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MODELING WINDOWS IN DOE-2.1E

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Abstract

The most recent version of the DOE-2 building energy simulation program, DOE-2.1E, provides for more detailed modeling of the thermal and optical properties of windows. The window calculations account for the temperature effects on U-value, and update the incident angle correlations for the solar heat gain properties and visible transmittance. Initial studies show up to a 35% difference in calculating peak solar heat gain between the detailed approach and a constant shading-coefficient approach. The modeling approach is adapted from Lawrence Berkeley Laboratory's WINDOW 4 computer program, which is used in the National Fenestration Rating Council (NFRC) U-value rating procedure 100-91. This gives DOE-2.1E the capability to assess the annual and peak energy performance of windows consistent with the NFRC procedure. The program has an extensive window library and algorithms for simulating switchable glazings. The program also accounts for the influence of framing elements on the heat transfer and solar heat gain through the window.

Introduction

Building energy simulation programs generally take simplified approaches to modeling windows because of the complexity of a building environment. For example, the conduction and solar heat gain are often calculated using a constant U-value and shading coefficient. However, a more detailed analysis is required to accurately evaluate the influence of fluctuating environmental conditions (temperature, wind speed, solar intensity and position) on the energy use associated with windows. This is especially true now with the advent of new window designs incorporating low-E coatings, low-conductivity gas fills, and spectrally selective glazings.

DOE-2.1E is the most recently released version of the DOE-2 building energy simulation program, which has the capability to model the thermal and optical behavior of windows in more detail. DOE-2.1E adopted the procedure used in the WINDOW 4 computer program (LBL 1992) for calculating the thermal performance of windows, which is consistent with the National Fenestration Rating Council's U-value rating procedure 100-91 (NFRC 1991). Therefore, NFRC-rated products can now be accurately simulated with DOE-2. The calculations also account for the solar energy absorbed and transmitted inside by the window-framing elements.

The WINDOW 4 program was also used to compile an extensive window library for DOE-2.1E. The library lists the solar and visible properties as a function of angle of incidence and the thermal properties of 200 currently-available windows plus a selection of experimental electrochromic glazings. Among the currently-available products are single-, double-, triple-, and quadruple-pane windows with different tints, coatings, glass thicknesses, gas fills, and gap widths. Algorithms have been incorporated for modeling switchable glazing technologies using the library, and the glazings can be controlled through various switching strategies. DOE-2.1E retains the window library from the earlier versions of the program. The option to model windows assuming a constant shading coefficient also exists in order to afford upward compatibility with the previous versions.

Methodology

To model a particular window in DOE-2.1E, the user can choose a window from the window library in DOE-2.1E or design a window within procedural limits with WINDOW 4 and add it to the window library. Each library entry is listed with its thermal and optical properties and individual layer designations (Table 1). The U-value and solar heat gain properties—shading coefficient (SC) and solar heat gain coefficient (SHGC)—calculated at ASHRAE winter and summer design conditions, respectively, are listed to help identify products. The total solar transmittance (T_{sol}), solar reflectance of the outside exposed surface (Rf_{sol}), the visible transmittance (T_{vis}), and the visible reflectance of the outside exposed surface (Rf_{vis}) are given at normal incidence. Each glazing layer within the window has an associated identification number (ID) and width (WID). The ID number refers to the records in WINDOW 4's glass library. The type of gas fill is listed for each gap along with the gap width (WID).

Associated with each of the DOE-2.1E window library entries is the WINDOW 4 output file (Figure 1), which contains detailed information on the window system. These data serve as input to the heat transfer calculations in DOE-2.1E. The information includes the solar and visible optical properties, the solar heat gain coefficient for the glazing system at 10° increments from 0° to 90° (0° is normal incidence), and the hemispherical values. The infrared hemispherical transmittance and emittances, the thickness, and the conductivity for each glazing layer are listed, as are the gas properties and gap width for the individual gas layers. Frame and spacer U-values are given along with the height and width of the window and the glazing system.

