive heat loss (or gain). Movable insulation is also known as night insulation, or as insulating window treatments. It can be installed on the inside or outside of fenestration or between glazing layers, and may be manually operated by the building occupants, or automatically operated by motorized or by non-electrical devices.

Since a movable insulation system is always installed with a conventional fenestration, the term "effectiveness" is often used as a characteristic of thermal performance. Effectiveness is defined as the ratio of the difference in U-value between the window system with and without the insulation deployed, to U-value of the basic (undeployed) system. Effectiveness is, therefore, the fraction of energy saved relative to a particular fenestration system. Obviously, effectiveness of a movable insulation will vary; depending on the particular reference fenestration selected, the outdoor and indoor air temperatures and surface conductances, and possibly with system size, and method of installation. Therefore, development of a standard method for measuring thermal performance, requires that all of the factors that can possibly cause variation in test results must be defined. This section will discuss some of the test methods and apparatus for meauring thermal performance of movable insulations that have appeared in the literature.

4.1 FEDERAL PROGRAMS TO DEVELOP MOVABLE INSULATION

As part of a National Program for Solar Application, the Department of Energy initiated a program for the development and commercialization of components that would improve the performance of passive solar buildings [U.S. Department of Energy, 1979]. As part of the commercialization efforts, thermal performance testing was required, however the details of how this was to be done were left to the discretion of the grantee. Of the 26 grants made, six were for companies developing movable insulations, primarily insulating curtains or shutters. As described in the Department of Energy final report [Mueller Associates, 1984], thermal test results for those movable insulation systems actually tested were often far less the expectations of the grantee. In general, insufficient detail was provided in the grantee reports or in the final report to evaluate the adequacy of the thermal test methods used for measuring component performance, however it is instructive to review the attempts to comply with the program testing requirements.

One of the primary concerns in the design of movable insulation was the sealing of joints located on the perimeter between moving and stationary components. A loss of thermal performance is anticipated due to the potential for free convection exchange between the cold air space adjacent to the glazing and insulation, and the room air. A related concern is the possibility of condensation of moisture from room air on cold surfaces and the deterioration in thermal performance due to change in surface properties and insulating properties of the components. Therefore a significant design effort was undertaken by private sector participants in the DOE program to develop effective perimeter seals and a number of different test methods evolved to evaluate thermal performance of the seals in the various proprietary movable insulation systems.

One participant in the DOE Passive Components Program, the ABRI Company, developed an inflatable insulation window curtain [Mueller Associates, 1984, p. 80-85]. ABRI reported of new testing approaches that perhaps typify the development of movable insulation products [ABRI Inc., 1981]. While recognizing the value of testing in an ASTM hot box in a commercial laboratory, ABRI judged that a less costly and time consuming test method was needed to permit optimization of various design parameters and to permit experimentation with design changes in an incremental manner.

The ABRI test facility consisted of two small boxes constructed of extruded polystyrene insulation joined by a wall containing a single glazed window and the test specimen. One box was heated to constant temperature using a shielded heating element and circulating fan. The other box was cooled by circulating chilled water through a liquid-to-air heat exchanger. An array of thermocouples monitored temperatures in the facility. Measurement of heat flow through the test specimen and window was based on the assumption that the hot box heat source dissipated a known and constant power and that heat loss through the hot box walls could be calculated knowing the air temperatures on both sides of the box and thermal conductivity of the walls. Knowing the hot and cold side temperatures and heat transfer rate, the U-value of the test specimen could be then calculated. The reported time period for temperature stabilization of this facility was one hour and data were taken over three one-half hour periods. It is not clear whether the power input to the heating element was independantly measured, or whether the U-value calculations were based on the nominal power rating of the heater. It is also not clear whether the test facility produced any useful thermal test data, since the final report indicated that only estimated values for the product were developed.

In another DOE commercialization project, researchers at the Thermal Technology Corp (TTC) received a grant to develop a movable insulation product consisting of a roller shade containing four reflective layers with provisions for inflating and deflating the air space between layers. A prototype shade was tested under both laboratory and field conditions [Steele et al., 1982] with substantial disagreement in measured thermal performance. In one field test, four heat flux sensors were taped to the outer layer of a prototype shade facing a single-glazed patio door in a residence and used to measure the heat flow rate. The prototype test shade consisted of the four reflective fabric layers stretched over individual wooden frames that maintained 18 mm (3/4 in) air space dimensions and sealed all the edges, thus providing an idealized test configuration for comparison with actual shade performance. The thermal resistance of the glass/shade combination indicated by the heat flux sensors exceeded the maximum possible theoretical resistance calculated using ASHRAE Handbook data. A second field test using a larger-sized unit with actual roller shade hardware was performed, resulting in R-values derived from heat flux sensor readings that were about 35 percent below that of the ideal shade configuration.

Subsequent laboratory testing of production shades in a commercial hot box indicated far lower thermal resistance than that from the field tests. Although a number of explanations for the anomolous test results were hypothesized based primarily on the size differences and edge sealing of the units tested, the heat flux sensors used in the field testing were also suspect. The potential sources of error from using heat flux sensors as the primary measurement sensors are discussed in Section 4.5. An important conclusion stated in the TTC report, ".... to be drawn from this testing is that sizes of the curtains, the method of test, and the effectiveness of layer separations and edge seals can allow the product to demonstrate R-values ranging from 2.97 to 11.008".

4.2 HISTORICAL THERMAL TESTING OF ROLLER SHADES

Roller shades are probably the oldest example of movable insulations for fenestration systems, even though their primary function has often been to reduce solar gain and to provide a measure of privacy for occupants. It has long been recognized that the presence of opaque shade fabrics that are suspended vertically a short distance from the interior of cold glazing surfaces, reduced the radiative heat loss from the warmer room surfaces, however the magnitude of the reduction in heat loss was difficult to estimate. ASHVE Research Bulletin No. 1 [Parmelee, 1947b] reported published U-values for windows with and without roller shades based on hot box measurements made as early as 1919. Those measurements showed significant reduction in heat loss relative to an unshaded window, depending on the particular method of mounting. The ASHRAE Research Laboratory [Ozisik and Schutrum, 1959] examined the effects of different shade materials, shade mounting positions and edge sealing techniques using a field test method involving the ASHRAE Solar Calorimeter. Winter nighttime U-value data were obtained and adjusted for standard outside and inside surface conductances. The test results indicated a significant reduction in U-value for roller shades having a low emittance shade material (aluminum-foil) in conjunction with sealed edges that was not evident in the same material without the sealed edges.

More recently, a variety of field and laboratory test methods have been reported for measuring the thermal performance of movable insulation systems, varying in sophistication from complexity equal to hot box methods to extreme simplicity. The following sections describe some of these test methods.

4.3. FIELD TEST METHODS

Field test methods using actual outdoor conditions can often be performed at a lesser cost than laboratory hot box test methods and with greater realism, however generalization of test results may be difficult, due to measurement uncertainties in climatic variables such as nocturnal radiation and wind speed, and in unsteady heat transfer conditions. Moreover, variation in these climatic factors tends to make the measured thermal performance somewhat time-of-year and site-specific, thereby requiring longer testing periods and necessitating the use of well-characterized control specimens for comparison purposes. Three approaches have been taken for field measurement of movable insulation, depending on the type of test facility. These include the following: 1) in-situ testing in buildings, 2) test cells, and 3) field calorimeters.

4.3.1 In-Situ Testing in Buildings

Perhaps the least costly test method for field evaluation of movable insulation thermal performance was proposed by Shurcliff [1980]. In this method, three conventional liquid-in-glass thermometers are installed; one indoors, one outdoors and one in the air-space between the movable insulation and the window. By measuring the temperature difference between the air space thermometer and the outdoor thermometer, with and without the movable insulation in place, the fractional reduction in nighttime heat loss is determined. The indoor and outdoor thermometer readings are used to adjust these results to standard indoor and outdoor conditions of 21°C (70°F) and -1°C (30°F), respectively.

Aside from the questionable accuracy and difficulties in temperature measurement with unshielded, liquid-in-glass thermometers, inferring U-values of movable insulations from measurements of air space temperatures has probably the lowest accuracy of all the proposed methods. Fowlkes [1980] reported significantly higher U-values for movable insulations using air space temperatures and Shurcliff's method than expected based on the thermal properties of the materials comprising the insulation system.

In another in-situ test method, thermal performance of insulating window shades were compared with conventional draperies by installing the shades over north-facing, single-glazed windows in identical rooms in a commercial inn, and monitoring each room's energy consumption over a three month heating period [Grasso and Anderson, 1986]. The measured reduction in room energy consumption was 47% compared to a 49% reduction based on calculated U-values for the insulating shades and conventional draperies, however no attempt was made to monitor either the frequency of opening and closing of the window treatments or the setpoints of the room thermostats, which were controlled at the discretion of the room occupants.

Another in-situ measurement technique is described by McCabe and Hill [1987], which involves the use of portable calorimeters to measure comparative thermal performance of identical north-facing windows with different types of thermal coatings. This technique would also be applicable for in-situ testing of movable insulation provided some means of deploying and retracting the interior mounted insulation without removing the metering boxes, is available. Alternatively, testing two identical side-by-side windows; one with a deployed insulation and one with a retracted insulation would provide useful test results for measuring the effectiveness of these products as actually installed in buildings.

4.3.2 Nighttime Measurements in Test Cells

Researchers at the Los Alamos National Laboratory established a methodology for comparative field testing of a range of passive solar systems, including movable insulations, using room-size test cells [Balcomb et al., 1978; Hyde, 1980]. A number of different systems, including solar storage walls with different movable insulations were installed in identical, south-facing test cells and exposed to prevailing winter climatic conditions in the high desert of New Mexico. Performance evaluation consisted of comparing auxiliary heater energy requirements and air temperature variation between the different test cells, however, no attempt was made to evaluate nighttime U-values for the commercial movable insulation products tested.

Lexen and Muldary [1985] describe an arrangement of three side-by-side, room-size test cells designed for field comparison testing of prototypes and new window products including shades, blinds, films, shutters and movable insulations. One of the test cells is designated as a reference and contains a heavily insulated "plug" of known thermal conductivity, instead of a window. The second cell has a standard double-glazed window, and the third cell has the standard window plus the window accessory being evaluated. For purposes of nighttime U-value testing, the test cells face north to avoid daytime solar gains, interior temperatures are held constant at 22 C (72 F), and heater power is monitored for each test cell. By using the three-cell arrangement described, both absolute U-values and differential U-values are obtained with sufficient accuracy to meet the stated objectives of the test facility.

4.3.3 Nighttime Measurements in Calorimeters

It was apparent that field testing either in actual rooms or in test cells had shortcomings of one kind or another that limited the generality and the usefulness of the test results. It was reasoned that the thermal environments in the test cells and actual buildings were both uncontrolled and largely unmeasured. There was also the distinct possibility for uncontrolled air leakage in a test component or room, and that heat storage or heat release by room surfaces could contribute significantly to uncertainties in test results. In consideration of those problems, NBS under sponsorship of the Passive Solar Division of the U.S. Department of Energy, constructed a calorimetric type of test facility that was used to test a range of passive solar components, including movable insulation systems [McCabe et al., 1982; McCabe et al., 1984]. In the NBS facility shown in Figure 7, the temperature of interior surfaces and air was closely controlled and the mounting interface between the test specimen and calorimeter was carefully designed to minimize edge heat loss. The design objectives for the NBS calorimeter were to eliminate, or to at least minimize the previously mentioned shortcomings of the test cells and rooms.

A single-glazed window with interior bifold insulating shutters was tested in the NBS facility in Gaithersburg, Maryland during the winter of 1982-1983. The same shutter/window combination had previously been tested in two different laboratory hot box facilities [McCabe et al., 1986], and although the field measurements were generally in the range of the laboratory measurements, significant scatter in the U-value data occurred. It was concluded that a major problem in field testing in the NBS calorimeter was the imprecise measurement of the outdoor conditions, including air temperature, radiative heat loss and wind. Furthermore, it was evident that data collection needed to be taken over a much longer time than the one-week test period actually chosen, in order to ensure a statistically valid sample of climatic conditions representative of winter conditions.

An advanced, outdoor-calorimetric test facility, which uses large-area heat flux meters instead of water-cooled walls, was constructed by the Lawrence Berkeley Laboratories under sponsorship of the Building Systems Division of the U.S. Department of Energy, which is known by the acronym MoWITT [Klems, 1982]. The planned use of the MoWITT includes the testing of windows and movable insulation systems for windows. This test facility, which is shown in Figure 8, is designed to make highly accurate performance measurements under field conditions, and utilizes two air-guarded, metering chambers mounted on a truck chassis for mobility. The initial testing phase of this facility was recently completed [Klems and Keller, 1987]. Current plans are to conduct field measurements with MoWITT and compare these with laboratory measurements for three sealed insulating glass units made at the University of Massachusetts as part of an overall U-value measurements program sponsored by the Department of Energy [Goss and McCabe, 1985].

4.4 LABORATORY TEST METHODS

A variety of laboratory test methods have been reported for measuring U-values for movable insulation systems. In addition to the conventional hot box test methods previously described, a number of alternative test methods have been reported.

4.4.1 Single Chamber with Heat Flux Transducers

New Shelter, a consumer-oriented magazine focusing on energy issues in housing, tested eleven different commercial products, including roller shades, curtains, interior shutters and interior storm windows [Rawlings 1980]. The test facility consisted of a single-glazed window installed in a wall located between a room heated to "regular" temperatures and a room maintained at least 17°C (30 F) colder, with a small fan directing cold air at the cold side of the window "to simulate a breeze". Test specimens were mounted to the warm side of the window and a commercial heat flux transducer was taped to the warm side window surface. Details regarding the method of attachment of the test specimens, were not provided. The test results reported were "percent heat saved", which varied between 46 and 89% for the products tested. This index was computed by comparing the heat flux transducer output voltage reading for the movable insulation products in the deployed and non-deployed positions and adjusting the results in some unspecified manner to a 6.7 m/s (15 mph) wind.

Fabric and textile researchers at several universities utilized similar techniques to investigate the thermal performance of various drapery systems. Horridge and coworkers [1983] at Texas Tech University, report on a test method in which a small refrigerated box maintained between -15 and-7 C (5 and 20 F) was positioned on the exterior side of a single-glazed window mounted in the wall of an environmental test chamber. A single heat flux transducer was attached at midheight to the interior surface of the glass, as shown in Figure 9, and various insulating treatments were mounted to a wooden frame on the interior side of the window. The window treatment was exposed to environmental chamber air maintained at 21 C (70 F) and 60% relative humidity. R-values varying between 1.50 and 2.15 were reported for the various systems (window plus treatment) tested, however the basis of these reported R-values was not stated.

Epps and coworkers [1984] at the University of Georgia, report on measured U-values of various textile fabrics using a similar apparatus, however, with three heat flux transducers tightly clamped to the glazing surface and a cold chamber cooled by an air conditioning unit with controlled convective heat transfer on the exterior side of the reference window. The warm side was maintained at 21 C (70 F) and at two levels of relative humidity (45 and 68%). U-values were reported for the window-fabric system at the two relative humidity levels, based on the measured output of the heat flux transducer and the air-to-air temperature difference.

Despite the widespread use of heat flux transducers in measurement of the thermal performance of windows with movable insulation, several problems are evident. These problems, which will be discussed in some detail in Section 4.5, tend to limit the utility of the test method, because of the possibility that the test results may not be reproducible by others using the same technique, but with different sensors.

