Chapter 3
Development of the Test Protocol

The test protocol was developed while considering two important issues: physics of the thermal response and design parameters for the system. Each of these is discussed in detail.

3.1 Fenestration Energy Balance

The understanding of the double glass façade and development of a thermal performance test protocol begins with knowledge of the properties of glass and solar heat gain through the system. The simplified method for predicting heat transfer through fenestration is described as followings.

3.1.1 Solar Heat Gain

As described in the ASHRAE Handbook of Fundamentals, the total instantaneous rate of heat gain through glazing material is shown in Figure 3.1 and may be expressed as equation 3.1 through 3.5:

Total heat admission through glass	=	Radiation transmitted through glass	+	Heat flow inward by radiation-convection from inner glass surface

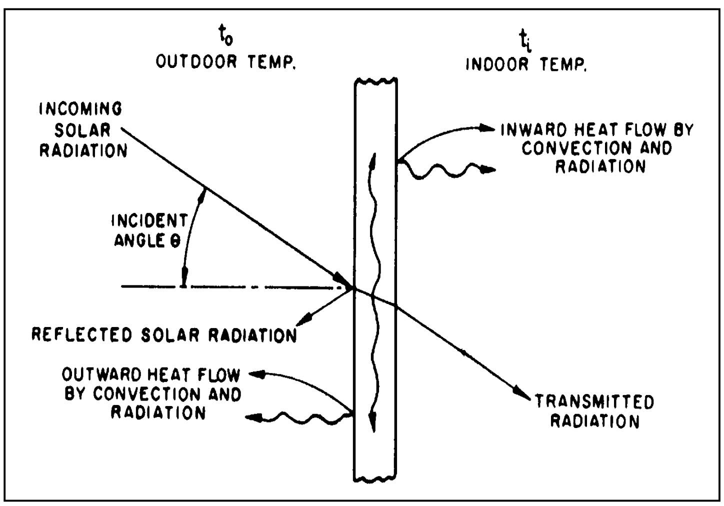

Figure 3.1 Instantaneous heat balance for sunlit glazing material

$$q_A = E_{D\tau D} + E_{d\tau d} + q_{RCi} \tag{3.1}$$

where: q_A = Instantaneous rate of heat admission through fenestration, Btu/h*ft^2

$E_{D\tau D}$ = Direct solar radiation transmitted through glass, Btu/h*ft^2

$E_{d\tau d}$ = Diffuse solar radiation transmitted through glass, Btu/h*ft^2

q_{RCi} = The rate of heat flux inward by radiation and convection, Btu/h*ft^2

This equation may also be written:

Total heat admission through glass	=	Radiation transmitted through glass	+	Inward flow of absorbed solar radiation	+	Heat flow due to outdoor-indoor temperature difference

For single glazing;

$$q_A = E_t \tau + Ni\ (\alpha E_t) + U\ (t_0 - t_i) \qquad (3.2)$$

where: E_t = Incident total irradiance, Btu/h*ft^2
τ = Transmittance, non-dimensional
Ni = Heat transfer factor, inward flow fraction
α = Absorptance, non-dimensional
U = U-value, Btu/h*ft^2 °F
t_0 = Outdoor temperature, °F
t_i = Indoor temperature, °F

For double glazing, the transmittance through both glass layers can be calculated by:

$$\bar{\tau} = \tau_0\ \tau_i / (1 - \rho_2 \rho_3) \qquad (3.3)$$

where: $\bar{\tau}$ = Transmittance of double glazing
τ_0 = Transmittance of outer glass
τ_i = Transmittance of inner glass
ρ_2 = Cavity air density, lb$_m$/ft^3
ρ_3 = Outdoor air density, lb$_m$/ft^3

The first two terms of equation 3.2 are related to the incident solar radiation, while the third occurs whether or not the sun is shining. As a result, Equation 3.2 and 3.3 may be combined as:

$$q_A = E_t\ \bar{\tau} + N_{io}\ (\alpha\ E_o) + N_{ii}\ (\alpha\ E_i) + U(t_o - t_i) \qquad (3.4)$$

where: N_{io} = Inward heat flow fraction of the outdoor glass
N_{ii} = Inward heat flow fraction of the indoor glass
E_o = Solar radiation transmitted through outdoor glass, Btu/h*ft^2
E_i = Solar radiation transmitted through indoor glass, Btu/h*ft^2

Total heat admission through glass	=	Solar heat gain	+	Conduction heat gain

These may both be written as:

$$q_A = SHGC\ E_t + U\ (t_0 - t_i) \qquad (3.5)$$

where: ***SHGC*** = Solar heat gain coefficient (ratio of solar heat gains to incident solar radiation) (ASHRAE, 1989)

3.1.2 Double Envelope Heat Removal Rate

The double glass façade differs from the typical window due to ventilation air flowing through the cavity. The ventilation airflow rate required to remove a specific amount of heat can be calculated from Equation 3.6.
(ASHRAE, 1989)

$$Q = H / c_p\rho\ (t_i - t_o) \quad (3.6)$$

where: Q = Air flow rate required to remove heat, cfm
H = Heat to be removed, Btu/min
c_p = Specific heat of air, Btu/lb_m°F (about 0.24)
ρ = Air density, lb_m/ft^3
t_0 = Air outlet temperature, °F
t_i = Air inlet temperature, °F

In this study, Equation 3.5 will be used for calculation of the solar heat gain in the cavity and Equation 3.6 will be used for the calculation of the cavity solar heat removed as will be discussed in Chapter Four.