Conventional glazing

Except for the electrochromic glazings, the window library represents products available on the market today. Figures 2 and 3 show the range of center-of-glass U-value, shading coefficient and visible transmittance for these products. The total optical properties were calculated from glazing manufacturers' optical data. The total solar, visible, and infrared properties for each glazing layer were used to find the total optical properties for the glazing system. The angular properties, which are valid for homogeneous glass (uncoated), are found by applying the Fresnel equations and Snell's law (Furler 1991). The angular calculations are valid for homogeneous glass (uncoated). For coated glass, the assumptions were made that for a solar transmittance greater than 0.65 the glazing behaves like clear glass and for glazings with a transmittance less than 0.65 the glazing behaves like bronze glass. Although the total optical properties for the glazing layers were used to find the system optical properties, spectral data can be used for individual glazing layers (angular calculations are performed wavelength by wavelength). For glazing with a strong spectral dependence, the spectral calculations offer greater accuracy.

Electrochromic glazing

The solar-optical data for the experimental electrochromic entries in the library were compiled from measurements made at Lawrence Berkeley Laboratory and at other organizations. Electrochromic choices (Figure 4) include absorbing or reflecting in single and double pane configurations. Each electrochromic glass type is represented by two entries, one for the bleached state and one for the colored state. If electrochromic glass is used in the DOE-2.1E switchable glazing simulation, the program will use a weighted average of the bleached and colored state properties each hour, where the weighting is determined by the control mechanism selected by the user.

Custom glazing

In addition to the existing window library entries, the user has the flexibility to design a window system and add it to the DOE-2.1E library. The user can model more complex systems and input the properties into the computer program's reporting format for use in DOE-2.1E. The user can also override the frame and spacer properties and window dimensions in the window library by specifying values within the DOE-2 input file (LBL 1993).

Thermal calculations

The thermal calculations in DOE-2.1E were adopted directly from WINDOW 4, which calculates the U-value for window systems using a finite-difference method. The temperature distribution across the center of the glazing system for a given set of environmental conditions is solved through an iterative technique that performs an energy balance at each glazing surface (Arasteh et al. 1989). Heat transfer by combined conduction, convection, and long-wave radiation are accounted for. From these results the fraction of absorbed solar radiation flowing inward is found.

Given the inside and outside air temperatures, the sky conditions and incident solar radiation, and the outside wind speed and direction, DOE-2.1E solves for the steady-state temperature distribution, U-value, and the solar heat gain for the center-of-glass area. The outside wind speed and direction are used to determine the convective conductance of the outside air film, which is based on a new empirical correlation from the LBL MoWiTT calorimeter (Yazdanian 1994). The glazing system can have up to five glazing layers and can be filled with air, argon, krypton, sulfur hexafluoride, carbon dioxide, or a mixture of these gases. The possible glazing materials include, but are not limited to, tinted glass, coated and uncoated glass, and coated polyester films. Note that glazing temperatures can be accessed and used to study condensation and occupant thermal comfort.

The total U-value and solar heat gain for the complete window system is then calculated taking into account the spacer and frame effects on the heat transfer. The U-value is an area-weighted average of the U-values for the center-of-glass, edge-of-glass, and frame areas. The edge-of-glass area is a 2.5-inch perimeter area measured from the site line inward. The solar heat gain is an area-weighted average of the solar heat gain for the glazing area and frame area. The edge-of-glass area is assumed to have the same properties as the center-of-glass region. Because frames are opaque to solar radiation, the solar heat gain through the frame equals the inward-flowing fraction of the absorbed solar radiation multiplied by the incident solar radiation. Additional information on total window U-values, solar heat gain, and optical properties is given in LBL (1993).

Switchable glazing algorithm

Another addition to the DOE-2.1E program is the switchable glazing algorithm. Switchable glazings are materials whose solar-optical properties vary in response to an impulse. The response may be to an electrical impulse, as with electrochromic devices; it may respond to temperature, as with thermochromic devices; or it may respond to the amount of incident solar radiation, as with photochromic devices. The properties of electrochromic devices and photochromic devices vary between a clear and colored state, and those of a thermochromic window switch only from a clear to a colored state or vice versa.