4.4.2 Guarded Hot Plate

A popular method for measuring the thermal properties of textile fabrics based on principles of the guarded hot plate has been adapted for the testing of windows with movable insulations [Anderson, 1982]. A similar apparatus located in the merchandise testing center of a major retailer was used by researchers at Cornell Univerity to measure the effectiveness of roller shades [Grasso and Buchanan, 1979], and insulating shades, draperies and blinds [Cukierski and Buchanan, 1979]. Figure 10 shows a schematic drawing of the guarded window test apparatus described by Anderson [1982], which consists of three heater panels installed in a wooden framed calorimeter box. The primary or test heater is installed as a vertical plate facing the exterior surface of the test window/movable insulation. Two guard heaters; a vertical panel heater located behind the test heater and a narrow perimeter heater, limit the rear and edge to flow horizontally through the test window. The window treatment test specimen is located outboard of the test window and is exposed to the laboratory environment. Anderson´s comparison of percent reduction of heat loss (effectiveness) made for five different shade fabrics using an AAMA hot box and the Guarded Hot Plate apparatus showed excellant agreement.

The primary advantage of this test method over a hot box test method in testing of insulating window treatments is the substantially lower initial costs of the facility, the smaller laboratory floor space occupied and the rapid achievement of steady-state conditions [Anderson, 1982]. This permits quantitative measurements of window treatment products to be rapidly made at low cost. One possible disadvantage of this test method is that the direction of heat flow is reversed from the normal inside-to-outside, winter time direction. Atypical air space and surface temperatures that occur as a result of the reverse heat flow direction may either suppress or enhance convection loops that mask performance attributes of the window treatment in an uncertain manner. Dix and Lavan [1974], at the Illinois Institute of Technology investigated the thermal performance of window coverings with a two room test module, in which one room represented the outdoor environment, and the other the inside of a house. The wall dividing the two rooms had a double glazed window over which the test shades were installed. Summer conditions were simulated with a bank of lamps and winter conditions were simulated with a refrigeration unit.

Tomany [1981], concluded that the Dix and Lavan method was best for measuring the effectiveness of movable insulations in both summer and winter conditions and constructed a similar facility, however with improved measurement techniques and controls. Figure 11 shows a schematic drawing of the facility described by Tomany. An energy balance on the room chamber, which is maintained at constant temperature by means of the air circulation system, is performed by measuring circulating system air flow rate and temperature change, and by measuring heat loss through the walls, floor and ceiling with a differential thermopile. The heat loss through the window/movable insulation is the difference between the energy supplied by the air system and the heat loss through the room surfaces.

4.4.3 Hot Boxes

The previously described hot box method for laboratory testing of windows have also been applied for measuring thermal effectiveness of movable insulation. The primary advantage of the hot box method over all other methods discussed is the ability to accurately control the thermal environment on each side of the test specimen. This suggests that testing of a movable insulation and fenestration system in each of its operating modes by a single testing laboratory should be the most accurate test method available.

Miller and Carey [1982] describe the hot box testing performed on two types of insulating shutters installed on the interior of a double glazed window and on a sliding glass door. Their test facility can operate in either the guarded mode [ASTM C236] or the calibrated mode [ASTM C976], to accomodate different test sample sizes. In the guarded mode that was used for testing the double-glazed window and wall combination, the percent reduction in heat flow for the two types of shutters varied from 38 to 47 percent. In the calibrated mode that was used for testing the double-glazed sliding door, the percent reduction in heat flow for the sliding type shutter tested was 70 percent. Unfortunately, in testing the window in the guarded mode the guard box covered a substantial portion of the mask wall, therefore, the effectiveness of the movable insulation and window could not be compared to the test results for the sliding glass door system.

The Thermal Insulation Laboratory of the Technical University of Denmark reported on the design and thermal performance testing of insulating window shutters proposed for use in new low energy housing and in retrofit housing [Byberg et al., 1983]. The test facility consisted of a guarded hot box shown in Figure 12 with specially constructed 0.35 m (13.8 in) thick mask wall representative of construction in new buildings. The wall has an opening in which a double glazed window and the test shutters are located. Small fans in the cold box and metering box circulate air parallel to the window and shutter surfaces, respectively, with flow velocities that result in free convection surface coefficients. The test results with and without the insulating shutters in place were used to estimate annual energy savings in typical Danish residential buildings. The significance of this report is that it adequately describes the test specimen and test facility and provides an excellent model by which the development, testing and marketing of movable insulation products could follow.

Because of the differences in the various hot box methods used for testing windows, NBS participated in a testing program to compare U-values of movable insulations and windows using alternative test methods [McCabe et al., 1986]. Four representative components, including a multiple-glazed window and three single-glazed windows with movable insulation systems, were purchased and tested at two commercial testing laboratories, using the ASTM C236 and the AAMA procedures for a range of simulated outdoor conditions.

A number of conclusions from this study were presented. At the zero wind speed test condition, the two laboratories using different apparatus and test methods but testing the same component, provided U-value measurements that compared favorably. Agreement was closest (within 10%) when the test component was either non-operable (i.e., fixed glazing) or tightly-sealed, with somewhat less favorable agreement (between 10% and 16%) for operable components that do not seal consistently. At simulated wind conditions of 6.7 m/s (15 mph), there were no favorable comparisons between the test results with different simulated wind directions. These test results also suggested that the U-value measured at one test condition should not be adjusted to different wind conditions. The significant increase in U-value experienced in both test laboratories at the higher wind conditions for two test components suggested the possibility of additional heat transfer due to leakage of cold air into the warm box.

Other conclusions in that report were that component manufacturer's thermal performance claims, even when based on test data, differed significantly from the test results. Estimates of energy savings based on comparing product performance data for one set of conditions with single-glazing performance at the 6.7 m/s (15 mph) winter conditions could be very misleading. Significant variations in U-value were observed for the two components tested with variable wind speed and ambient temperature conditions. These variations, which could not always be explained by heat transfer theory, might be the result of subtleties in testing, such as what might be caused by reversing the test specimen in the hot box during simulated summer conditions.

In Section 6 of this report, several of the recommendations made in the NBS study are presented.

4.5 PROBLEMS USING HEAT FLUX TRANSDUCERS

As previously mentioned, Heat Flux Transducers (HFTs) have been used in a number of different testing applications with varying degrees of success. This section discusses some of the concerns for their use in testing movable insulation.

A HFT is typically a thin wafer of material with a known, stable thermal resistance. The temperature difference across the wafer is measured with a series arrangement of thermocouple junctions across the wafer in a thermopile arrangement. The thermopile multiplies the small electrical signal produced by each pair of thermocouple junctions to give the average heat flux across the wafer. The device can be affixed to a wall and connected to an appropriate readout device to measure the heat flow.

The use of a HFT in testing movable insulation systems is complicated by several factors. First by adding a heat flux transducer to a relatively thin and low thermal resistance surface such as a glass window pane, the local thermal resistance and heat flux is changed relative to an undisturbed glass surface and the measured heat flux is not representative. Second, the local changes in thermal resistance result in multi-dimensional heat flow paths, therefore, the heat flux sensor design and calibration, which is based on the principal of one-dimensional heat flow, is violated. Third, the local convection heat transfer coefficient at the sensor are affected by the discontinuity resulting from attaching the sensor to a large flat vertical surface. These considerations result in errors in measured heat flux, which can probably be corrected by proper calibration techniques and by very careful evaluation of the particular application, otherwise errors of 100% are possible [Courville et al., 1983].

Another area of concern in use of commercial HFT's has been the inaccuracy in calibration data provided by the sensor manufacturer. Researchers at the Massachusetts Insitute of Technology (MIT) report on large percent differences (as much as 50%) between one particular manufacturer's calibration data and calibration performed in a special, high accuracy, MIT facility [Bligh and Apthorp 1983]. One of the reasons proposed for these discrepancies is that the manufacturers calibrations are conducted at flux levels that were two orders of magnitude greater than that of the proposed application. Moreover, individual HFTs designed to the same specifications had calibration factors that varied by 100%. It was concluded that all commercial HFTs "should be recalibrated for the flux level at which they will be used, because the manufacturer's quoted values may be effectively useless."

4.6 TESTING STANDARDS FOR MOVABLE INSULATION SYSTEMS

In spite of the fact that consensus standards were not available for windows and there was no technical basis on which to develop a standard for movable insulation, several standards were prepared to address the thermal performance requirements of movable insulation.

4.6.1 Canada Housing and Mortgage Standard

A standard for movable insulation devices was prepared by the Canada Mortgage and Housing Corporation [1979] for the administration of a grant program for existing residential buildings and for a finance program for new construction in Canada. The standard applied to insulating shutters and blinds located on the interior or exterior of glazing or to any insulating devices inserted between glazings, however the standard specifically excluded storm windows. Although absolute values of thermal performance were not specified, the added R-value relative to a reference window of the movable insulation was required to be at least 0.35 $m^2 \cdot K/W$ (1.99 $ft^2 \cdot hr \cdot F/Btu$). The Standard prescribed the reference window size and type, test chamber size, test temperatures, and an exterior surface coefficient of 22.7 $W/m^2 \cdot K$ (4.0 Btu/hr•ft•F) and required the use of an ASTM C236 guarded hot box apparatus.

4.6.2 Window Energy Systems Standard 1584

In 1984, the Window Energy Systems (WES) Division of the International Fabrics Association adopted a test method for measuring U-value of movable insulations and insulating window treatments [Window Energy Systems, 1984]. The membership of the Window Energy Systems Division includes manufacturers, distributors, suppliers, dealers and retailers of window treatment products, including awnings, blinds, draperies, films, interior shutters, screens and shades. The WES Standard was patterned essentially after the AAMA Standard 1503 [AAMA, 1980] with several modifications introduced to address the specific issues relative to testing of these products. These include provision for maintaining the warm chamber air at relative humidity levels less than 30%, the requirement for a base window unit consisting of a single layer of glass mounted in a insulated wooden test buck with bottom extension panel to simulate a carpeted floor, and the format for presenting test results. In addition, detailed installation specifications, mounting procedures and clearance dimensions were provided to suit specific types of insulating treatments and movable insulations. Although a "round robin" comparison test of the several movable insulation systems has been mentioned in WES correspondence, the results of this comparison have not been made public.

