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A METHOD FOR COMPARING THE THERMAL PERFORMANCE OF WINDOWS

by S.J. Harrison and S.A. Barakat

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RÉSUMÉ

Cette communication présente une méthode simple de comparaison de la performance thermique des vitrages. Il est possible d'établir une caractéristique universelle de rendement pour chaque type de vitrage en utilisant uniquement son coefficient global moyen de transfert de chaleur et son coefficient d'ombre. La méthode permet également de calculer les apports nets de chaleur que peut permettre un type de vitrage donné. On a pu confirmer que les propriétés thermiques et optiques des fenêtres restent constantes en analysant les valeurs des apports nets de chaleur obtenues par des calculs détaillés fondés sur des données atmosphériques horaires réelles de quatre villes du Canada. La méthode sert également à prévoir le rendement des fenêtres lorsqu'on utilise des persiennes isolantes la nuit.

No. 2735

A Method for Comparing the Thermal Performance of Windows

S.J. Harrison **S.A. Barakat**

ABSTRACT

A simple method of comparing the thermal performance of glazing systems is presented. A universal performance characteristic can be established for each glazing system, using only its average over-all heat-transfer coefficient and shading coefficient. The method also permits the calculation of the net heat gain attainable with a given glazing system. The validity of the assumption of constant window thermal and optical properties is confirmed through comparison with values of net heat gain obtained by detailed calculations using actual hourly atmospheric data for four Canadian locations. The method is extended to permit prediction of the performance of windows using nighttime insulating shutters. An example of its use is given.

INTRODUCTION

It has long been recognized that windows can increase the heating and cooling energy requirements of buildings.[1] Recently, however, their potential as suppliers of energy for the heating of buildings has received increased attention.[2] Calculated values of net heat gain through windows have shown that even under severe winter conditions double- and triple-glazed windows can supply a positive net heat gain to the indoor space over the heating season.[3]

The net heat gain through a window is a function of the glazing design (i.e., single, double, etc.), orientation, and the climate to which it is exposed. The selection of a window should therefore account for all these factors. If, however, a window is located for reasons other than maximizing energy gain (i.e., visual communication, lighting, or aesthetics), the glazing system should be designed to minimize energy loss.

A method for selecting windows based on thermal performance would be of assistance to building designers who wish to compare glazing options for a specific application. For example, such a method would enable determination of the energy (and ultimately the cost) benefit of reorienting or adding windows or of substituting different windows in a building. The thermal and cost performance of single, double, and triple glazing and of nighttime shutters could also be compared.

The thermal performance of a window is similar to that of a solar collector and should lend itself to the same sort of rating.[4,5] This paper presents a method of comparing the thermal performance of glazing systems. A universal performance characteristic is presented for each glazing system, using only its over-all heat-transfer coefficient and shading coefficient. The method also allows the calculation of the net heat gain attainable with a given glazing system. It is assessed through comparison with values of net heat gain obtained by detailed calculations that use actual hourly atmospheric data for four Canadian locations.[3]

THERMAL PERFORMANCE OF GLAZING SYSTEMS

The instantaneous rate of energy flow through a glazing system is equal to the difference between the heat gain due to solar radiation and the heat loss by conduction, convection, and

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S.J. Harrison and S.A. Barakat, Research Officers, Thermal Performance Section, Division of Building Research, National Research Council of Canada, Ottawa, Canada.

long-wave radiation. Following the convention of Ref 1,

$$q_A = F(I_t) - U(T_i - T_o) \tag{1}$$

where

q_A = instantaneous rate of heat admission through the glazing, W/m^2
F = solar heat-gain coefficient (the dimensionless ratio of the solar heat gain to the incident solar radiation)
I_t = solar radiation incident on glazing surface, W/m^2
U = over-all heat-transfer coefficient of the window, W/m^2K
T_o, T_i = outdoor and indoor air temperatures, respectively, K

The over-all heat-transfer coefficient, U, takes into account long-wave radiation losses as well as conduction and convection losses due to indoor-outdoor temperature difference. The value of U varies with outdoor air temperature, wind speed, and incident solar radiation.