The algorithms allow the user to choose two glazings from the window library representative of the clear and colored states of the window. DOE-2 varies the state of the window between the clear colored states in accordance with the control strategy specified by the user. The control strategies include switching with respect to (1) the amount of direct solar radiation incident on the glazing, (2) the total solar radiation incident on the surface, (3) the direct solar radiation transmitted by the glazing in the clear state, (4) the total solar radiation transmitted by the glazing in the clear state, (5) the total solar radiation incident on an unobstructed horizontal plane, (6) the outside temperature, (7) the previous-hour space load per square foot of floor area, or (8) the daylight level at a reference point in the space. The user specifies the high and low values for the control strategy at which the window is either in its clear or colored state (Figure 5).

Results

The new window models in DOE-2.1E provide greater accuracy and flexibility in simulating the thermal and daylighting effects of windows. In this section we compare the results of calculating solar heat gain with a shading-coefficient approach versus a detailed approach with correct incident angle correlations. We also illustrate the switchable glazing simulation.

Solar gain: detailed calculation vs. shading coefficient approach

In the detailed method the solar gain is determined from the actual angular dependence of solar transmission and absorption of the selected glazing as obtained from the window library. The solar gain is the sum of that due to transmitted solar radiation (direct radiation from the sun and diffuse radiation from the sky and ground) and solar radiation that is absorbed in the glass. The fraction of absorbed radiation that is conducted into the room, and thus contributes to the solar gain, is given by the outside air film resistance (which decreases with wind speed) divided by the overall thermal resistance of the glazing.

In the ASHRAE shading coefficient method (ASHRAE 1989), the solar gain is first determined for a *reference glazing* consisting of 1/8-inch (3 mm) clear glass under ASHRAE standard summer conditions—95F (35C) outside temperature, 75F (24C) inside temperature, 7.5 mph (3.3 m/s) wind speed, and near-normal irradiance of 248 Btu/h-ft^2 (783 W/m^2). The reference glazing has a solar transmittance of 86% and an absorptance of 8.8% at normal incidence. The solar gain for the selected glazing is then determined each hour by multiplying the solar gain of the reference glazing by the shading coefficient of the selected glazing.The shading coefficient is determined by measurement in a solar calorimeter or by calculating it with a program like WINDOW 4.

As illustrated in the following comparisons, the shading coefficient method gives incorrect hourly results in two main cases:

(1) When the transmittance angular distribution of the actual glazing differs substantially from that of the reference glazing; this is the case for *all* multipane glazing at angles of incidence above 60°.

(2) When the solar gain is primarily due to absorption (which is true for half of the glazings in the DOE-2 window library) and the wind speed is not close to the wind speed at which the shading

coefficient was determined (7.5 mph).

Despite these limitations, which can seriously effect the accuracy of calculating peak cooling loads and, therefore, peak electric demand, the shading coefficient is still commonly used in simplified energy analysis programs.

Hourly comparison

Figure 6 compares the hourly results for the two methods for vertical, south-facing glazing on a clear June day in Chicago for two wind speeds. The glazings analyzed are *single-pane reflective* (7% transmittance, 80% absorptance, 0.29 shading coefficient) and *double-pane clear* (70% transmittance, 17% absorptance, 0.89 shading coefficient). At 7.5 mph (the wind speed at which the shading coefficient is determined) the shading coefficient method underpredicts the solar gain by up to 10% for the single/reflective glass and overpredicts by up to 17% for the double/clear glass. At zero wind speed the agreement is worse: the shading coefficient method underpredicts by up to *35%* for the single/reflective glass and overpredicts by up to 12% for the double/clear glass. The differences can be explained as follows:

At 7.5 mph the difference for double/clear glass is worst around noon when the sun is high in the sky and the angle of incidence on the glass (about 70°) is furthest from the angle of incidence at which the shading coefficient is calculated (0°). Figure 7 shows that the relative transmittance of the reference glass is higher than that of the double/clear glass above 50°; as a result the shading coefficient method gives transmitted solar gains that are too high at the larger angles of incidence. On the other hand, the absorptance angular distribution for the single/reflective glass (not shown) is, fortuitously, close in shape to the transmittance angular distribution for the reference glass, which leads to relatively good agreement between the two methods for all hours at 7.5 mph.