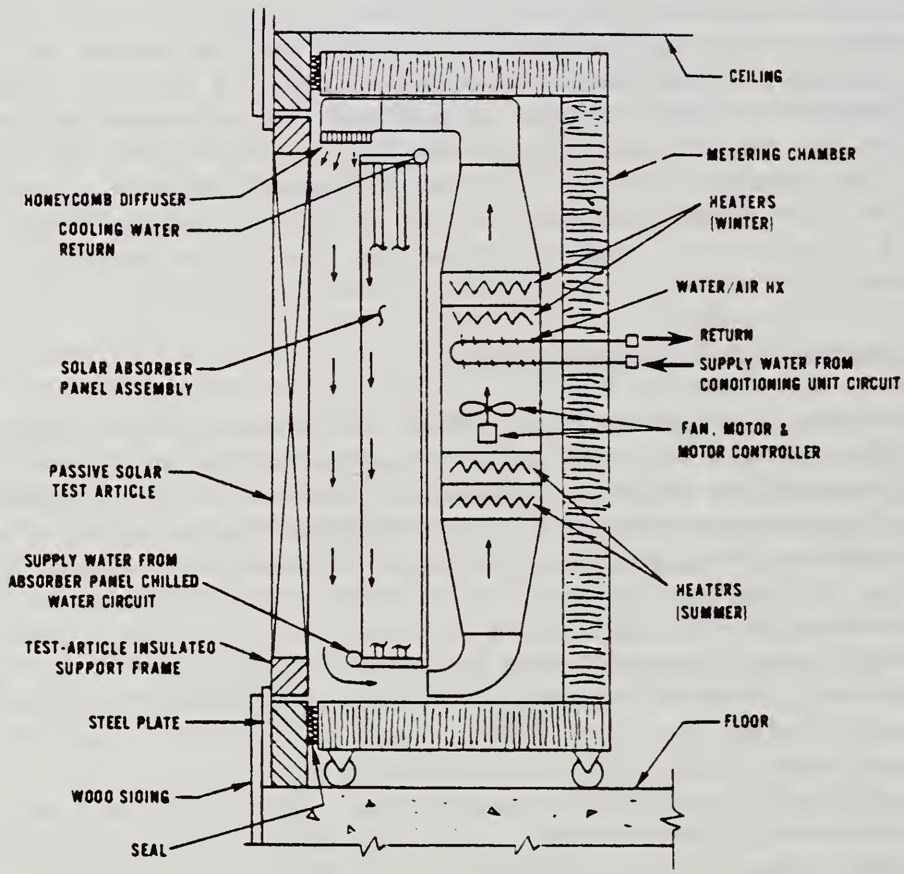

Figure 7. NBS Passive Solar Calorimeter

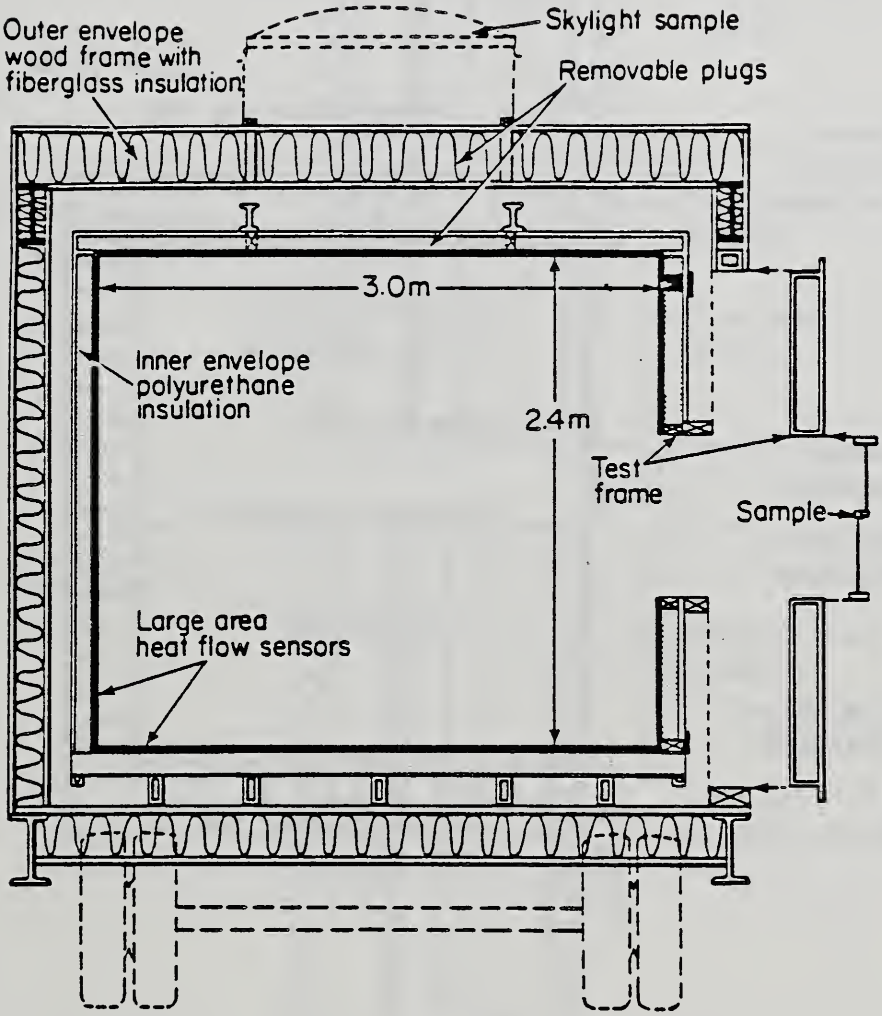

Figure 8. LBL MoWITT Calorimeter

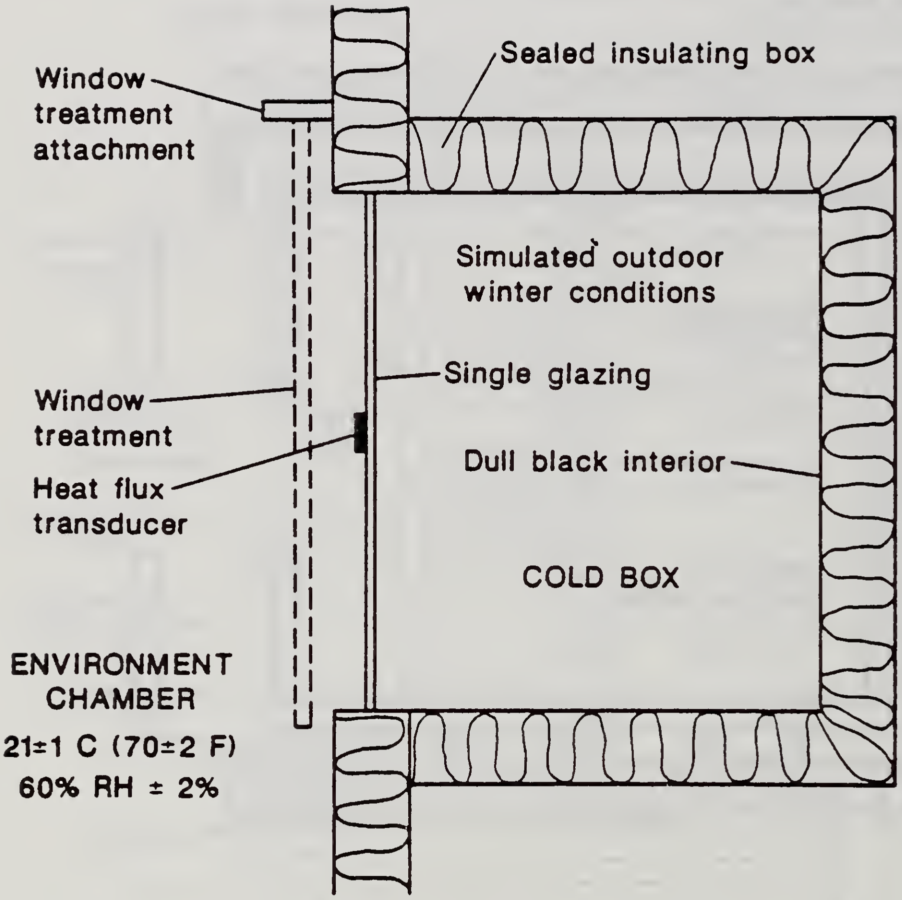

Figure 9. Window Treatment Test Facilty
Using a Heat Flux Transducer

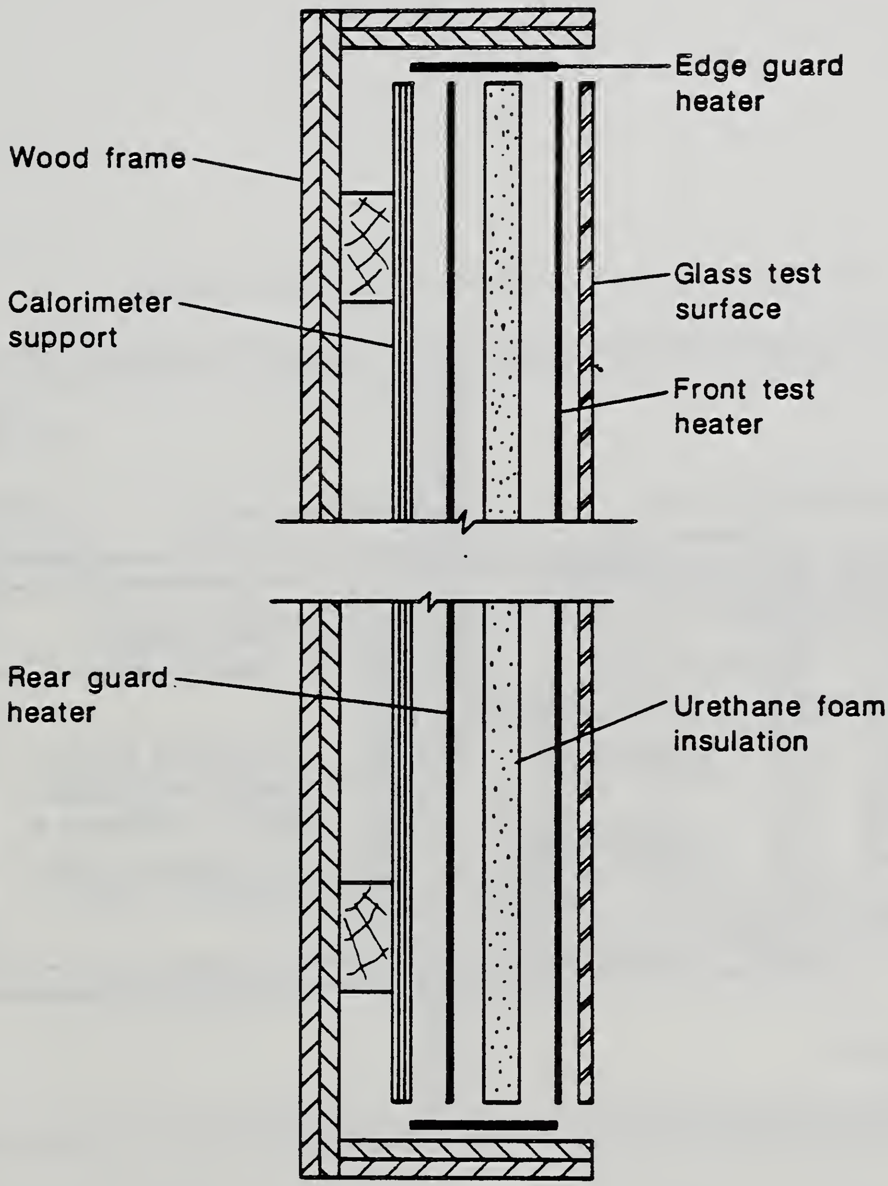

Figure 10. Window Treatment Test Facility Using a Guarded Hot Plate

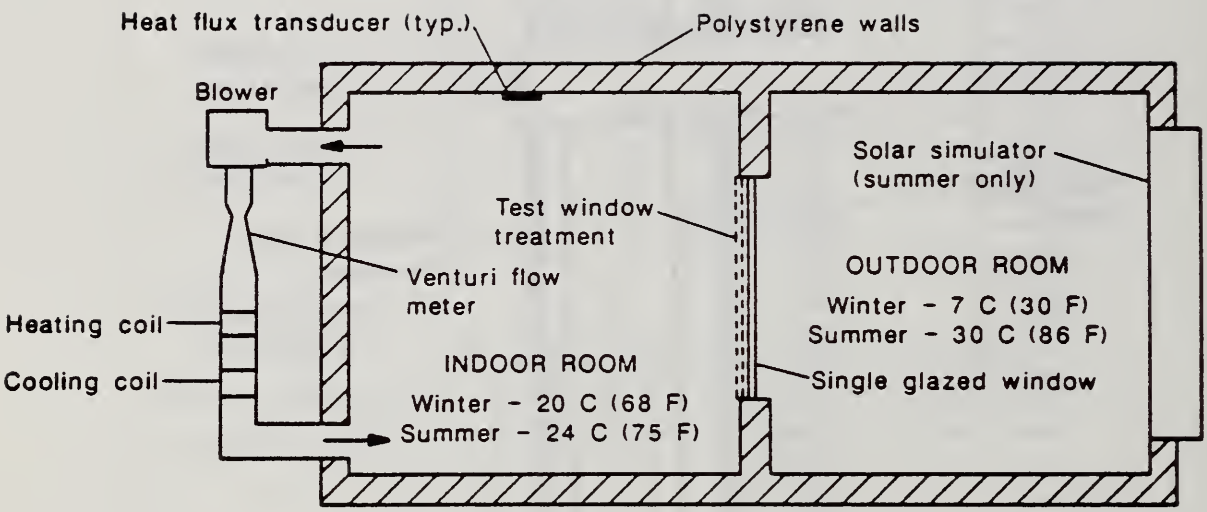

Figure 11. Window Treat Test Facility
Using Laboratory Rooms

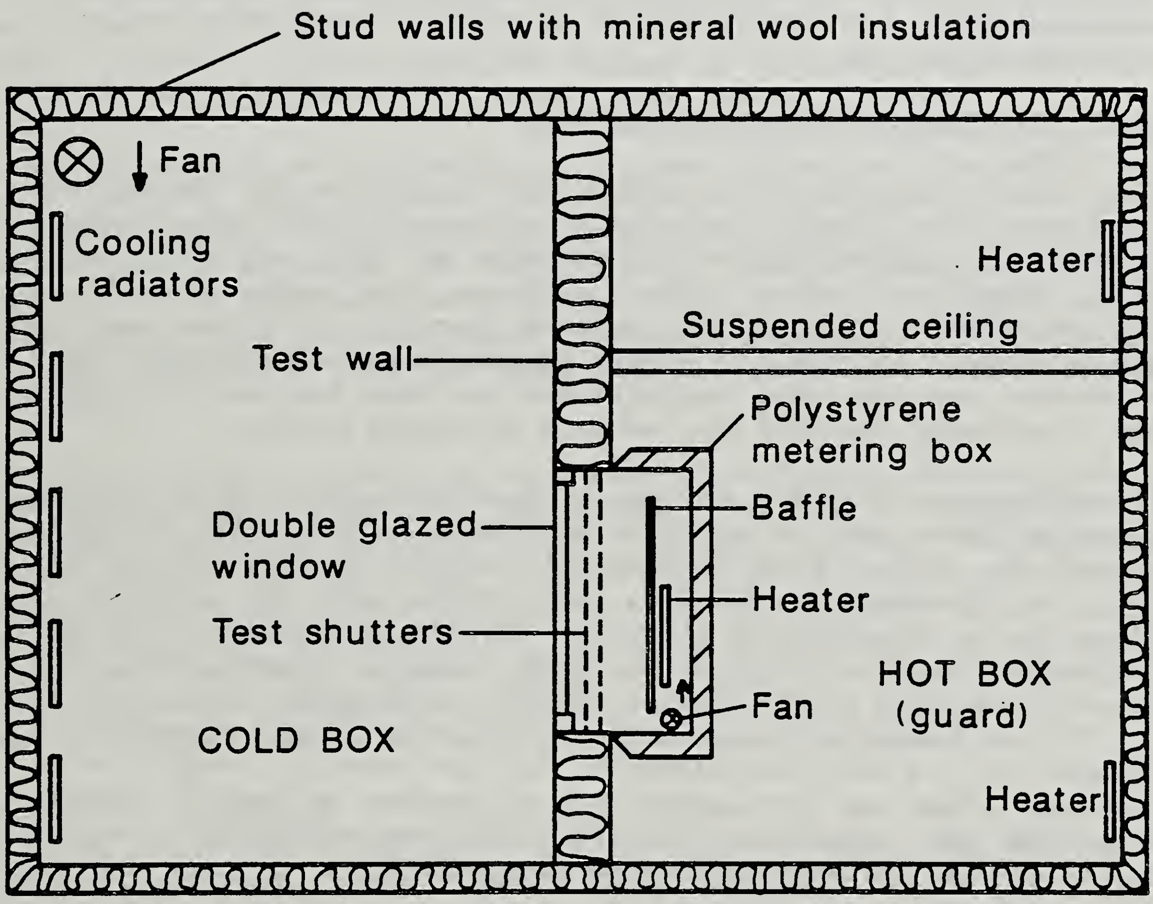

Figure 12. Guarded Hot Box at Technical University of Denmark

5. TEST STANDARDS UNDER DEVELOPMENT

Although both the ASTM C236 and C976 test standards and AAMA Standard 1503 have been used extensively for thermal testing of window systems, considerable controversy exists with regard to which test method is the most appropriate for that purpose. As described in 4.4.3, significant differences in test results were obtained in applying the ASTM C236 and the AAMA 1503 test method to a limited number of windows. Furthermore, it was apparant that both the ASTM and AAMA test methods had weaknesses that tend to reduce confidence in the accuracy and repeatability of these methods when applied to window systems. In this section a number of potential weaknesses in the current ASTM and AAMA test methods are outlined. These weaknesses provide the rationale for changes to be addressed in the new uniform test standard for window and door systems which is currently under developmnet by an ASTM standards group. A working draft of the new standard practice is included in Appendix B.

5.1 RATIONALE FOR CHANGES TO ASTM TEST METHODS

The ASTM C236 Guarded Hot Box and the ASTM C976 Calibrated Hot Box methods were not developed specifically for window systems but for more general building construction assemblies, building panels and other applications of nonhomogeneous assemblies such as walls, ceilings, and roofs, as well as homogeneous assemblies of materials such as thermal insulation used in building applications. In general, window systems have intrinsically lower thermal resistance than the other applications and this has led to certain difficulties in applying the ASTM test methods to window system.

The thermal performance of window systems is much more sensitive to surface heat transfer effects and to possible air leakage than other building components, and the current ASTM test methods do not specifically address these needs. As discussed in 3.1.4.3, air motion over the surfaces of window systems has a considerable affect on thermal performance, however, characterization of the flow field in the ASTM standards is ambiguous, with parallel forced convection on the outside of the test specimen being left as an option. It was concluded in section 3.1.4.5 that simply directing an airflow stream in a direction parallel to the exterior surface at a specified average speed was not sufficient to produce a desired average convective surface heat transfer coefficient, but some additional means of determining the average surface coefficient is required.

The ASTM test chambers are usually configured with baffles parallel to the specimen surfaces, to confine the airflow to a uniform channel. However, with the low velocities usually applied to the interior side of the test windows, non-uniform surface temperatures often occur in the baffle in the proximity of a low resistance window or glazing unit due to radiative heat transfer. Non-uniform surface temperatures appear to be a particular problem in thermal testing of windows because of the prevalence of these baffles in ASTM test chambers.

Although calibration of the ASTM test chambers is a significant issue that is addressed at great length particularly in ASTM Standard C976, the calibration requirements for testing of window systems is not specifically addressed. Furthermore, since the vast majority of window systems have not been tested in ASTM hot boxes, there is a lack of operating experience in this application and the need for a round-robin to establish repeatability.

5.2 RATIONALE FOR CHANGES TO THE AAMA TEST METHOD

In contrast to the ASTM test methods, AAMA Standard 1503 was specifically developed for thermal testing of window systems. However, one of the criticisms directed at AAMA has been due to the lack of publication of technical papers by AAMA in referred journals and at national conferences sponsored by the technical societies. It is believed that more active participation in technical society activities, involving open discussion of test methods and participation in round robins and interlaboratory comparisons will lead to increased confidence in the AAMA method. The primary considerations for possible changes to the AAMA test method are due to calibration, air leakage and temperature sensor placement.

The method used by AAMA to adjust air speed to achieve the ASHRAE winter-design surface heat transfer coefficient was described in 3.1.3. The double-glazed panel used in that procedure, in effect, is the calibration specimen used to determine the overall heat transfer characteristics of the facility. It is believed that a better characterized test panel and better defined calibration procedure would increase the accuracy of testing in AAMA hot boxes, especially with the newer, higher resistance window systems on the market.

Air leakage has been thought to be a greater problem in AAMA hot boxes than in ASTM hot boxes because of the dynamic pressure of perpendicular wind impacting the exterior surfaces of test windows. Although the AAMA standard requires static pressurization of the warm side to counteract the dynamic pressurization of the cold side, quantitative measurements of air leakage in AAMA hot boxes are not available. It is believed that sealing techniques are available to reduce window leakage to negligible values, however until comprehensive air leakage measurements are made, air leakage will remain a potential source of error and uncertainty in the AAMA method.