The solar heat gain coefficient, F, is a unique characteristic for each type of window and represents the sum of the solar radiation transmitted through the glass and the inward flow of solar radiation absorbed by the glazing. It is given by

$$F = \tau + N_i \alpha \tag{2}$$

where

τ = over-all solar transmittance of window
N_i = inward-flowing fraction of absorbed solar radiation (for example, $N_i = U/h_o$ for single glazing)
α = solar absorptance of glazing material
h_o = outside film heat-transfer coefficient

For windows with multiple glazings, values of F can be calculated by the method presented in Ref 3. Alternatively, for all glazing systems F can be presented as a fraction of F_s single glazing, that is,

$$F = SC \cdot F_s \tag{3}$$

where

SC is the shading coefficient, defined as the ratio of the solar heat gain through a glazing system under a specific set of conditions to the solar gain through a single light of double-strength sheet glass under the same conditions. Values of shading coefficient for a number of glazing systems are given in Ref 1.

From Eq 1 an instantaneous thermal performance factor, η, for a window can be defined as,

$$\eta = \frac{q_A}{I_t} = F - U\frac{(T_i - T_o)}{I_t} \tag{4}$$

The relation between η and $(T_i - T_o)/I_t$ for any glazing system can be presented graphically as shown in Fig. 1.

AVERAGE THERMAL PERFORMANCE

Similar to an analysis presented by Lunde for the thermal efficiency of solar collectors,[6] a relation for the average thermal performance factor of glazing systems can be derived. Consider the instantaneous thermal performance factor of a window represented by Eq 4. If it is assumed that the shading coefficient, the solar heat gain coefficient for single glazing, and the window over-all heat-transfer coefficient are constants over any time period and given by $\overline{SC}$, $\overline{F_s}$, and $\overline{U}$, respectively, then the average heat gain through the window, $\overline{Q}$, over the same time period is given by:

$$\overline{Q} = \overline{F} \cdot \overline{H} - \overline{U}(\overline{T}_i - \overline{T}_o) \tag{5}$$

where

$\overline{T}_o$ and $\overline{T}_i$ represent the time-average outdoor and indoor temperatures over the time interval, and $\overline{H}$ represents the time-average solar radiation incident on the glazing surface.

For a particular time period, $\overline{F}$ and $\overline{U}$ are average values over the period calculated as

$$\overline{F} = \frac{\text{total solar gain}}{\text{total incident radiation}}$$

$$\overline{U} = \frac{\text{total heat loss}}{\text{average temperature difference times number of hours}}$$

The average thermal performance factor, $\overline{\eta}$, of the window during the time period, therefore, is,

$$\overline{\eta} = \frac{\overline{Q}}{\overline{H}} = \overline{F} - \overline{U}\ \frac{(\overline{T}_i - \overline{T}_o)}{\overline{H}} \tag{6}$$

Eq 6 describes the relation between the average values of the performance factor, incident radiation, outdoor air temperature, and room temperature. It can be graphically represented in the same manner as the instantaneous performance curve (Fig. 1). Note that the slope of the characteristic line in the figure represents the over-all heat-transfer coefficient, $\overline{U}$. The optical efficiency of the glazing system ($\overline{\eta}_o = \overline{SC}\cdot\overline{F}_s$) is represented by the condition at zero loss ($\overline{T}_i = \overline{T}_o$). The value of solar radiation transmitted through the glazing system to the indoor space over the time period, p, is thus given by:

$$Q_{solar} = \overline{F}_s\cdot\overline{SC}\cdot(\overline{H})\cdot p \tag{7}$$

The seasonal net heat gain, Q, for a particular combination of outdoor and indoor conditions and a specific glazing system can be determined analytically from Eq 6 or by using the graphical representation of the thermal performance as in Fig. 1. The graphical approach has the advantage that a number of glazing systems can be compared directly on the same plot.