3.2 System Design Parameters

In addition to environmental factors, the thermal response and energy savings from glass double façade systems depend on many design parameters. These parameters include: the properties of the glass, properties of the shading element, and size and location of vents. These complex interactions must be considered when selecting a research methodology.

In Chapter 2, it was mentioned that the options for configuring the system include: natural or mechanically assisted ventilation, single story or multiple story module. The system configuration may also have differences, such as varying glass layer properties and sequence, cavity size and depth and shading device location and properties.

Based on the case studies presented in Chapter 2, the placement of the glass can be double pane at the exterior layer, single pane at the interior layer (Occidental Chemical Center, New York), or it can be single pane at the exterior layer, and double pane at the interior layer (RWE Headquarter Tower, Essen). It can also be single pane on both interior and exterior layers (Independent Television News Headquarters Building, London). The system test protocol must allow for these system differences.

Additionally, the cavity width can vary from 3 inch (Lloyd's Building, London) to 5 ft (Occidental Chemical Center, New York). The cavity height may vary from one story high (Commerbank Headquarters, Frankfurt) to 9 story high (Occidental Chemical Center, New York). The test protocol must also consider these variations.

Finally, the shading devices can be located on the outside of the cavity (Lloyd's Building, London) or inside the cavity (RWE Headquarter Tower, Essen) and may be of various materials and shapes and sizes. These must be considered in the test protocol development.

3.3 Developing the Test Protocol

3.3.1 Data measurement

The issues presented in section 3.1 and 3.2 were applied to the test protocol. According to the Equation 3.5 and 3.6, to obtain the solar heat gain through the glazing and cavity heat removal rate, the solar heat gain coefficient (SHGC), total incident solar radiation (Et), U-value (U), cavity air flow rate (Q), and outlet and inlet air temperature (to, ti) are needed. Therefore, measurable variables associated with these factors are necessary for developing the test protocol.

The following table describes what environmental factors and measurable or calculated variables that are related to these variables.

Table 3.1 Development of the data measurement

Heat Transfer Factor	**Environmental Factor**	**Measurable or Calculated Variables**	**Method of Determination**
SHGC	Sun angle	Sun altitude Sun azimuth	Computer program (*Windows 4.1 User's Manual & Sun Position*)
Et	Solar radiation	Vertical solar radiation Horizontal solar radiation	Vertical pyranometer Horizontal pyranometer
U-value	Air velocity	Wind speed Wind direction	Anemometer
ΔT	Air temperature	Air temperature	Thermocouples
Q	Air flow rate	Wind speed Wind direction Cavity air flow rate	Anemometer Air flow transducer
ti, to	Air temperature	Cavity inlet air temperature Cavity outlet air temperature	Thermocouples

- **Solar heat gain coefficient (SHGC)**
  The SHGC is the fraction of incident solar radiation admitted through a window, both directly transmitted, and absorbed and subsequently released inward. SHGC is expressed as a number between 0 and 1. The lower a window's solar heat gain coefficient, the less solar heat it transmits (National Fenestration Rating Council, 1998).

– sun altitude, sun azimuth
The value of the SHGC varies with the different incident solar angle in relation with the glass surface. The SHGC was adjusted as a function of sun altitude and azimuth angles. Then based on the computer program Sun Position, by Seattle Energy Works, the sun altitude and azimuth were calculated every 15 minutes for days and times corresponding to the experimental test period. Depending on which angle was determined to be larger, either sun altitude or azimuth was used as the incident sun angle. The Window 4.1 User's Manual, developed by Lawrence Berkeley Labs, was used to determine the SHGC value as a function of this calculated angle of incidence (Table 3.2).

Table 3.2 The optical value for different incident sun angle from The Window 4.1 User's Manual

WINDOW 4.1 OPTICAL PROPERTIES

Multi Band Calculations

Optical Properties for Glazing System '2 double'

Angle	0	10	20	30	40	50	60	70	80	90	Hemis
Vtc :	0.817	0.816	0.815	0.811	0.799	0.768	0.685	0.538	0.273	0.000	0.714
Rf :	0.148	0.148	0.148	0.151	0.162	0.191	0.262	0.417	0.682	1.000	0.236
Rb :	0.148	0.148	0.148	0.151	0.162	0.191	0.262	0.417	0.682	1.000	0.236
Tsol :	0.727	0.726	0.723	0.716	0.702	0.669	0.599	0.455	0.215	0.000	0.623
Rf :	0.129	0.129	0.129	0.131	0.140	0.166	0.230	0.370	0.619	1.000	0.208
Rb :	0.129	0.129	0.129	0.131	0.140	0.166	0.230	0.370	0.619	1.000	0.208
Abs 1:	0.080	0.081	0.082	0.085	0.089	0.094	0.101	0.110	0.117	0.000	0.093
Abs 2:	0.064	0.065	0.066	0.068	0.070	0.071	0.071	0.065	0.049	0.000	0.067
Abs 3:											
Abs 4:											
Abs 5:											
Abs 6:											
SHGCc:	0.775	0.775	0.773	0.768	0.755	0.724	0.654	0.508	0.260	0.000	0.674