Although the placement of temperature sensors in hot boxes and on test specimens is often a matter of operator preference, the AAMA standard appears to require fewer sensors than the ASTM stndards, especially regarding air temperature sensors. It would appear that with uniform minimum standards for placement of sensors, the accuracy and installation requirements could be developed with little difficulty or controversy.

5.3 NEW ASTM TEST STANDARDS FOR WINDOWS

A joint ASTM task group, comprised of the members of Subcommittees C-16.30 and E6.51 was formed in 1984 to develop a new standard for measuring the thermal transmittance of window systems, using a hot box method. Since two hot box test methods for measuring U-value and C-value of building assemblies; ASTM C236 - Guarded Hot Box, and ASTM C976 - Calibrated Hot Box, were already in existance, it was evident that these standards would form the basis of a new standard which would address the unique features of window systems, however, giving due consideration to integration of significant features of the AAMA Standard.

The efforts of this task group have resulted in three documents:

1) Recommended modifications to ASTM C236-80,
2) Recommended modifications to ASTM C976-82, and
3) Draft standard practice for determining the thermal performance of window and door systems.

The intention of the task group is to have a uniform test method, which permits test facilities having either parallel or a perpendicular wind simulation, to conform to the requirements of an ASTM standard. It is also anticipated that the ASTM window test standard will conform to the ISO standard for windows, when both standards are completed.

The current status of the ASTM standards is that the task group is currently preparing working draft 4, however, balloting within either of the C16.30 or E6.51 subcommittees has not yet occurred. In its present state, only minor revisions to ASTM C236 and ASTM C976 have been recommended. These revision primarily address sections of the standards that either specifically prohibit perpendicular wind or fail to mention it, when discussing air flow direction.

The major accomplishment of the task group is the development of a new standard practice. Appendix B presents the third working draft of this document. It should be noted that the draft status of these documents implies that significant revisions or restructuring is quite possible. The purpose of presenting this information is to provide some benchmarks in the current format and content of the draft standards. It is also apparant that a significant effort remains to develop a technical data base of experience and test results, before the final standard can be made available for ballot. The next chapter outlines a research program that is aimed at development of this data base.

6. RESEARCH PROGRAM FOR DEVELOPING WINDOW TEST STANDARDS

The authors have prepared an outline for a two-phase research program to address the needs of the ASTM standards activities described in Section 5 [Goss and McCabe, 1985]. This program addresses specific measurements deemed necessary to accelerate the development and acceptance of the ASTM test standards for window systems.

6.1 PHASE 1 RESEARCH

The first phase of the program is jointly sponsored by NBS and DOE and 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). The first phase focuses on measuring the U-values of insulated glass units (IGUs) for a range of environmental conditions. The following sections present some primary features of Phase 1 research.

6.1.1 Test Facility Description

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

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

6.1.2 Heat Flux Transducer

A 1016 x 1016 mm (40 x 40 in) heat flux transducer (HFT) used for the Phase I research program is identical in design to the HFT used by NRC/Canada. It consists of a 13 mm (1/2 in) 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.

6.1.3 Temperature Measurements

Small diameter (30-gauge) calibrated thermcouples are used to measure the IGU surface temperatures and the air temperature near the IGU surfaces. In addition, the RCHB baffle wall temperatures are 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.

6.1.4 Test Specimens

During the Phase 1 program, testing will be performed on the following 1016 x 1016 mm (40 x 40 in) test specimens:

1. Standard, double glazed unit:
   6 mm (1/4 in) glass - 13 mm (1/2 in) airspace - 6 mm (1/4 in) uncoated glass,

2. Low emittance, double glazed unit:
   6 mm (1/4 in) glass - 13 mm (1/2 in) airspace - 6 mm (1/4 in) glass with low emittance coating on inner surface,

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

6.1.5 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 C (F)

winter:	-8/20 (18/68)
summer:	35/20 (97/75)
fall/spring:	3/20 (38/68)

2. Wind speeds m/s (mph)

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

3. Wind direction
   parallel
   perpendicular

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

6.2 PHASE 2 RESEARCH

Specific details for the Phase 2 research program will obviously depend on the outcome of the Phase 1 research, currently underway. Results of this research will be 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. A broad-based testing and analysis program is envisioned for Phase 2, including continuation of the Research Calibrated Hot Box (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.

In addition to measurement of window U-value in a 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 should be performed in a wind tunnel for several window/building configurations to determine the distribution of surface heat transfer coefficients with depth of reveal, wind speed and wind direction. Flow visualization techniques and methods of measuring convective heat transfer coefficients are available for small scale wind tunnel experiments; however, they need to be modified for full scale window geometry and typical wind speeds used in hot box testing.

6.2.1 Research Laboratory Testing and Analysis

The Insulating Glass Units (IGU) tested in the RCHB facility in Phase 1 will be further tested in order to enlarge the technical data based from which the thermal performance standards will be develped. In Phase 2, several of the standard-size, IGU will be fabricated into windows by adding sash and frame members comprised of wood, aluminum and PVC plastic materials. These windows will be tested in the RCHB according to the draft standard practice described in Appendix B. Heat transfer models will also be prepared for each window and computer predictions made of window thermal performance. The computer model predictions and the test results of each individual IGU, and IGU sash combination 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 effects both of test specimen size and of slope angle (deviation from vertical) on U-value will also be determined. Several IGU of the same generic configuration as the standard types tested in Phase 1, except for differing size will be tested. The specimens will have nominal dimensions of 610 by 610 mm (24 x 24 in) and 1219 by 2032 mm (48 by 80 in), corresponding to a smaller window and a larger patio door, respectively. This testing will include window specimens, with and without an edge frame, to establish sizing effects of the individual IGU and the IGU plus frame on U-value. In addition, several standard IGU from Phase 1 will be tested at various orientation angles between vertical and horizontal, with heat flow in both the up and down direction. Determination of size and slope adjustment factors are essential to establishing whether testing is required for each unique window size, and whether non-vertical glazing systems, such as these used in atria and sunspace applications, require special testing.

6.2.2 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 comparability between differing test facilities. Previous research [McCabe et al., 1986] indicated that substantial discrepancy in measured U-values for windows exists between different laboratory test methods. This discrepancy was attributed to the different methods of simulating wind and was 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 to an acceptable level 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 test specimens from Phase 1. At least two testing laboratories for each type of hot box testing facilities should participate; including facilities designed according to the ASTM C234, ASTM C976, and the AAMA test methods.

6.2.3 Field Testing

Several field testing facilities have been constructed, each having different capabilities to measure the thermal performance of full-sized building fenestration systems such as windows and doors under carefully controlled indoor conditions with prevailing outdoor conditions of air temperature, wind velocity and solar radiation. This method of testing produces more realistic performance data than possible using simulated 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 reduce data scatter and the length of the testing season is limited by local climatic conditions. Extrapolation of the test results to other times of year, weather patterns or to other climatic regions is required.

The IGU test specimens from Phase 1 will be installed in the participating outdoor testing laboratories and tested during both the winter-time and the 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 and flow and radiant heat flux measurements will be required, which may require new sensors and measuring techniques.

7.0 CONCLUSIONS AND RECOMMENDATIONS

This report reviewed the current status of thermal performance testing for window systems in the United States. Since there are a number of alternative objectives for thermal testing, a variety of testing apparatus, test specimens and test conditions have evolved. Laboratory testing of windows, skylights and glass doors has traditionally been performed using one of the three hot box methods described in Section 3.1. Section 4 discusses many of the test methods used for movable insulations. Industry estimates conclude that more than 90% of the testing of windows, skylights and doors are performed according to AAMA Standard 1503. Although no estimates are available for the movable insulation test methods, WES 1584, the standard adopted by the fabrics industry of window treatments, is also based on the AAMA standard.

The primary concern over the current status of window systems testing based on the AAMA test method is that the AAMA method has never been given national recognition by ASTM or ANSI. As discussed in Section 5, current efforts within ASTM are to modify both ASTM C236 and C976 to include provisions for measuring window thermal transmittance and also to develop a new standard practice for testing of window systems. Since the development of any new standard within ASTM requires extensive review by a host of different groups, and the technical basis for the standard requires extensive testing by users as described in Section 6, it is apparent that a national standard for window systems thermal performance will require substantial effort and thus, will not be available for possibly several years.

To assist BPA in administration of energy conservation standards related to window systems in residential buildings, NBS recommendations for an interim test method are as follows:

1. Thermal transmittance measurements of window systems should be performed under simulated winter time conditions using either of the guarded hot box, calibrated hot box or laboratory room test methods previously described. Either of ASTM C236, C976 or AAMA Standard 1503 are acceptable for windows, doors or skylights. WES 1584 is acceptable for movable insulations. A non-standard laboratory room technique is acceptable provided the following conditions are followed:

   a) Heat flow measurement is performed using an electrical energy transducer with a certified accuracy of 2% at the anticipated heat flux levels.

   b) The warm room heat balance should be determined by using a calibration panel in place of the test specimen. The calibration panel should be constructed from a homogeneous material of known thermal conductivity and the mean temperature difference between the warm and cold surfaces measured to an accuracy of 0.1 C (0.2 F), using a multiple-junction thermopile or other type of differential temperature measuring apparatus of similar accuracy. The use of commercial heat flux sensors, liquid-in-glass thermometers or other non-electrical means of measuring power dissipation and test specimen heat flux is not acceptable for measurement of heat transfer through the test specimen. The use of heat flux sensors or differential temperature sensors is permissible in measuring heat loss through other surfaces of the metered room, provided the aggregate heat loss through these surfaces does not exceed 20% of the measured heat loss through the test specimen.

2. Simulated winter conditions should be 20 ± 1 C (68 ± 2 F) interior, -8 ± 1 C (18 ± 2 F) exterior, with either 6.7 m/s (15 mph) simulated wind in any direction or at essentially still air conditions. Experimental U-values (air-to-air thermal transmittance), C-values (surface-to-surface thermal conductance), and the inside and outside surface heat transfer coefficient should be provided in window thermal performance test reports. Measurements with free convection conditions on the environmental (cold) side shall also provide a corrected U-value that is calculated by adding the inside surface heat transfer coefficient and the ASHRAE Fundamentals Handbook 6.7 m/s (15 mph) outside surface heat transfer coefficient value of 34.1 $W./m^2 \cdot K$ (6.0 $Btu/h.ft^2 \cdot f$) to the experimental C-value. (Note: use equation 6 to do this calculation).

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SEALED GLAZING UNITS: THERMAL INSULATION AND SURFACE TEMPERATURE NBI-138, 1982

1. Orientation

The method concerns the measurement of the thermal resistance and surface temperature of sealed glazing units. The measurement is done in a hot box.

The method is a functional testing of sealed glazing units. The thermal insulation is measured in the entire clearance of the pane in a way that takes into account the cold bridges at the sealing edges. The surface temperature is measured so that the qualities of the pane with respect to formation of condensation can be specified.

The method fulfills the requirement for measurement of thermal insulation in the building codes.

2. Area of Application

The method is used for all types of sealed glazing units. The dimension of the pane should preferably be 1120 mm x 1120 mm.

3. References

Norwegian Standard, NS 3161 - Thermal Insulation. Determination of Thermal Resistance by Means of a Hot Box.

NS 3031 - Calculation of Energy and Power Required to Heat a Building.

NS 8040 - Thermal Insulation. Determination of Thermal Resistance or Thermal Conductivity of Material with Heat Flux Sensors.

Building Codes, with emendations as of 4 November 1980, chapter 54:4 - thermal insulation and tightness.

Directions to the Building Codes, Chapter 54.

4. Definitions

NS 3161

5. Sampling

The usual glass pane size is 1120 mm x 1120 mm. Two identical panes are supplied. The NBI chooses one specimen for the testing.

6. Testing

The thermal insulation is measured in the entire clearance of the pane, so that cold bridges at the sealing edges are taken into account. Installation in a frame ensures that the temperature and the heat transfer conditions along the outer edges of the pane remain such as in ordinary use.

6.1. Methodology

The measurement is taken as per NS 3161 at stationary heat flux and temperature conditions. The coefficient of thermal transmission (k value) applies to the entire clearance of the glass pane.

The measurement is taken with the pane installed in a solid wood frame. The frame has a groove for the glass as per building part sheet A533.133/134, but without the bottom drained rabbet. (The influence of the drained bottom rabbet is assumed to be included in the frame/molding product in which the pane is installed.)

The frame is calibrated as a part of the boundary zone (separation wall) between the warm and cold room in the heat box layout.

6.2. Equipment

NS 3161 describes the heat box.

In the measurement of sealed glazing units, both the measurement chamber and the cold room are provided with radiative screens (internal partition). The screen is designed so that the surface maintains the same temperature as the air.

The heat transfer conditions at the cold side are established by means of fan-circulated air. At the warm side, natural convection prevails.

Appendix 1 shows the placement of the air temperature sensors.

6.3. Preparation of Samples

The pane is cleaned at the outer surface, but is otherwise measured in the as-delivered state.

Equalization of pressure of the sealed glazing unit is done only if specified. Pressure equalization is not done for gas-filled glazing units.

Appendix 1 shows the placement of the surface temperature sensors at either side of the pane.

6.4. Procedure

NS 3161 shows how the stationary heat flux and temperature conditions are controlled.

The sealed glazing unit is measured at 30 K temperature difference between the interior and exterior air temperature. The mean air temperature at the warm side is 20°C±2°C, that at the cold side -10°C±2°C.

The measurement interval is 5 hours with a registration period of 30 minutes.

6.5. Results - Reporting

The heat balance during the measurement is reported along with the average and weighted temperatures in the air and at the surface.

The coefficient of thermal transmission (k values) is calculated from the measured thermal resistance in the pane and the standardized heat transfer resistances inside and outside (NS 3031).

The surface temperature along the vertical center line of the pane is indicated, along with the air temperatures.

The normalized surface temperatures are calculated from the measured air temperatures and the heat transfer resistances to reference conditions of 20°C/-10°C air temperature and 0.17 m^2K/W (NS 3031) cumulative heat transfer resistance.

6.6. Accuracy

The accuracy of the method depends on the calibration of the hot box.

The sealed glazing units are measured in a solid frame which is calibrated as part of the boundary zone by means of a laminated, glass-expanded polystyrene glass and a heat flux sensor. This heat flux sensor is calibrated in a sheet apparatus (NS 8040).

The replicability is regularly checked by measuring solid reference panes.

6.7. Test Report

NS 3161 indicates the framework for the measurement reporting. Beyond this, reference is made to the general guidelines in NBI G01/1981.

7. Appendix

Appendix 1 shows the arrangement of temperature sensors on the glass surfaces and in the hot box when measuring sealed glazing units with dimension of 1120 mm x 1120 mm.