The linear prescription of $\overline{\eta}$ in Eq 6 relies on the assumptions that $\overline{SC}$, $\overline{F}_s$, and $\overline{U}$ are constants for all periods and that the solar gain through the glazing is unaffected by the thermal losses and vice versa. These assumptions are discussed and verified below.

WINDOWS WITH NIGHT INSULATING SHUTTERS

Night insulating shutters are often recommended as a means of decreasing the conduction heat loss of windows during nighttime. Since the over-all heat-transfer coefficient, $\overline{U}$, in Eq 6 is the average value for the window over the period (as defined earlier), it should be possible to represent the case of insulating shutter with a time-weighted-average of U, that is:

$$\overline{U} = \frac{U_{\text{with shutter}}\cdot t_1 + U_{\text{no shutter}}\cdot(24 - t_1)}{24}$$

where

t_1 is the hours of use of the shutters over a 24-hour period.

SENSITIVITY TO VARIATIONS OF PROPERTIES

In the derivation of Eq 5 it was assumed that the optical properties of the glazing, τ,α, were constants. The same assumption was also applied to the over-all heat-transfer coefficient (including the outside film coefficient and the air space resistance). These values, however, do vary with outdoor air temperature, wind speed, and angle of incidence of solar radiation.

Values of the net heat gain through single-, double-, and triple-glazing systems for eight glazing orientations and several Canadian locations were analyzed to verify whether the variability of thermal and optical properties would affect a linear representation of the thermal performance characteristic of a window. The analysis was also intended to establish appropriate average values of the shading coefficients and the over-all heat-transfer coefficient. These values of the net heat gain were calculated hourly, taking into account the hourly variation in the glazing transmission and absorptance, as well as that of the over-all heat-transfer coefficient, U. The calculation procedures are described in detail in Refs 3 and 8.

Integrated monthly values, for the heating months, of the performance factor, $\overline{\eta}$, and $(\overline{T}_i - \overline{T}_o)/\overline{H}$ for the three glazing types were obtained and plotted in Figs. 2, 3, and 4. Each figure combines calculated values for four locations (Vancouver, Winnipeg, Ottawa, and Fredericton) and eight glazing orientations (north, northeast, east, southeast, south, southwest, west, and northwest). A line representing a least-squares fit to the data points is also shown. In addition, the calculated thermal performance characteristics of a double-glazed window with an insulating shutter having a thermal resistance value of 1.06 m^2C/W and closed for 8 hours and 12 hours per day are given in Figs. 5 and 6, respectively.

As shown in Figs. 2 to 6, the data points for all locations and eight glazing orientations can be well represented by straight lines. The maximum rms error between the calculated value of $\overline{\eta}$ and the straight line fit, which is for the single-glazing case, is less than 0.08. This also indicates that constant values of $\overline{SC}$, $\overline{F}_s$, and $\overline{U}$ can be used with minimum error in Eqs 5 and 6 for calculating the average thermal performance factor of the glazing or the net heat flow through it for a period of time.

COMPARISON OF GLAZING SYSTEMS

The characteristic lines representing the various glazing systems discussed previously are shown together in Fig. 7. The values of $\overline{\eta}_o(=\overline{SC}\cdot\overline{F}_s)$ and $\overline{U}$ are presented in Tab. 1, in addition to the corresponding values from Ref. 1. It should be noted that the values of Ref 1 can be used to construct the thermal characteristic lines of the glazings or to calculate the solar heat gain with no significant loss of accuracy.

Fig. 7 shows clearly the advantage of using windows with a high thermal resistance value, especially in locations that experience low outdoor air temperature and/or low levels of solar radiation, or for window orientations other than south.

It should be possible to develop similar performance characteristics for improved glazing systems, such as honeycomb windows and windows with selective reflecting films (e.g., heat mirrors), provided that values of shading coefficient and over-all heat-transfer coefficient can be established by testing or calculation.