SCc:	0.90	Color Properties	DomWL	Purity	L*	a*	b*
Tdw:	N/A	Transmittance	um	%			
Tuv:	N/A	Reflectance	um	%			

- **Incident solar radiation (Et)**
  The incident solar radiation is the total solar radiation falling on the outer glass pane. The incident solar radiation was measured using Li-Cor pyranometers. The value of incident solar radiation was associated with SHGC to obtain the solar heat gain of the window models.

– Vertical solar radiation and horizontal solar radiation
Two pyranometers were placed near the window models. Two measurements were taken, vertical and horizontal radiation. The vertical solar radiation is applicable to the solar heat gain calculation, and the horizontal solar radiation can be used to determine cloud cover and the vertical to horizontal solar ratio.

- **U-value (U)**
  The rate of heat gain or loss due to conduction is indicated in terms of the U-factor (U-value) of a window assembly. The U-value is the reciprocal of the sum of the R-values in a system, including the resistance of the inside and outside air films. The resistance of the outside air film, and therefore the U-value of the system, will depend on the wind speed and convective heat transfer at the outer layer. Because the wind speed is dynamic, the U-value will be dynamic. Therefore, the test protocol must include wind speed near the window models.

  – wind speed, wind direction
  Since the air movement across the window surface can affect the U-value, the wind information around the window is needed. Therefore, an anemometer was set up nearby the window model for measuring the wind speed and wind direction.

- **Temperature difference (ΔT)**
  The temperature difference between outdoor and indoor air will cause the convective heat transfer through fenestration.
  – air temperature
  The surrounding air temperature is an important determinant for heat flow. The thermocouples were applied at indoor, outdoor, and adjacent to the window models to measure the air temperature difference.

- **Air flow rate (Q)**
  The cavity air flow rate is required for calculating the cavity heat removal rate (Equation 3.6). For the active system, the cavity air flow was created by the mechanical fan that connected to the air cavity. For the passive system, the cavity air flow primarily relied on the wind and thermal buoyancy.

  – wind speed, wind direction
  Because, for the passive system, the cavity air flow rate is strongly related to the wind, an anemometer was placed near the window models to measure the wind speed and wind direction.

  – cavity air flow rate
  Air transducers were installed in the air cavity to measure the air flow velocity. The passive system was projected to have a less stable and larger range of cavity air flow rate, so two transducers were located at the upper and lower cavity in the passive system to obtain an average airflow rate. Also, because it was desirable to measure

the air flow rate in a non-turbulent location, the probes were located away from the cavity air inlets and outlets.

- **Cavity air temperature**
  The air temperature at the cavity outlet (to) and inlet (ti) are required for calculation of the cavity heat removal rate (Equation 3.6).

  – cavity outlet temperature (to) and inlet temperature (ti)
  Using thermocouples, air temperatures were measured in the center of the cavity inlet and outlet.

  In addition to the cavity outlet and inlet air temperatures, other temperature measurements were needed to calculate the temperature difference between the indoor glass and indoor air. To collect the sufficient temperature data, the windows were divided into several zones. Vertically, the window was divided into four zones: cavity air outlet, upper cavity area, lower cavity area, and cavity air inlet. Horizontally, the window was divided into six zones: an outdoor zone, outer glass pane, outside blinds, inside blinds, inner glass pane, and indoors. Additional locations would have been measured, but the experimental protocol was constrained by the data acquisition equipment.

3.3.2 System Operation

In this study, two mechanical fans were used respectively in both test cells for ventilation purpose. The ventilation flow rate for the active system was determined based on the assumption of a constant air volume HVAC system with return air through the cavity. For this, the ventilation rate was based on an assumed space depth of 15 feet and a required air flow rate of 1.2 cfm/ft^2. This is a representative design air flow rate for perimeter rooms. Thus, for a 5 foot wide wall cavity opening, the ventilation rate was approximated by: 5’ wide x 15’ depth x 1.2 cfm/ft^2 = 90 cfm. A 90 cfm fan was used to produce an average 33 feet per minute (fpm) air flow rate in the active system air cavity. The fan used in the passive system supplies about 60 cfm and is used to mix air and maintain the indoor air temperature.

The electrical heaters were also provided in both test cells to prevent unacceptably cold indoor temperatures during the test period. These fans and heaters need to be activated throughout the data collection period to simulate an occupied condition in a non-residential building.

In order to synchronize the data measurement (temperature, solar radiation, wind speed and wind direction) and the calculation of the sun position (the computer program, Sun Position), the data collection frequency was set at every 15 minutes. During the daytime, the sun altitude will change about 2 to 3 degree for every 15 minutes. This difference allows for synchronization with the SHGC value calculation.

The more detailed experimental set up will be discussed in the Chapter 4.