The excerpt of the building code and directions of 4 November 1980, Chapter 54:4, indicates the foundation of the NBI testing methods:

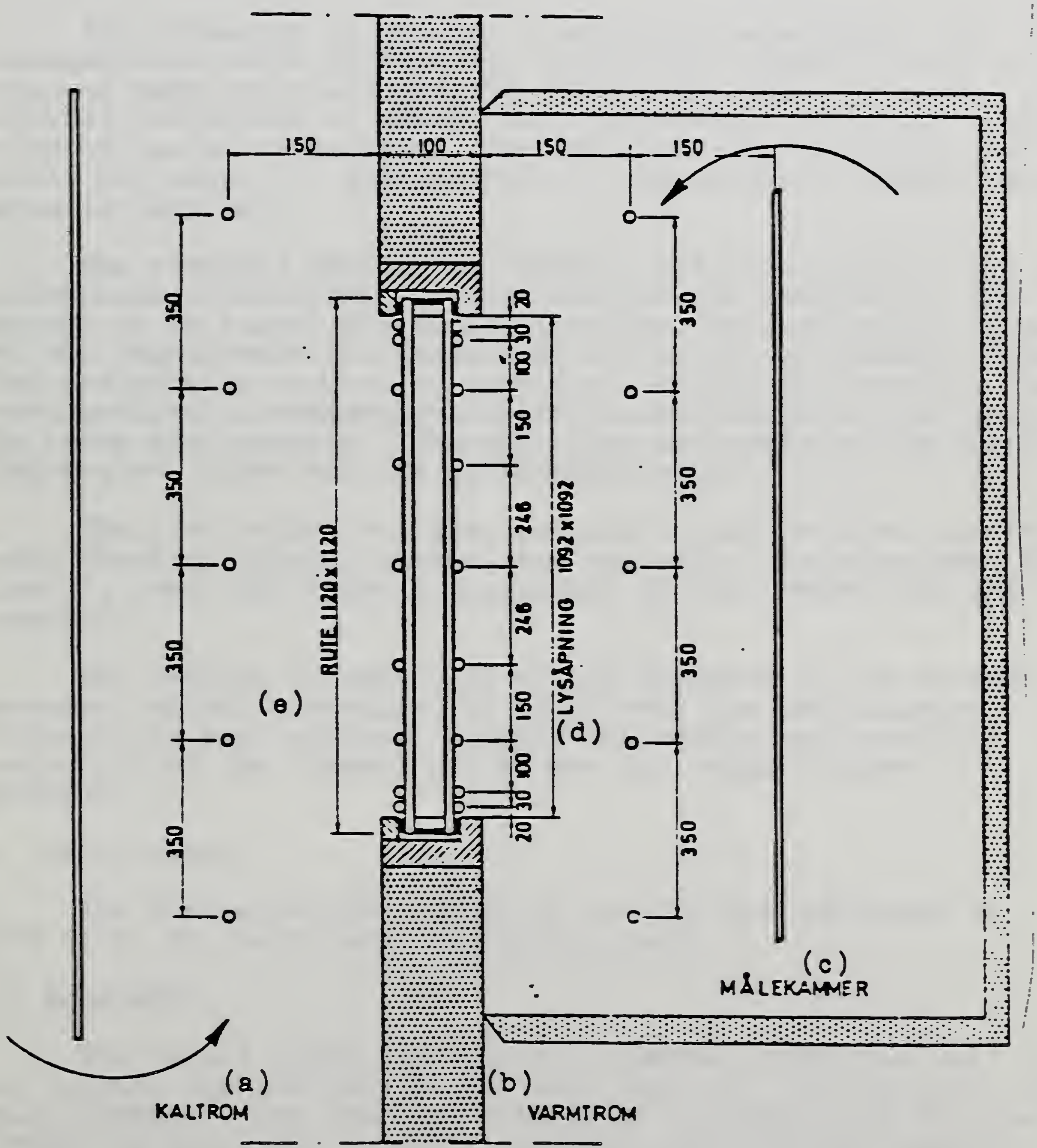
- Indication of the k values can be done by calculation as per NS 3031, second edition, or by measurement after a recognized method. The effects of cold bridges as a result of breakthrough of the insulation in the individual parts of the building are to be factored in.

- For other structures, e.g., sealed glazing units with insulating gas in the middle space or with reflecting coating, the k values must be specified, or both the night k-values and the equivalent k-values.

NBI-138/1982

The Hot Box

Placement of temperature sensors at the glass surfaces and in the measurement chamber and cold room in the hot box. All temperatures measured along the vertical center line of the glass pane.



Key: a - cold room; b - warm room; c - measurement chamber; d - clearance; e - glass pane.
Scale: width 1:5, height 1:10

Swedish Standard SS 81 81 29
Compiled by the Construction Standardization Administration (BST)

WINDOWS - THERMAL RESISTANCE TEST

1. Orientation

This standard reports on a method of determining the thermal resistance of windows, taking into account the heat loss through both the glass and the frame and molding. If the thermal resistance is known, the coefficient of thermal transmission can be calculated. Ongoing developments within this field may result in modification of the standard as more experience is acquired.

The standard applies to windows (and glass-paned doors), regardless of material, in the ready-to-use condition. The window to be tested should be air-tight, corresponding at least to the requirement for class B in SIS 81 81 03, Windows, Categorization with respect to function. During the testing, the manufacturer's recommendations for installation and use should be taken into account. The test does not apply to the joints between the frame and the surrounding wall.

The test method can also be used to test windows provided with Venetian blinds, shades, and the like. In this case, the test is done with these arrangements in the lowered and shut position.

The testing is done with an air movement in the outside chamber, which is required to carry away the heat passing through the test window. A rapid air motion may result in worsening of the thermal resistance for certain types of windows.

2. Definitions

The thermotechnical terms to be used are explained in SIS 01 61 50, Magnitudes and units, Heat.

3. Equipment

Two joined rooms, divided by a thermal insulated wall with an opening for the test window (cf. Fig. 2). In one room (inside chamber), the interior climate of a house is to be simulated; in the other (outside chamber), the climate outdoors.

An arrangement that can maintain temperatures of +20±1°C in the inside chamber and -10±1°C in the outside chamber.

A measurement box as per Fig. 2 with one side open and the other five sides made of thermal insulated material. The width and height of the box should at least correspond to the width and height of the test window. The depth of the box shall be 0.6 m. In the lower part of the box there will be a heat source, the power of which can be measured and regulated so that the heat flux and the temperature difference between the box and the warm chamber remains zero or close to zero. The box shall contain a screen, preventing radiation from the heat source against the test window, but promoting convection in the box.

An instrument that can measure the power supplied to the measurement box.

An instrument that can measure the air temperature in the measurement box at three points, situated at 100 mm from the window and between the side walls, with one point at the half-height of the box and the other two points 200 mm from the bottom and top, respectively.

An instrument that can measure the air temperature in the cold chamber at three points, situated 100 mm from the window and opposite the points in the measurement box.

An instrument that can measure the surface temperature of the window at the outside and inside.

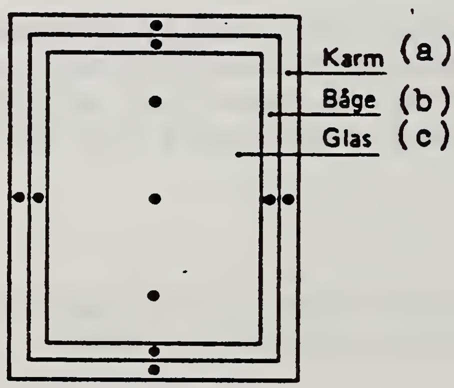


Fig. 1. Measurement points (a dark circle) on the inside and outside of the test window. Key: a - frame; b - molding; c - glass.

4. Preparations for the Test

The test window is installed in the opening between the frames with the inside against the inside chamber. The joints between the wall and the frame are made tight and insulated, so that leakage of air and heat can be disregarded in the test.

The window is to be clean and dry.

The thickness of glass, the distance from the glass, the type of glass and the installation will correspond to the recommendations of the manufacturer. In default of such, or if the window is to be used with different glass, the test should be done with the minimum allowable thickness of glass in relation to the glass area.

The sensors of the instrument measuring the surface temperature of the window are mounted on the outside and inside of the window (cf. Fig. 1). The sensors are mounted on the surface of the glass, molding and frame. Three are mounted on the glass: one at the center of the glass and the others at a distance of 1/6 of the height of the glass from the upper and lower pieces, respectively. One sensor is mounted on the frame and molding in the middle of the top, bottom and side pieces. If these points are unsuitable on account of the location of fixtures, or if it is suspected that they produce measured values which are not representative, other measurement points in the same vicinity can be used.

The measurement box is arranged centrally outside the window in the warm chamber (cf. Fig. 2). The joint between the measurement box and the wall is sealed, so that possible leakage during the test can be disregarded.

The measurement box should be checked against a wall with known thermal resistance.

5. Procedure

The window is exposed to a difference in air temperature between the outside and the inside.

The temperature in the inside chamber and in the measurement box shall be 20-25°C, maintained within ±1°C during the test. The temperature of the outside chamber shall be 30±1°C lower than that of the inside chamber.

Measurement of the power supplied to the measurement box is done when the heat flux between the measurement box and the inside chamber is constant or nearly constant.

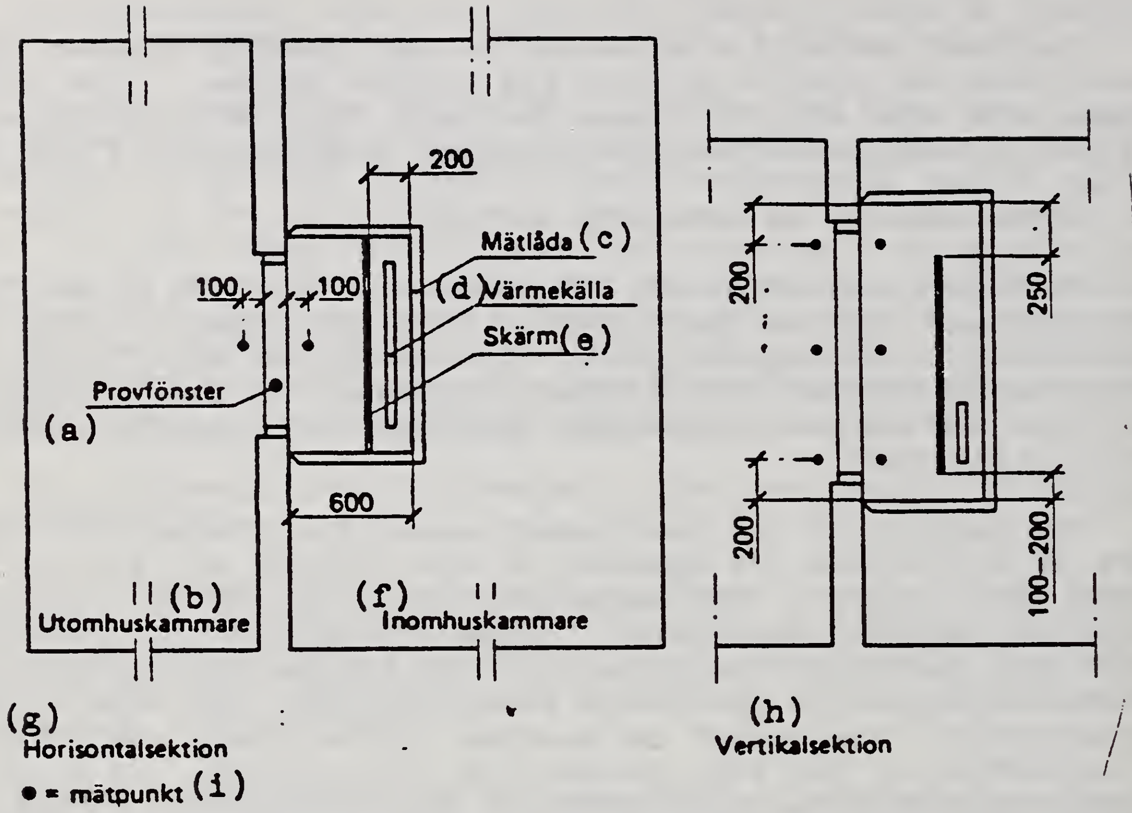


Fig. 2. Measurement box. Key: a - test window; b - outside chamber; c - measurement box; d - heat source; e - screen; f - inside chamber; g - horizontal section; h - vertical section; i - measurement point.

6. Result

The thermal resistance of the window is:

$$M = \frac{A \cdot \Delta \vartheta}{\Phi} \ (m^2 \ °C/W)$$

where:

M is the thermal resistance in $m^2 °C/W$;

A is the total area of the test window (outside dimension of the frame) in m^2;

Φ is the total heat flux through the test window in W;

$\Delta\theta$ is the average temperature difference between the outer surface of the window and the inner surface in °C, where

$$\Delta\vartheta = (A_k \cdot \Delta\vartheta_k + A_b \cdot \Delta\vartheta_b + A_g \cdot \Delta\vartheta_g) / A \quad (^\circ C)$$

where:

A_k and A_b is the area in m^2 of the frame or molding, respectively, projected onto a plane parallel with the window, and A_g is the clearance of the molding in m^2.

$\Delta\theta_k$, $\Delta\theta_b$ and $\Delta\theta_g$ are the median values of the temperature differences between the inside and the outside of the frame, molding, and glass, respectively.

The coefficient of thermal transmission of the window is:

$$k = \frac{1}{M + m_i + m_u}$$

where:

k is the coefficient of thermal transmission in $W/m^2{}^\circ C$;

M is the thermal resistance in $m^2{}^\circ C/W$

$m_i + m_u$ are the actual heat transfer resistances as per the applicable norm.

7. Reporting

The test report will contain the following minimum information.

A drawing of the test arrangement

A description (details) of the installation of the window in the test arrangement.

Brief description of the window, containing at least the following information:

- manufacturer
- window type
- material and surface treatment
- total window area (outside dimension of frame)

areas of frame, molding and glass used to compute the thermal resistance

weatherstrip (manufacturer, type, material and profile shape)

glass (number of panes, type, thickness, distance between glass and installation)

types of locks and fixtures

Venetian blinds, shades and so forth (manufacturer, type and material).

A view of the window, indicating the arrangement of the fixtures: hinges, slide bars, pivots, locks, etc., as well as horizontal and vertical sections showing the exact position of the sealing strips.

Median air temperature values at the warm and cold side.

Median surface temperature values of the glass, frame and mounting at the warm and cold side.

Total power supplied to the measurement box, as well as the power passed through the window structure.

Calculated thermal resistance for the window structure, expressed in $m^2 {}^\circ C/W$, with three decimal places, the last rounded off to 0 or 5.

Calculated coefficient of thermal transmission (k value), expressed in $W/m^2 {}^\circ C$ with two decimal places, the last rounded off to 0 or 5.

APPENDIX A-3

Determination of the Coefficient k of Windows
New Standardized Method

J. Uyttenbroeck (*)
P. Wouters (*)

Within the framework of the preparation of the NBN-B62-002 standard "calculation of the thermal transmission coefficient of the walls of buildings (1), a new method was developed to calculate the coefficient k of the windows.

This article gives a review of the most important aspects of the new method. In order not to make this text too difficult to read we refer the reader to the text of the standard in a certain number of exceptional cases.

1. Introduction

In the past there was no very definite method of calculation to determine the coefficient k of windows.

Thus the NBN B62-002 standard draft (2) of December 1983 confined itself to indicating only 2values (windows with single panes $k_1 = 6.4\ W/m^2K$ and windows with double panes $k_1 = 3.8\ W/m^2K$) which, in the absence of measured values, were certainly too pessimistic.

This article presents and explains the new method which will be standardized through the new standard NBN B62-002 (2) without discussing for all that the complete text retained in the standard in all its details.

2. Preliminary Research

2.1 Series of Tests: Coefficient k of the Windows (***)

On the request of the programming services of scientific policy and with the additional help of the technical union of the metal joiners (UTMM) and other industrial sectors, the C.S.T.C. carried out extensive series of measurements and

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(***)The measurements, calculations and analysis of the results were carried out by D. L'Heureux, chief technician, P. Voordecker, technician and P. Wouters, head of the section.

(*) Civil Engineer-Director of Research

(**) Civil Engineer-Head of the Hygrothermy Department calculations on the thermal transmission coefficient of windows.