Example

Consider a comparison of glazing systems located in the north and south walls of a building in Ottawa, Ontario. The mean monthly values of total solar radiation for each orientation can be obtained from Ref 3 or 7. For a heating season assumed to extend from 1 October to 30 April, monthly values are averaged to produce a mean value for the heating season. Values of mean daily temperature can be obtained from Ref 9. (Values of mean daily outdoor temperature can be estimated from degree-day values if the actual values are not available.)

The glazing characteristics of Fig 7 are reproduced in Fig. 8, which also shows the values of $\overline{\Delta T}/\overline{H}$ for the south and north windows in this example. The resulting values of the performance factor and net heat gain for each case are given in Tab. 2 for the different glazing systems.

As might be expected, all windows facing north will experience a net heat loss. On the south face, however, only the single-glazed window will experience a net heat loss; all the other glazing systems experience a net heat gain.

The most energy-efficient glazing system in the example is the double-glazed window with shutter. Its performance is nearly matched, however, by that of the triple-glazed window. The choice of an appropriate glazing for both orientations must ultimately take into consideration the capital cost of the window as well as its thermal characteristic.

It should be noted that the net heat gain calculated by this method does not account for the dynamic thermal behaviour of the building, that is, no account is taken of heat storage effects or of heat dumping due to overheating. The net heat gain value represents the maximum possible reduction of heating demand of a building. In most instances the useful solar gain depends on such factors as building heating load, thermal storage mass, glazed area, and allowable indoor overheating.

A utilization factor, defined as the fraction of the solar gain that directly contributes to the reduction in heating requirement, can be calculated for combinations of the above-mentioned factors, as described in Ref 10. This, combined with solar gain values as might be calculated using this paper, provides a simple procedure for calculating the useful solar contribution to the heating of houses.

SUMMARY

A simple graphical method for comparing the thermal performance of glazing systems is presented. Thermal performance is represented by just two parameters: the over-all heat-transfer coefficient and the shading coefficient. A universal performance characteristic is established for each glazing system, independent of geographical location and window orientation. The results indicate that this performance characteristic can be constructed using constant glazing properties. The method permits calculation of the maximum net heat gain attainable with a given glazing system and should be useful to building designers in selecting the most efficient and cost-effective glazing system for a specific application.

This paper is a contribution from the Division of Building Research, National Research Council Canada, and is published with the approval of the Director of the Division.

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TABLE 1

Glazing Characteristics

Glazing Type	Fig. 7			Ref 1		
	η_o	$\overline{SC}$	$\overline{U}$, (W/k•m^2)	η_o	SC	U, (W/k•m^2)
Single glass	0.83	1	5.63	0.87	1	6.25
Insulating glass: double 1.27-cm air space	0.73	0.88	2.85	0.77	0.89	2.78
Insulating glass: triple 1.27-cm air space	0.67	0.81	1.89	0.7	0.80	1.75
Double with R1.06 shutter closed 12 h per day	0.73	0.88	1.86	0.77	0.89	-

TABLE 2

Net Heat Gain for Windows in Ottawa

	Vertical S Window		Vertical N Window	
$\overline{H}$ (W/m^2)	118.63		47.92	
$\overline{T}_o$ (°C)	-2.19		-2.19	
$(\overline{T}_i-\overline{T}_o)/\overline{H}$, (°C/Wm^{-2})	0.19		0.46	
	$\overline{\eta}$	$\overline{Q}$(W/m^2)	$\overline{\eta}$	$\overline{Q}$(W/m^2)
Single-glazed	-0.25	-29.6	-1.77	-84.8
Double-glazed	0.185	21.9	-0.58	-28
Triple-glazed	0.31	36.3	-0.20	-9.8
Double-glazed with 12-h shutter closure (R=1.06 m^2•C/W)	0.38	44.7	-0.12	-6.