The main purpose of this investigation was not to gather a large number of k values of the windows, but was to arrive at the detailed analysis of the possibilities of achieving a standardized method to determine the k coefficient.

Right from the start we established the following goals:

-the determination of the value k of the window by calculation should be done with a better position than that of the current method;

-a clear and simple enough method should be achieved;

-an attempt must be made to achieve an acceptable compromise between the desire for precision and the necessary effort to obtain this precision (cost-measurements-calculations-time).

Altogether 69 tests were conducted according to the standard NBN B62-204 (3) but also according to the standard DIN 52619 (4).

The parameters studied were:

-the type of framework: the 9 types of frameworks studied were:

4 types in aluminum with thermal cutoff

1 type in aluminum with localized thermal protection

1 type in PVC with 3 air chambers without mental reinforcement

1 type in polyurethane with metal reinforcement

1 type in wood.

-the type of panes: the objects of the tests were of three types:

- ordinary double panes (4/12/4)
- improved double panes (4/12/4)
- a panel in synthetic material including 2 air layers and without peripheral element.

-the dimensions of the panes or the filling for frameworks with a single opening where:

-1.2 x 0.6 m^2

-1.2 x 1.2 m^2

-1.7 x 1.7 m^2.

For the frameworks with double openings:

-2 x (1.2 x 0.6) m^2

-2 x (1.7 x 0.8) m^2.

Besides these tests, a large number of bidimensional thermal calculations were carried out by means of the KOBRU program (5); the purpose was either to examine the possibilities of this method of calculation or to study the effects of certain parameters.

The results of these measurements and calculations made it possible for us to evaluate the relative effect of the characteristics of the windows on the k coefficient of the latter.

2.2 Draft of ISO Method to Calculate the k Coefficient of Panes (Central Region)

The ISO (International Standardization Organization) established a draft standard making it possible to calculate the thermal transmission coefficient of panes in the central region. This method is based on the knowledge of the composition of each gas layer (contained between the panes) as well as the factors of emissivity in the infra-red region e of the superficial layers of the glass (coatings).

This ISO draft will be the object of the publication of a new Belgian standard.

3. The standardized Method of Calculating the Coefficient k of Windows

3.1 The Coefficient k for Windows

Essentially base of the results of the activity mentioned in paragraph 2, the following formula was retained to calculate k:

$$k_f = \frac{k_{vc} A_{vc} + k_{pc} A_{pc} + k_{ch} A_{ch} + k_L L_p}{A_{vc} + A_{pc} + A_{ch}} \qquad (W/m^2K)$$

In this expression:

k_f = transmission coefficients of the window (W/m^2K)

k_{pc}= coefficient of transmission of the opaque panels possibly present in a framework (W/m^2K)

k_{vc}= coefficient of transmission of the central region of the panes (W/m^2K)

k_{ch}= equivilent transmission coefficient of the framework (W/m^2K)

k_L = linear transmission coefficient taking into consideration the effect of the insert in the panes (W/m^2K)

A_{vc}= area of the visible portions of the pane (m^2)

A_{pc}= area of the visible portions of the possible opaque panels (m^2)

A_{ch}= area of the projection of all the portions of the framework on a plane parallel to the pane (m^2)

L_p = length of the perimeter of the glazed and opaque portions.

3.2 Determination of k_{vc} (Central Portion of the Pane)

3.2.1 General Case

For all the panes which do not allow the passage of infra-red rays, the coefficient k_{vc} may be calculated by means of a method of calculation described in the standard NBN B62-004.

The application of this method implies the knowledge of the composition of each gas layer and the factors of emissivity of the surfaces of the possibly processed glasses.

These characteristics may be measured with high precision.

3.2.2 Normal Panes with Dry Air Layers and without Processing of the Surfaces

For panes including sheets of clear or colored glass in the mass and one or two layers of air the application of the method of calculation described in paragraph 3.2.1 leads to the values of $k_{v.c.}$ indicated in table 1.

TABLE 1

VALUES OF $k_{v.c.}$ FOR PANES INCLUDING SHEETS OF CLEAR OR COLORED GLASS IN THE MASS AND WITHOUT SURFACE PROCESSING TO DECREASE EMISSIVITY

type of pane		k_{vc} (W/m^2K)
single pane : thickness 5 mm		5.76
double pane		
thickness of the two sheets of glass:		
	5 mm (1)	
air layer (mm):	4	3.59
	6	3.28
	8	3.09
	9	3.02
	10	2.96
	12	2.86
	15	2.76

Table 1 continued

type of pane		k_{vc} (W/m^2K)
triple panes		
thickness of the three sheets of glass: 5 mm (1)		
thickness of the 2 identical air layers (mm):		
	4	2.61
	6	2.29
	8	2.11
	9	2.04
	10	1.99
	12	1.90

(1) the same values $k_{v.c.}$ may be used for glass sheets whose thickness is between 4 and 6 mm.

3.2.3. For special panes, which cannot be calculated in accordance with NBN B62-004, the measurement of $k_{v.c.}$ according to NBN B62-201 or NBN B62-203 remains indispensible.

In some exceptional cases, the method according to NBN B62-204 may remain the only applicable one. We refer to the text of the standard (NBN B-62-002) for further information about the special cases.

3.3 Determination of $k_{p.c.}$ (Opaque Panels)

The determination of $k_{p.c.}$ is possible with the methods described in the standard NBN B62-002 (by calculation or by measurement).

3.4 Determination of $k_{c.h.}$ (of the framework)

3.4.1. All-inclusive Values

For current profiles of the framework (*) the all-inclusive values of $k_{c.h.}$

of table 2 may be used.

TABLE 2

ALL-INCLUSIVE VALUES OF $k_{c.h.}$

Material of the framework	$k_{c.h.}$ W/m^{2}K
Wood:	1.8
Polyurethane:	2.9
PVC:	
-with several compartments without reinforcement	1.5
-with several compartments with reinforcement	1.7
-with single chamber without reinforcement	2.8
-with single chamber with reinforcement	3.0
Aluminum or steel	
-without thermal cut off	6.0
-with metal connections in points	4.8
-with localized thermal protection including	
$R \geq 0.14$ m^2 K/W	4.2
$R < 0.14$ m^2 K/W	4.8
-with continual thermal cut off including	
$R \geq 0.035$ m^2 K/W	3.5
$R < 0.035$ m^2 K/W	4.0

3.4.2 Determination of $k_{c.h.}$ by measurement

In some cases the value of $k_{c.h.}$ must be noted, in particular for structural sections which cannot be taken into consideration according to NBN B62-002 as ordinary structural sections.

A measurement of $k_{c.h.}$ may be recommended also when there are implications that a given sectional section should be more insulating than the all-inclusive values of table 2.

The NBN B62-002 standard recommends in these cases the measurement according to NBN B62-204 where the element of the tested includes at least 33% of the elements of the framework (measuring the surfaces of the projection of the frame-

*For exact definition see NBN B62-002

work elements on a plane parallel to the measurement rack of the box case) and where the filling panels are characterized by a coefficient k known precisely and less than or equal to the coefficient k of the plane which the frame should receive.

An example of the arrangement of the element to be tested is given in fig. 1.

3.4.3 Determination of $k_{c.h.}$ by Combination of Measurement and Calculation

In these exceptional cases where a very high precision is required the standard provides for a method which combines a measurement on a structural section with calculations on other structural sections whose $k_{c.h.}$ have to be determined.

Seeing that this combined method will be used only rarely, we refer to the text of the standard for more information.

3.5. Determination of k_L - Effect of the Insert

3.5.1. All-inclusive Values

For ordinary panes the values of table 3 of k_L may be used.

TABLE 3

VALUES OF k_L (W/mK) IN ORDINARY CASES

Type of pane or filling panel	Type of framework	k_L (W/mK)
single pane or panel without edges or insert	all types	0
All types of panes or filling panel	metal framework without thermal cut off	0
Panes with metal insert or panel with edges or metal insert k_{vc} or $k_{pc} \geq 2\ W/m^2K$	All types of framework except metal frameworks without thermal cut offs	0.05
idem but $k_{vc} < 2\ W/m^2K$	idem	0.07

3.5.2 Calculation of k_L

For all cases not provided for in table 3 or 4 panes or panels for which the coefficient k_L is assumed to be better than the values of table 3, it is possible to determine k_L by calculation. In this calculation it is assumed that the pane or panel is placed in a standardized structural section (fig. 2) and the heat losses through this element are calculated with and without insert.

The difference between the two results of calculation makes it possible to determine k_L.

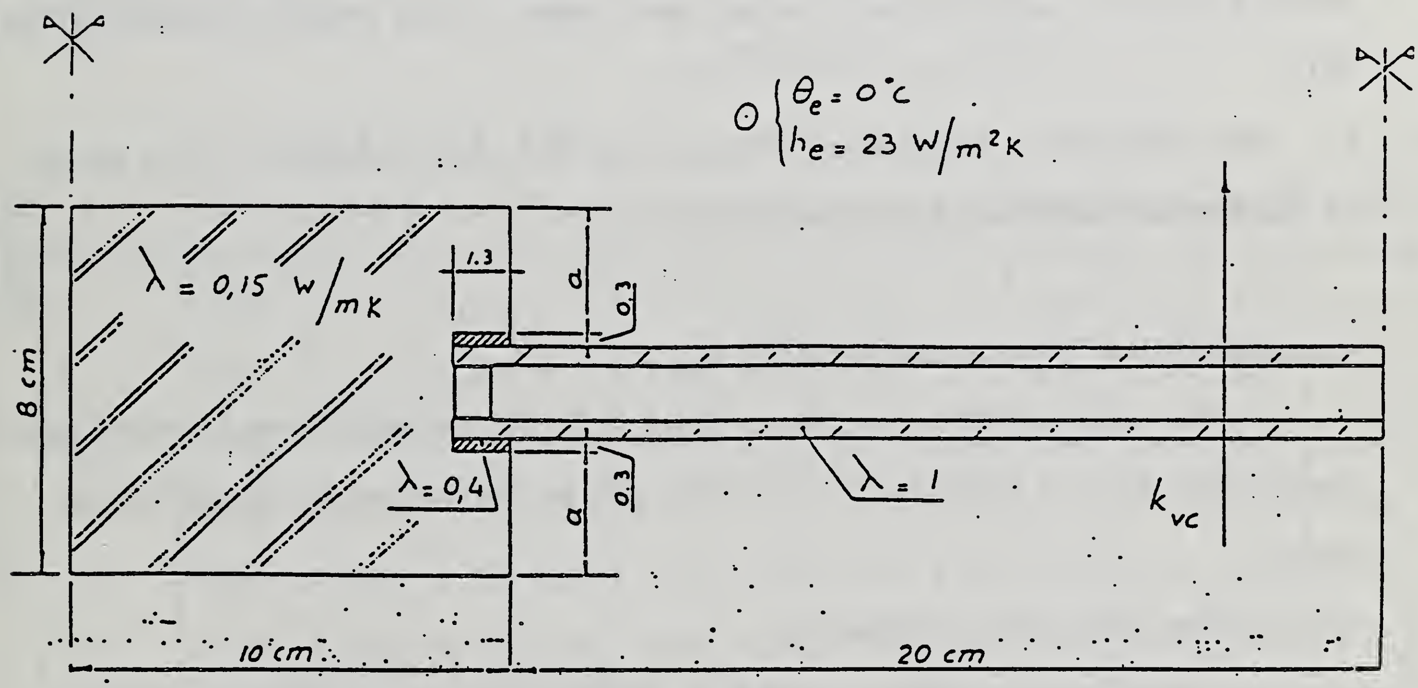

Figure 2 Standardized Structural Section

4. Average Value of the Transmission Coefficient for all the Windows of a Given Building

4.1. Simplifications Foreseen

4.1.1. It is permissible to use for certain calculations (losses, energy require-

*Fig. 1 does not appear in the text

ments) the average value of the thermal transmission coefficient of all the windows of a building instead of the individual values for each window.

This average value is given by:

$$k_f, T = \frac{\Sigma k_f, i \cdot A_f, i}{\Sigma A_f, i} \qquad (W/m^2K)$$

In this expression A_{fi} is the area of the rack (seen from the outside)of the window i. See fig. 3.

4.1.2. It is also permissible for small size projects (*) to use a simplified formula given in paragraph 4.2, unless the author of the project does not allow this.

This simplified formula may also be used for other projects if the author of the project mentions this specifically.

4.2. Simplified Formula to Calculate k_f, T

In the cases mentioned in paragraph 4.1.2, the average thermal transmission coefficient for all windows of a building may be determined by the following method:

-for windows with metal framework:

$$k_{f,T} = 0.75\ k_{vc} + 0.25\ k_{ch} + 3\ k_L \quad (W/m^2K)$$

-for windows with other frameworks:

$$k_{f,T} = 0.7\ k_{vc} + 0.3\ k_{ch} + 3\ k_L \qquad (W/m^2K)$$

Moreover the panes are of ordinary type (normal panes with dry air layers and without surface processing, as specified in table 1), and if the frameworks are of standard type for which the all-inclusive values of table 2 may used, the

*The small size projects on individual houses and apartment buildings with at least 5 apartments.

previous formula makes it possible to calculate directly the value of k_{fT}. The values thus obtained are given in table 4.

TABLE 4
VALUES OF k_{fT} FOR SMALL PROJECTS (HOUSES + BUILDINGS WITH LESS THAN 5 APARTMENTS)

TYPE	pane: thickness of the air layer mm	k_{vc} W/m²K	Material + type of framework: wood	PVC	PVC several chambers, without reinforcement	PVC several chambers, with reinforcement	PVC 1 chamber, without reinforcement	PVC 1 chamber, with reinforcement	aluminum or metal: without cut off	localized connection	localized protection R ≧ 0.14	localized protection R < 0.14	thermal cut off R ≧ 0.035	thermal cut off R < 0.035
		coefficient k_{ch} (W/m²K)	1.8	2.9	1.5	1.7	2.8	3.0	6.0	4.8	4.2	4.8	3.5	4.0
SINGLE (*)	-	5,76	4,57	4,90	4,48	4,54	4,87	4,93	5,82	5,52	5,37	5,52	5,20	5,32
DOUBLE (*)	4	3.59	3,20	3,53	3,11	3,17	3,50	3,56	4,19	4,04	3,89	4,04	3,72	3,84
	6	3.28	2,99	3,32	2,90	2,96	3,29	3,35	3,96	3,81	3,66	3,81	3,49	3,61
	8	3.09	2,85	3,18	2,76	2,82	3,15	3,21	3,82	3,67	3,52	3,67	3,35	3,47
	10	2.96	2,80	3,13	2,71	2,77	3,10	3,16	3,72	3,62	3,47	3,62	3,30	3,42
	12	2.86	2,69	3,02	2,60	2,66	2,99	3,05	3,65	3,49	3,34	3,49	3,17	3,29
	15	2.76	2,62	2,95	2,53	2,59	2,92	2,98	3,57	3,42	3,27	3,42	3,10	3,22
TRIPLE (*)	4	2.61	2,52	2,85	2,43	2,49	2,82	2,88	3,46	3,31	3,16	3,31	2,99	3,11
	6	2.29	2,29	2,62	2,20	2,26	2,59	2,65	3,22	3,07	2,92	3,07	2,75	2,87
	8	2.11	2,17	2,50	2,08	2,14	2,47	2,53	3,08	2,93	2,78	2,93	2,61	2,73
	9	2.04	2,12	2,45	2,03	2,09	2,42	2,48	3,03	2,88	2,73	2,88	2,56	2,68
	10	1.99	2,14	2,47	2,05	2,11	2,42	2,50	2,99	2,90	2,75	2,90	2,58	2,70
	12	1.90	2,08	2,41	1,99	2,05	2,38	2,44	2,93	2,84	2,69	2,84	2,52	2,64

*The thickness of the pane varied between 4 and 6 mm.

Also for the same small project and assuming that we are dealing with standard framework whose all-inclusive values (table 2) may be used, table 5 gives the average values of k_{fT} according to the type of framework and as a function of the coefficient k_{vc}.

TABLE 5

AVERAGE VALUES OF k_{fT} FOR SMALL PROJECTS (W/m^2K) FOR STANDARD FRAMEWORKS AND AS A FUNCTION OF k_{vc}.

k_{vc}	wood	PVC	PVC several compartments, without reinforcement	PVC several compartments, with reinforcement	PVC 1 compartment, without reinforcement	PVC 1 compartment, with reinforcement	Aluminum or metal, without cut off	Aluminum or metal, localized connections	Aluminum or metal, localized protection, R ≥ 0.14	Aluminum or metal, localized protection, R < 0.14	Aluminum or metal, thermal cut off, R ≥ 0.035	Aluminum or metal, thermal cut off, R < 0.035
k_{ch}	1.8	2.9	1.5	1.7	2.8	3.0	6.0	4.8	4.2	4.8	3.5	4.0
3.6	3,21	3,54	3,12	3,18	3,51	3,57	4,20	4,05	3,90	4,05	3,72	3,85
3.5	3,14	3,47	3,05	3,11	3,44	3,50	4,12	3,97	3,82	3,97	3,65	3,77
3.4	3,07	3,40	2,98	3,04	3,37	3,43	4,05	3,90	3,75	3,90	3,57	3,70
3.3	3,00	3,33	2,91	2,97	3,30	3,36	3,97	3,82	3,67	3,82	3,50	3,62
3.2	2,93	3,26	2,84	2,90	3,23	3,29	3,90	3,75	3,60	3,75	3,42	3,55
3.1	2,86	3,19	2,77	2,83	3,16	3,22	3,82	3,67	3,52	3,67	3,35	3,47
3.0	2,79	3,12	2,70	2,76	3,09	3,15	3,75	3,60	3,45	3,60	3,27	3,40
2.9	2,72	3,05	2,63	2,69	3,02	3,08	3,67	3,52	3,37	3,52	3,20	3,32
2.8	2,65	2,98	2,56	2,62	2,95	3,01	3,60	3,45	3,30	3,45	3,12	3,25
2.7	2,58	2,91	2,49	2,55	2,88	2,94	3,52	3,37	3,22	3,37	3,05	3,17
2.6	2,51	2,84	2,42	2,48	2,81	2,87	3,45	3,30	3,15	3,30	2,97	3,10
2.5	2,44	2,77	2,35	2,41	2,74	2,80	3,37	3,22	3,07	3,22	2,90	3,02
2.4	2,37	2,70	2,28	2,34	2,67	2,73	3,30	3,15	3,00	3,15	2,82	2,95
2.3	2,30	2,63	2,21	2,27	2,60	2,66	3,22	3,07	2,92	3,07	2,75	2,87
2.2	2,23	2,56	2,14	2,20	2,53	2,59	3,15	3,00	2,85	3,00	2,67	2,80
2.1	2,16	2,49	2,07	2,13	2,46	2,52	3,07	2,92	2,77	2,92	2,60	2,72
2.0	2,09	2,42	2,00	2,06	2,39	2,45	3,00	2,85	2,70	2,85	2,52	2,65
1.9	2,08	2,41	1,99	2,05	2,38	2,44	2,92	2,83	2,68	2,83	2,51	2,63
1.8	2,01	2,34	1,92	1,98	2,31	2,37	2,85	2,76	2,61	2,76	2,43	2,56
1.7	1,94	2,27	1,85	1,91	2,24	2,30	2,77	2,68	2,53	2,68	2,36	2,48
1.6	1,87	2,20	1,78	1,84	2,17	2,23	2,70	2,61	2,46	2,61	2,28	2,41
1.5	1,80	2,13	1,71	1,77	2,10	2,16	2,62	2,53	2,38	2,53	2,21	2,33
1.4	1,73	2,06	1,64	1,70	2,03	2,09	2,55	2,46	2,31	2,46	2,13	2,26
1.3	1,66	1,99	1,57	1,63	1,96	2,02	2,47	2,38	2,23	2,38	2,06	2,18
1.2	1,59	1,92	1,50	1,56	1,89	1,95	2,40	2,31	2,16	2,31	1,98	2,11
1.1	1,52	1,85	1,43	1,49	1,82	1,88	2,32	2,23	2,08	2,23	1,91	2,03
1.0	1,45	1,78	1,36	1,42	1,75	1,81	2,25	2,16	2,01	2,16	1,83	1,96
0.9	1,38	1,71	1,29	1,35	1,68	1,74	2,17	2,08	1,93	2,08	1,76	1,80
0.8	1,31	1,64	1,22	1,28	1,61	1,67	2,10	2,01	1,86	2,01	1,68	1,81
0.7	1,24	1,57	1,15	1,21	1,54	1,60	2,02	1,93	1,78	1,93	1,61	1,73
0.6	1,17	1,50	1,08	1,14	1,47	1,53	1,95	1,86	1,71	1,86	1,53	1,66
0.5	1,10	1,43	1,01	1,07	1,40	1,46	1,87	1,78	1,63	1,78	1,46	1,58

4.3. Discussion on the Values k_{fT} for Small Projects

The examination of table 4 and 5 make it possible to draw some conclusions.

1. For windows with wooden, PVC or polyurethane framework, the effect of the framework on the coefficient k of the window is constant: actually we find:

k (PUR) = k (wood) + 0.33 W/m^2K

k (PVC, several compartments, no reinforcement) = k (wood) - 0.09 W/m^2K

k (PVC, several compartments, with reinforcement)=k (wood) - 0.03 W/m^2K

k (PVC, 1 compartment, no reinforcement) = k (wood) + 0.30 W/m^2K

k (PVC, 1 compartment, with reinforcement) = k (wood) + 0.36 W/m^2K

The effect of a metal reinforcement on the coefficient k_f of a window with PVC framework is of the order 0.06 W/m^2K.

2. Seeing that the simplified formula takes into account a lower percentage of A_{ch} for metal frameworks (0.25 instead of 0.30), it is not possible to compare systematically the values of k_f for the frameworks in aluminum with those obtained for wood.

Nevertheless we find the following orders of magnitude:

k (aluminum, without thermal cutoff) = k (wood) + 0.9 to 1 W/m^2K

k (aluminum, with point junctions) = k (wood) + 0.75 to 0.85 W/m^2K

k (aluminum, local protection, $R \geq 0.14$) = k (wood) + 0.60 to 0.70 W/m^2K

K (aluminum, local protection, $R < 0.14$) = k (wood) + 0.75 to 0.85 W/m^2K

k (aluminum, thermal cut off, $R \geq 0.035$) = k (wood) + 0.45 to 0.55 W/m^2K

k (aluminum, thermal cut off, $R < 0.035$) = k (wood) + 0.55 to 0.65 W/m^2K

3. The coefficients k_f, rounded off to one decimal, for ordinary single or double glazing (12 mm air layer) are summarized in table 6.

TABLE 6

VALUES OF k_f OF WINDOWS FOR SMALL PROJECTS, ROUNDED OFF TO ONE DECIMAL (W/m^2K)

Framework	simple glazing	double glazing air layer (12 mm)
wood	4.6	2.7
Polyurethane	4.9	3.0
PVC, several compartments	4.5	2.6 - 2.7
single compartment	4.9	3.0
Aluminum, without thermal cut off	5.8	3.7
with localized joints	5.5	3.5
with localized protection	5.4 - 5.5	3.3 - 3.5
with thermal cut off	5.2 - 5.3	3.2 - 3.3

5. Summary

The new project of chapter 6 of the NBN B62-002 standard concerning the calculation of the coefficient k of the windows characterized by the following points:

- -an acceptable precision combined with a sufficient simplicity of application;
- -the possibility of determining by calculation the coefficient k at the center of the pane (k_{vc});
- -the fact that the effect of insertion of the pane and the proposal for a series of all-inclusive values of k_L is taken into consideration;
- -the proposal for a series of all-inclusive values of the coefficient k_{ch} of the framework;
- -for small projects with a presumably constant relationship between the area of the framework and the panes, in the indication of the practical values of k_f;
- -the possiblility of implementing in special situations by dimensional calculations of heat exchange.

6. Acknoledgements

The writing of this article and the text of chapter 6 of the standard, as well as the extensive series of tests and calculations on which these results are based were made possible by the collaboration and support:

-of the programming services of scientific policy

-the Technical Committee of External Techniques of Hygrothermy, Glazing and Carpentry of the CSTC;

-the Technical Union of Metal Joineries

-the working group of the Thermal Insulation Commission of the IBN, working group presided over by Mr. H. Remacle

-the representatives of the glass industry and the chemical industry.

7. Bibliographical References

APPENDIX B

WORKING DRAFT 3

APRIL, 1986

ASTM C XYZ/E XYZ

STANDARD PRACTICE FOR DETERMINING THE THERMAL PERFORMANCE OF WINDOW AND DOOR SYSTEMS

Please send all comments on this working draft by July 1, 1986 to:

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ASTM C16:30 - THERMAL MEASUREMENTS

STANDARD PRACTICE FOR DETERMINING THE THERMAL PERFORMANCE OF WINDOW AND DOOR SYSTEMS

CONTENTS

1. SCOPE

1.1 This standard practice provides requirements and guidelines for the determination of the thermal performance of window and door systems. The practice specifies the thermal measurements to be made using either ASTM C 236 or ASTM C 976 and the procedure for calculating the window or door system thermal performance.

1.2 Thermal performance, as used in this practice, refers to the thermal transmittance, U, and thermal conductance, C, of a window or door system in the absence of solar and air leakage effects.

1.3 A discussion of the definitions and underlying assumptions for calculating the thermal transmittance and thermal conductance is included.

2. APPLICABLE DOCUMENTS

2.1 ASTM Standards

C 236 Steady-state thermal performance of building assemblies by means of a guarded hot box.

C 976 Thermal performance of building assemblies by means of a calibrated hot box.

C 168 Definitions of terms relating to thermal insulating materials.

C 177 Test method for steady-state thermal transmission properties by means of the guarded hot plate.

E XXX Test method for rate of air leakage through exterior windows and doors under specified temperature differences across the specimen (in draft).

C 518 Test method for steady-state thermal transmission properties by means of the heat flow meter.

C XXX Standard practice for derived thermal transmission properties calculated from steady-state heat flux measurements (in draft).

E 230 Standard temperature-electromotive force (EMF) tables for thermocouples.

3. SIGNIFICANCE AND USE

3.1 This practice details the test conditions, procedures, and additional temperature instrumentation necessary to apply ASTM C 236 or C 976 to the measurement of thermal performance of window and door systems. It also provides the calculation procedure to reduce the basic data obtained from guarded and calibrated hot box tests to arrive at the window or door specimen thermal transmittance, U_s, and thermal conductance, C_s.

3.2 Standardized test conditions are provided for determining the thermal transmittance and thermal conductance of the test specimen. Since temperature and surface air film conditions will affect the results, use of these standard sets of conditions will reduce confusion caused by comparison of test results under dissimilar conditions. This procedure can however, be used with other conditions for research or product development.

3.3 This practice does not include procedures to determine the heat flow due to air leakage through the specimen under the test conditions.

3.4 Since the size and shape of a specimen will affect the specimen heat transfer, care must be exercised when extrapolating to product sizes smaller or larger than the test specimen. Once experience is gained with this procedure, limitations on the extrapolation of results will be provided in future editions of this standard.

4. TERMINOLOGY

4.1 Definitions - Definition and terms are in accordance with definitions C168, from which the following have been selected and modified to apply to window and door systems:

4.1.3 Specimen thermal conductance, C-the time rate of heat flow through a unit area of a specimen (window or door), induced by a unit temperature difference between the specimen surfaces. It is calculated as follows:

$$C_s = Q_s/A_s(t_1 - t_2) \tag{1}$$

4.1.4 Thermal transmittance, U_s (sometimes called overall coefficient of heat transfer)-the heat transmission in unit time through unit area of a specimen and its boundary air films, induced by unit temperature difference between the environments on each side. It is calculated as follows:

$$U_s = Q_s/A_s\ (t_h - t_c) \tag{2}$$

The transmittance can also be calculated from the thermal conductance and the surface conductances as follows:

$$1/U_s = (1/h_h) + (1/C_s) + (1/h_c) \tag{3}$$

4.1.5 Surface conductance, h (often called surface or film coefficient)-the time rate of heat flow from a unit area of a surface to its surroundings, induced by a unit temperature difference between the surface and the environment. Subscripts h and c are used to differentiate between room side and weather side surface conductances, respectively. These conductances are calculated as follows:

when $t_h = t_{b1}$:

$$h_h = q_s/(t_h - t_1) \quad (4a)$$

when $t_h \neq t_{b1}$:

$$h_h = q_{r1}/(t_{b1} - t_1) + q_{c1}/(t_h - t_1) \quad (4b)$$

when $t_c = t_{b2}$:

$$h_c = q_s/(t_2 - t_c) \quad (5a)$$

when $t_c \neq t_{b2}$:

$$h_c = q_{r2}/(t_2 - t_{b2}) + q_{c2}/(t_2 - t_c) \quad (5b)$$

4.1.6 Specimen thermal resistance R_c-the mean temperature difference, at equilibrium between two defined surfaces of a material or construction that induces a unit heat flow rate through unit area. It is calculated as follows:

$$R_c = (t_1 - t_2)\ A_s/Q_s = 1/C_s \tag{6}$$

4.2 Descriptions of Terms Specific to this Standard:

4.2.1 Surface resistance, r—the temperature difference between an isothermal surface and its surroundings when a unit heat flow per unit area is established between the surface and the surroundings under steady-state conditions by the combined effects of conduction, convection, and radiation. Subscripts h and c are used to differentiate between hot side and cold side surface resistances, respectively. Surface resistances are calculated as follows:

$$r_h = 1/h_n \tag{7}$$

$$r_c = 1/h_c \tag{8}$$

4.2.2 Overall thermal resistance, R_u,—the temperature difference between the environments on the two sides of a body or assembly when a unit heat flow per unit area is established through the body or assembly under steady-state conditions. It is the sum of the resistances of the body or assembly and of the two surface films and may be calculated as follows:

$$R_u = (t_h - t_c) \cdot A/Q = r_c + R_c + R_h = 1/U_s \quad (9)$$

4.3 Symbols-the symbols,terms, and units used in this method are the following:

A_{b1} area of room side baffle, m^2

A_{b1} = area of weather side baffle, m^2

A_s = rough opening area of specimen, m^2

C_s = thermal conductance of specimen (surface to surface), $W/(m^2 \cdot K)$

h_c = surface conductance, cold side, $W/(m^2.K)$

h_h = surface conductance, hot side, $W/(m^2 \cdot K)$

L = length of path (thickness of specimen),m

Q = time rate of heat flow, total power through the mask wall-window or-door system, W.