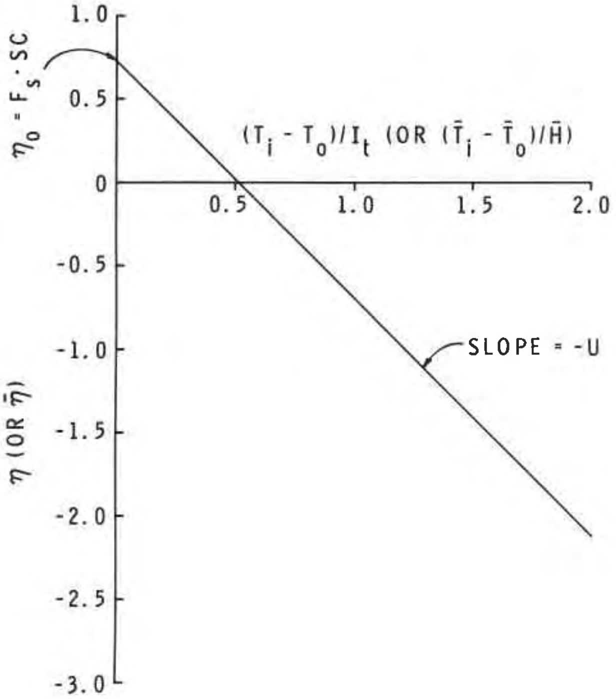

Figure 1. Glazing thermal characteristic

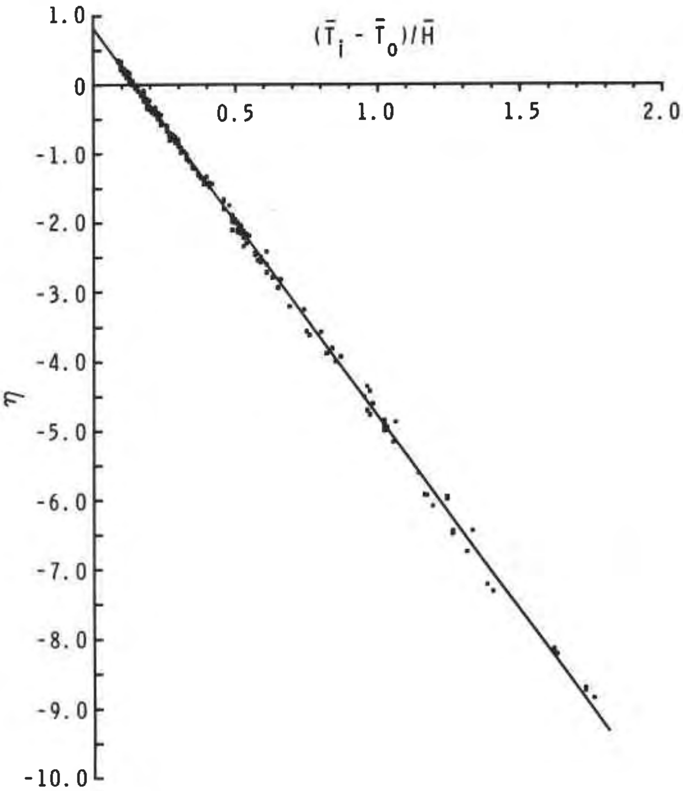

Figure 2. Single-glazing thermal characteristic

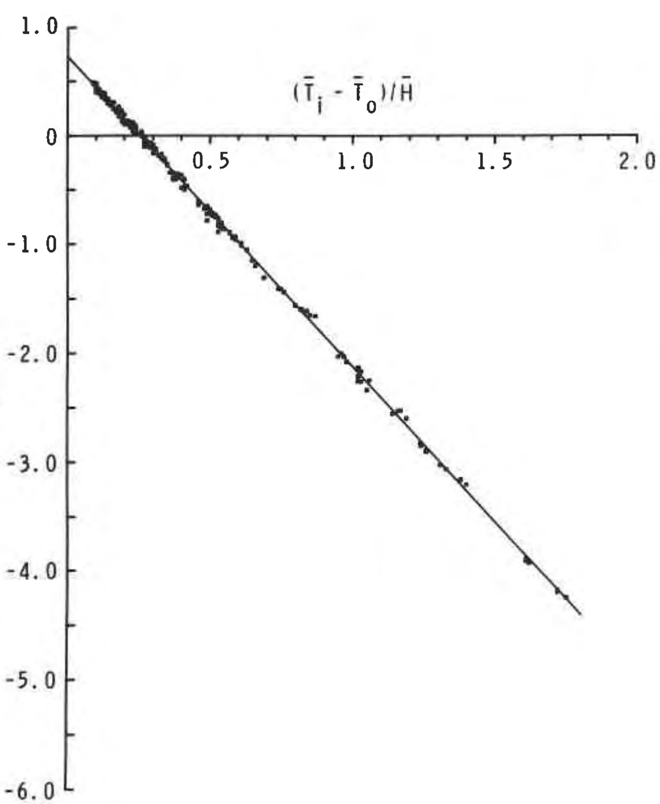

Figure 3. Double-glazing thermal characteristic

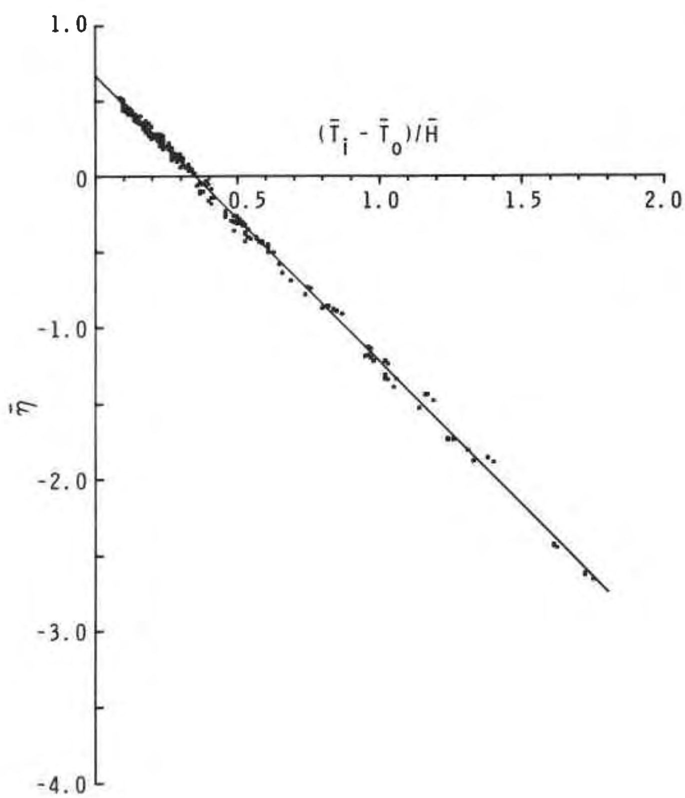

Figure 4. Triple-glazing thermal characteristic

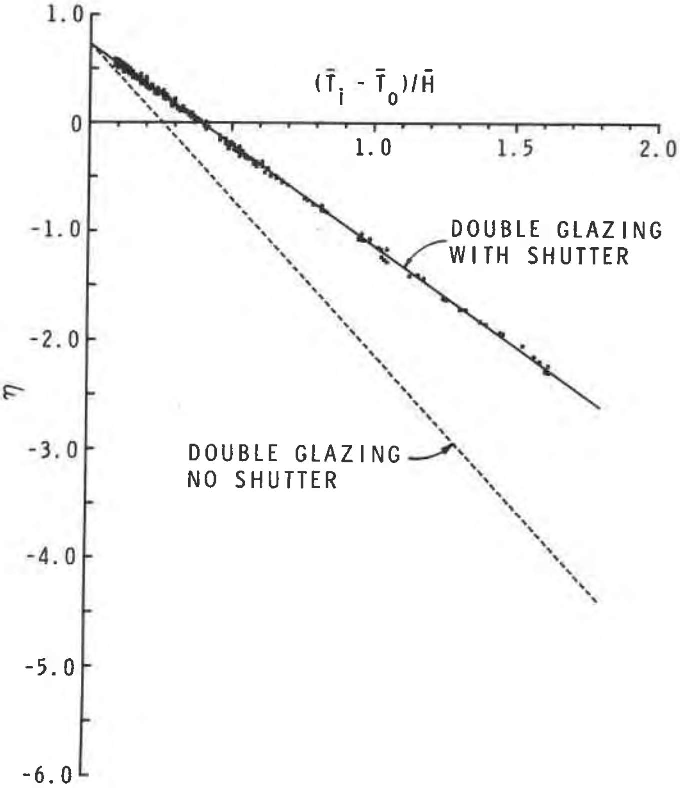

Figure 5. Thermal characteristic