Q_m = time rate of heat flow through the mass wall, W

Q_s = time rate of heat flow, total power through the specimen, W

q = heat flux (time rate of heat flow through unit area), W/m^2

q_s = time rate of heat flow per unit area through the window system, W/m^2

q_r = time rate of net radiative heat flow per unit area from window surface, W/m^2

q_c = time rate of convective heat flow per unit area from window surface, W/m^2

R_c = surface to surface thermal resistance of specimen, $K \cdot m^2/W$

r_c = surface resistance, cold side, $K \cdot m^2/W$

r_h = surface resistance, hot side, $K \cdot m^2/W$

R_u = overall thermal resistance of specimen (air to air under test conditions), $K \cdot m^2/W$

t_a = temperature of ambient air, K or °C

t_{b1} = baffle surface temperature, room side, K or °C

t_c = temperature of weather side air, K or °C

t_{b2} = baffle surface temperature, weather side, K or °C

t_h = temperature of room side air, K or °C

t_1 = temperature of specimen room surface, K or °C

t_2 = temperature of specimen weather surface, K or °C

U_s = thermal transmittance of specimen (air to air under test conditions), $W/(m^2 \cdot K)$

5. CALIBRATION

5.1 General

5.1.1 The test facility shall be calibrated using a heat flux transducer calibration specimen constructed as described in Annex 10.1, containing a core material of known characteristics traceable to primary standards such as the NBS and NRCC Guarded Hot Plates. The area of the specimen(s) shall be the same as the specimen sizes to be tested.

5.1.2 Two calibration procedures (calculations) are provided. procedure A is used when test U-Values are to be determined and Procedure B when test C-Values are to be determined. In general procedure A is used when good control on the room side and weather-side air films can be provided with the facility and when the test specimen is not likely to have through air leakage which will cause an erroneous heat transfer measurement. Procedure B is used when air film are not provided within the tolerances specified or when through specimen air leakage must be reduced by lower pressure differences across the specimen.

5.1.3 A mask wall shall be proceeded for mounting the test specimens, constructed in a layered fashion with homogeneous material without thermal bridges.

5.2 Instrumentation. In addition to the air and surface area weighted temperature measurements specified in ASTM C236 and ASTM C976, additional instrumentation is required as follows:

5.2.1 Radiative temperatures - the temperature of all surfaces exchanging radiation heat transfer with the window system shall be measured.

5.2.2 Air Temperature - Temperature measurements should be made in the room side and weather side air streams in the same locations as the surface temperature sensors.

Question - should the air temperature be determined in a line down center of window as in NRC approach?

5.2.3 Chamber Pressures - Two pressure taps are to be provided to measure the pressure difference across the specimen. They shall be located at mid height of the specimen at a potential leakage site and be shielded from direct air impingement. (See Figure XX).

5.3 Calibration Tests

5.3.1 Install calibration specimen in the center of the mask wall approximately half way between the room side and weather side of the mask. Seal the perimeter of the specimen to the mask to prevent air leakage by the specimen/

5.3.2 Balance the pressure between the room side and weather side chambers and monitor ΔP. The ΔP shall be 0±10 Pa (0±0.04) in H_2O) for steady state conditions.

5.3.3 Establish steady state temperature conditions for which the facility is to be calibrated and record measurements of power, temperature and pressure.

5.4 Calibration Data Analysis - In addition to the requirements of ASTM C236 and ASTM C976 the following shall be determined:

5.4.1 PROCEDURE A - U-Value Calibration

5.4.1.1 Total Heat Flow - The time rate of heat flow through the test assembly (mask wall and calibration specimen), Q, is determined by the procedures specified in ASTM C236 or ASTM C976.

5.4.1.2 Specimen heat flow, Q_s, is calculated from

$$Q_s = C_c A_s (T_1' - T_2') \tag{10}$$

where: C_c = conductance of calibration specimen core, $W/(m^2 \cdot K)$

A_s = Area of calibration specimen, m^2

t_1' = Average temperature of room side glass/core interface of calibration specimen, °C

t_2' = Average temperature of weather side glass/core interface of calibration specimen, °C

5.4.1.3 Mask Heat Flow, Q_m, and conductance C_m is then

$$Q_m = Q - Q_s \tag{11}$$

$$C_m = \frac{Q_m}{A_m x(t_{m1} - t_{m2})} \tag{12}$$

where A_m = mask area, m^2

t_{m1} = weighted room side mask surface temperature, °C

t_{m2} = Area weighted weather side mask surface temperature, °C

Note: If a mean temperature correction for the mask is required, conduct calibration tests at at least three sets of mean temperature conditions.

5.4.1.4 Surface Conductance, h_h and h_c,

$$h_h = \frac{Q_s}{A_s(t_h - t_1)} \tag{13}$$

where: t_h = Average room side air temperature, °C

t_1 = Weighted average room side specimen surface temperature, °C, which is calculated from the following:

$$t_1 = t_1' + \frac{C_c}{C_g}(t_1' - t_2') \qquad (14)$$

where C_g = Conductance of glass facing on calibration specimen

$$h_c = \frac{Q_s}{A_s(T - T_c)} \qquad (15)$$

where t_c = average weather side air temperature, °C

t_2 = weighted average weather side specimen surface temperature, °C, which is calculated from

$$t_2 = t_2' - \frac{C_c}{C_g}(t_1' - t_2') \qquad (16)$$

The surface conductances h_h and h_c, shall be 8.3 ± 1 and 34 ± 3 W/(m²·K) (1.5 and 6.0 BTU/h·ft²·F) when calculated as above.

Question - should U-value determined using procedure A be corrected back to standard film conditions if we do not have 8.3 and 34 W/(m²·K)?

5.4.2 PROCEDURE B - C Value Calibration

5.4.2.1 Total Heat Flow - The time rate of heat flow through the test assembly (mask wall and calibration specimen), Q, is determined by the procedures specified in ASTM C236 or ASTM C976.

5.4.2.2 Specimen Heat flow, Q_s, is calculated from

$$Q_s = C_c A_s (t_1' - t_2') \qquad (17)$$

where C_c = conductance of calibration specimen core, W/(m²·K)

A_s = Area of calibration specimen, m²

t_1' = Average temperature of room-side glass/core interface of calibration specimen, °C

t_2' = Average temperature of weather-side glass/core interface of calibration specimen, °C

5.4.2.3 Mask Heat Flow, Q_m, and Conductance C_m

$$Q_m = Q - Q_s \tag{18}$$

$$C_m = \frac{Q_m}{A_m \times (t_{m1} - t_{m2})} \tag{19}$$

5.4.2.4 Calculate the weighted average specimen surface temperatures t_1 and t_2

from

$$t_1 = t_1' + \frac{C_c}{C_g}(t_1' - t_2') \tag{20}$$

$$t_2 = t_2' - \frac{C_c}{C_g}(t_1' - t_2') \tag{21}$$

5.4.2.5 Radiative Heat Transfer, Q_r

Note: In procedure B the heat transfer to the specimen from the room-side enclosure is broken down into a radiative, Q_r, and a convective, Q_c, component which facilitates the determination of the room side surface conductance. When a window specimen is being evaluated, the relationship for Q_r and Q_c is used to calculate the equivalent surface temperature of the specimen.

If a baffle or box wall is close to the specimen and parallel plate heat transfer can be assumed.

$$\frac{Q_r}{A_s} = q_r = F_{1b} \cdot \sigma\,(t_b^4 - t_1^4) \tag{21}$$

where $F_{1b} = \dfrac{1}{\dfrac{1}{e_1} + \dfrac{A_s}{A_b}\left(\dfrac{1}{e_b} - 1\right)}$ (assuming a view factor of 1.0)

e_1 = emittance of glass

e_2 = emittance of the baffle or box wall

A_b = area of baffle, m^2

T_b = area weighted baffle temperature, K

σ = Stefan-Boltzman constant 5.6703×10^{-8} $W/(m^2 \cdot K^4)$

NOTE: If the view factor between the window surface and the baffle surface is not close to 1.0 or if the baffle is not isothermal, then the radiation heat transfer calculation procedure in Appendix 10.2 is recommended.

5.4.2.6 Convective heat transfer, Q_c

$$Q_c = Q_s - Q_r \qquad (22)$$

having calculated Q_c, the constant in the following equation for the convective heat transfer to the specimen can be determined.

$$\frac{Q_c}{A_s} = q_c = K * (t_h - t_1)^{1.25} \qquad (23)$$

NOTE: The convective heat transfer calculation assumes "near" natural convection on the room side of the specimen. To ensure that a single covection, K, can be used for window tests, the range of heat flows tobe encountered should be tested using the calibration specimen while the convection constant behavior, is K, determined.

5.4.2.7 Surface conductances h_h and h_c

$$h_h = \frac{q_r}{(t_b - t_1)} + \frac{q_c}{(t_h - t_1)} \qquad (24)$$

The weather side surface conductance can be calculated from the following simplified formula if the surfaces exchanging radiation with the specimen are at the same temperature as $T_c \pm 0.5°C$:

$$h_c = \frac{Q_s}{A_s\ (t_2 - t_c)} \tag{25}$$

If they are not at the same temperature, the radiative and convective components of the heat transfer must be established as done on the room side.

6. EXPERIMENTAL PROCEDURE

6.1 Temperature Measurements - In addition to the air and surface area weighted temperature measurements specified in C 236 or C 976, additional temperature measurements may be made on the mask wall, the window or door frame, the window or door glazing and on any other portions (sills, muntins, etc.) of the window or door system so as to allow an area weighted determination of the surface to surface temperature difference of the window or door system. It should be recognized that there is such a wide range of window and door designs that it is not possible to specify where to locate the temperature sensors so as to arrive at a correct area weighted determination of the window surface temperatures. The experience of the hot box operator will have to be drawn upon here. Also, any area weighted window surface temperature determined in this manner should be compared with the calculated equivalent window surface temperatures specified in Section 5. Calibration. If these two values differ by more than 5%, then additional temperature sensors should be installed on the window surfaces to arrive at more accurate area weighted window surface temperatures. In addition, temperature measurements should be made in the cold and hot air streams in the same locations as the window surface temperature sensors. This will allow for calculation of the cold and hot side surface conductances. This technique of area weighting may be applicable when the frame and glazing conductances are similar. If they are not, excessive use of temperature sensors may cause h_r to differ from calibration tests introducing further uncertainty in the results. The temperature sensors used may be special limit thermocouples (24 gage may be used, 30 gage or smaller are recommended for the window surface temperatures), thermistors or RTD's (resistance temperature detectors).

6.1.1 Radiation effects - to minimize the effect of radiation induced error on the temperature sensors, the temperatures of all of the surfaces exchanging radiation heat transfer with the window or door system must be measured. This includes cold and hot side baffles facing the mask wall/window system. Any heating and cooling devices must be shielded from the mask wall/window system and the surface temperature of the shield should be measured. The temperature sensors should be applied to these surfaces with tape or adhesive which has an emissivity similar to that of the surface. The air temperature sensors should be shielded so that they are not significantly effected by surfaces that they are exchanging radiation with.

6.2 Environmental Conditions - it is recognized that a single environmental condition does not adequately define the thermal performance of a window or door system. However, to allow for comparisons of U-values of different window and door products a single environmental condition is specified. For windows and doors where the seasonal thermal performance is desired, additional environmental conditions are specified.

6.2.1 Environmental condition for U-value testing - the test specimen shall be tested using the following conditions.

PROCEDURE A:

t_h = 21°C (70°F)

t_c = −18°C (0°F)

h_h = 8.3 W/(m²·K)

h_c = 34 W/(m²·K)

PROCEDURE B:

t_h = 21°C (70°F)

t_c = − 18°C (0°F)

h_h} as determined in calibration

h_c} as determined in calibration

NOTE: These conditions represent ASHRAE winter design conditions. The room side surface conductance h_h represents natural convection and the weatherside surface conductance h_c represents a 15 mph wind. If the U-Value procedure is used, the test facility will be calibrated to provide these surface conductances. If the C-Value procedure is used, the effect of these surface conductances will be added to the C-Value to arrive at a Design U-Value.

6.2.2 Environmental conditions for seasonal thermal performance studies-the test specimen shall be tested over a range of conditions which simulate winter, summer and spring conditions with weather side surface conductances ranging from natural convection to ASHRAE summer (7.5 mph) and winter (15 mph) design conditions.

7. CALCULATION PROCEDURE

7.1 General Calculations

The following shall be calculated for each test:

7.1.1 The time rate of heat flow through the test assembly, Q, is determined using procedures outlined in ASTM C236 and ASTM C976.

7.1.2 Mask heat flow, Q_m,

$$Q_m = C_m \cdot A_m \cdot (t_{m1} - t_{m2}) \tag{26}$$

where C_m is determine from calibration tests

7.1.3 Specimen heat flow, Q_s,

$$Q_s = Q - Q_m \tag{27}$$

7.2 Calculations for PROCEDURE A

7.2.1 Specimen thermal transmittance, U_s

$$U_s = \frac{Q_s}{A_s(t_h - t_c)} \tag{28}$$

7.2.2 Specimen Thermal Conductance, C_s

$$C_s = \frac{1}{\frac{1}{U_s} - \frac{1}{h_h} - \frac{1}{h_c}} \tag{29}$$

Question - should actual values for h_h and h_c as determined in the calibration test be used or use values of 8.3 and 34 $W/(m^2 \cdot K)$?

7.3 Calculations for PROCEDURE B

7.3.1 Equivalent room side surface temperature of specimen, t_1, is calculated by solving the following 3 equations for Q_r, q_c and t_1:

$$Q_s = Q_r + Q_c \tag{30}$$

$$Q_r = A_s \cdot F_{1b} \cdot \sigma \cdot (t_b^4 - t_1^4) \tag{31}$$

$$Q_c = A_s \cdot K \cdot (t_h - t_1)^{1.25} \tag{32}$$

where K is determined from the calibration tests discussed in section 5.

Note: One way to solve these equations is by iteration. Assume a value for t_1 in equation (31), calculate Q_r, determine Q_c from equation (30), then calculate a new t_1 from equation (32). If this new value is different than the first assumption, use the average of the two t_1 values in equation (31) and repeat the calculation until the t_1 values agree to within 0.1°C.

7.3.2 Equivalent weather side surface temperature, t_2,

$$t_2 = \frac{h_c}{Q_s} + t_c \tag{33}$$

where h_c is determined from the calibration tests discussed in section 5.

7.3.3 Specimen thermal conductance, C_s,

$$C_s = \frac{Q_s}{A_s\,(t_1 - t_2)} \tag{34}$$

7.3.4 Specimen thermal transmittance, U_s,

$$U_s = \frac{1}{\frac{1}{C_s} + \frac{1}{8.3} + \frac{1}{34}} \tag{35}$$

8. REPORT

8.1 The report shall include all of the information specified in C976 Section 11 or C236 Section 10.

8.2 In addition, the thermal conductance, C_s, and thermal transmittance, U_s, and the hot and cold side surface conductances, h_h and h_c, of the window or door system shall be reported and their estimated uncertainty specified.

10. ANNEX
The following annexes will be added to Draft 4:

10.1 Heat flux transducer calibration specimen design - this large heat flux transducer is used in the calibration of the surface conductances and for checking the mask wall conductance.

10.2 Radiation heat transfer calculation procedure - this calculation procedure is to be used when the assumption that the window and baffle surfaces are parallel surfaces and the window only exchanges radiation heat transfer with the isothermal baffles. However, in many situations, the window also exchanges radiation heat transfer with the mask wall opening surfaces and with nonisothermal baffle surfaces. In those situations, the radiation calculation procedure described in this annex is recommended.

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☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

11. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)*

The purpose of this report is to review current and historical sources of information on U-values for windows and window systems and to describe the current state of thermal test methods used for windows in order to provide the Bonneville Power Administration with some general guidelines in applying thermal test data in Model Conservation Standards.

A review of heat transfer theory and sources of U-value data for windows are presented along with descriptions of laboratory and field test methods from the technical literature. Draft test standards for window systems currently being developed by ASTM are presented, and current research and planned future research efforts to provide the technical information deemed necessary for approval of the standards are described.

12. KEY WORDS *(Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)*

calibrated hot box; fenestration; guarded hot box, heat transfer; movable insulation; U-value; window system

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