of double glazing with 12-h night shutte. (R = 1.06 $m^2 \cdot °C/W$)

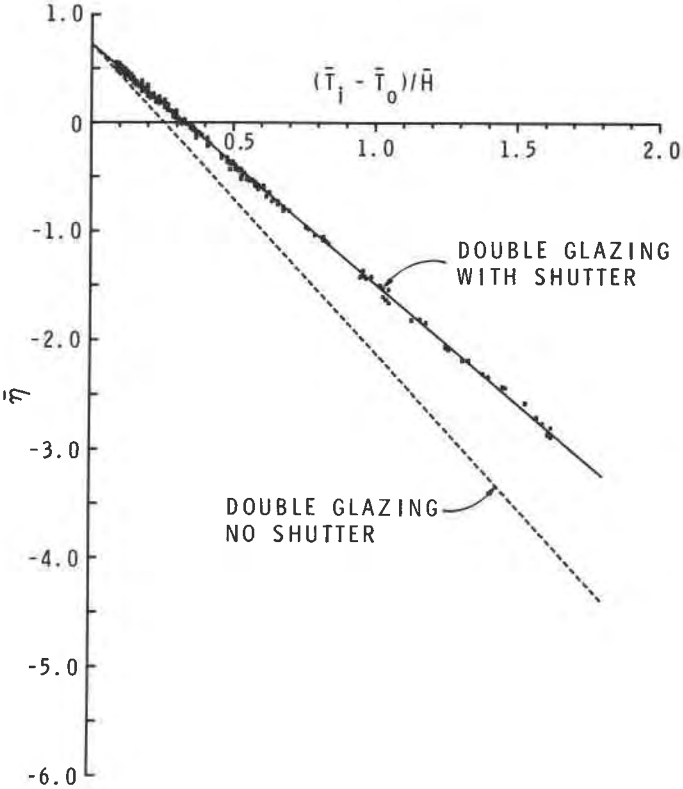

Figure 6. Thermal characteristic of double glazing with 8-h night shutter (R = 1.06 $m^2 \cdot °C/W$)

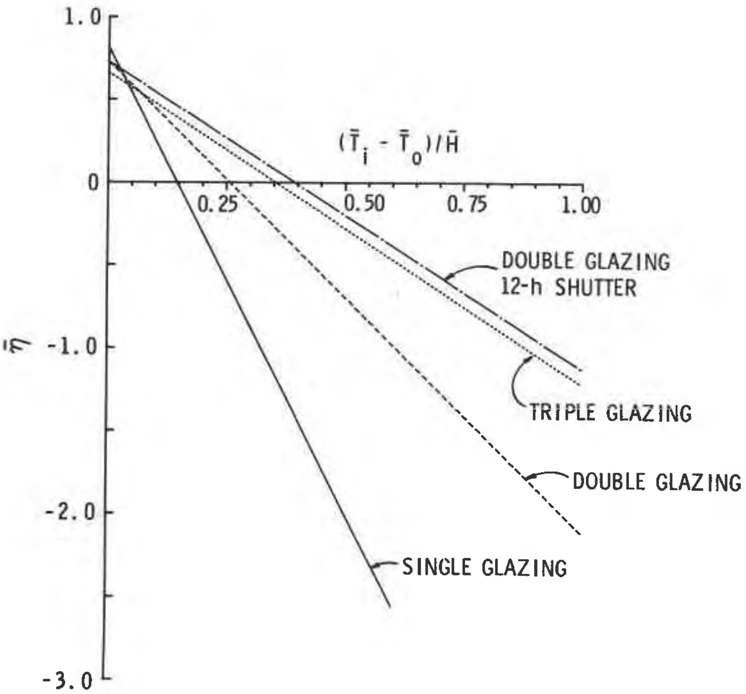

Figure 7. Comparison of thermal characteristics of different glazing systems

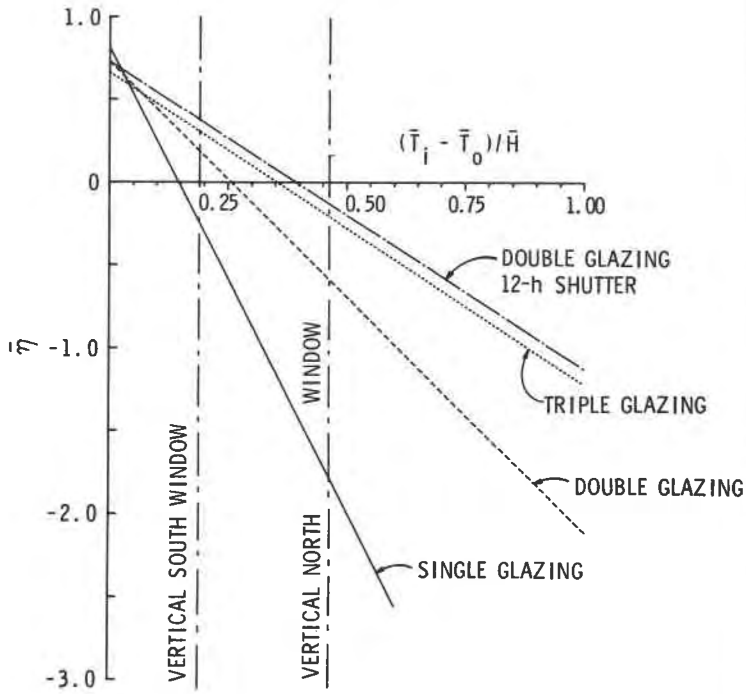

Figure 8. Example for windows in Ottawa

DISCUSSION

J.E. Rizzuto, New York State E.R.D.A., Albany: Is radiation to and from the window ignored or included in the U value?

S.J. Harrison: In calculating the U value of the window, the temperature of each glazing is calculated every hour. This calculation takes account of the variation in film coefficient, and the solar radiation absorbed by the glass. The glass temperature is then used to determine the air space resistance, utilizing an overall heat transfer coefficient accounting for radiation and convection heat transfer. The details of the calculations are presented in Refs. 3 and 8 listed in the paper.

P. Schatkun, New York State Div. of Housing, New York: What was the thickness of glass used in the study for single-, double-, and triple-glazing?

Harrison: Glass thickness was:
single 0.125 in. (0.3175 cm)
double 0.25 in. (0.635 cm) both
triple $\frac{1}{4}$-1/8-$\frac{1}{4}$ in. (0.3175 - 0.635)

Schatkun: What thickness of air space was utilized between the double and triple glazing?

Harrison: An air space of $\frac{1}{2}$ in. (1.27 cm) was given in Tab. 1 of the paper.

Schatkun: What time of year, i.e., heating or cooling seasons, were utilized in developing the heat transfer factors?

Harrison: The heating season was defined as Oct. 1st through Apr. 30.

Schatkun: Is there a follow-up theroetical or practical experiment being considered to determine the effect of different reflective film coatings for double and triple thickness glazing for heating or cooling applications?

Harrison: A theoretical study is underway to calculate the performance of reflective film coatings and other window improvements for heating applications. This study will also be accompanied in the future by window testing to determine their characteristics.

It should be noted that the values used for the window specifications were chosen to correspond with those presented in Ref. 1. The results presented are intended to illustrate and confirm the simple representation of window performance. In fact, any window may be represented and the analysis performed if values of SC and U are known.