At zero wind speed the solar gain difference for double/clear glass is again due to the higher relative transmittance of the reference glass above 50°; the wind speed effects are minimal because less than 10% of the solar gain is due to absorption in both the actual glass and the reference glass. On the other hand, almost all of the solar gain for the single/reflective glass is due to absorption. Therefore, since the inward-flowing fraction of absorbed radiation is *higher* at lower wind speed (because the outside air film resistance is higher), the actual solar gain for the single/reflective glass is *higher* at 0 mph than at 7.5 mph. But the solar gain for the reference glass, which has low absorptance, is insensitive to wind speed, so that the shading coefficient method gives almost the same solar gain at the two wind speeds, which leads to the 35% underprediction by this method.

Monthly comparison

Monthly integrated results for different orientations (Figures 8 and 9) show better agreement, but the shading coefficient approach can still over- or underpredict by 10–20% for certain months and orientations when the average monthly wind speed or angle of incidence differ from the ASHRAE standard values. Further discussion of the limitations of the shading coefficient approach can be found in McCluney (1991).

Switchable glazing example

An example of switchable glazing simulation with daylighting control is shown in Figure 10 for south vertical glazing on a clear July day in Chicago. The clear and colored states of the hypothetical electrochromic glass were chosen from the DOE-2.1E window library. The clear state is double-pane clear insulating glass with a visible transmittance (at normal incidence) of 0.78 and a shading coefficient of 0.81. The colored state is reflective insulating glass with a visible transmittance of 0.18 and a shading coefficient of 0.26. In the simulation, the control adjusts the visible transmittance of the glass between 0.78 and 0.18 so that the daylight illuminance at a reference point 10 feet (3 m) from the window is as close as possible to the 50 footcandle (538 lux) setpoint. In this type of control, the cooling load is minimized by excluding solar gain in excess of that needed to meet the illuminance requirement (the solar gain varies relative to the visible transmittance). For comparison, Figure 10 also shows two non-switching alternatives in which the glazing is fixed in its clear or colored state. (The switchable glazing model in DOE-2.1E allows the control to vary seasonally so that, for example, the glazing could be maintained in its clear state in the winter to maximize solar gains, thus reducing the heating load.)

Discussion

The results presented here show that the shading coefficient approach incorrectly estimates hourly solar heat gain values by as much as 35% compared to the more detailed calculation approach that uses the correct angular distributions for transmittance and absorptance. The difference is most pronounced for low-transmitting, highly absorbing glass at wind speeds that are higher or lower than the 7.5 mph wind speed at which the shading coefficient is determined. Significant differences are also observed for multipane glazings, which typically have transmittance distributions that differ substantially from that of the reference glazing at large angles of incidence.

In terms of monthly or annual energy use, the two approaches are more comparable. However, when considering peak loads and the short-time-step impact of solar gains, the detailed method is more accurate.

Conclusions

The latest revision to the DOE-2 building energy simulation program incorporates detailed thermal calculations for windows, along with algorithms for modeling switchable glazings. These calculations access an extensive window library. The WINDOW 4 program for calculating the thermal performance of windows has updated algorithms for determining glazing optical properties between 0° and 90°.

The shading coefficient approach can overpredict the solar heat gain through a window at a given hour by as much as 35%. The implications of this on load calculations are significant, and we recommend use of the detailed method for such simulations.

DOE-2.1E can also take advantage of any future improvements to the WINDOW 4 program. For example, at present the angular dependence of coated glazings is being studied. When more accurate results are available and incorporated into the computer program, DOE-2 can access the new files.

Acknowledgments

We thank Michael Rubin, Deborah Hopkins, and Elizabeth Finlayson for measurements, data compilation, and WINDOW 4 processing for the electrochromic entries in the DOE-2.1E window library.

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Table 1
Example of a DOE-2.1E Window Library Entry

									LAY 1		GAP 1		LAY 2	
ID	U-SI	U-IP	SC	SHGC	T_{sol}	Rf_{sol}	T_{vis}	Rf_{vis}	ID	WID	GAS	WID	ID	WID
2637	1.78	.31	.43	.37	.28	.10	.44	.05	451	6.0	Air	12.7	3	6.0

```
WINDOW 3.2  Data File : Single Band Calculation

Unit System: SI
Name         : DOE2 WINDOW LIB
Desc         : DOUBLE LOW-E (e3=.2) IG
Window ID    : 2612
Tilt         : 90.0
Glazings     : 2
Frame        : 3   Alum, flush           3.970
Spacer       : 1   Aluminum        1.310   0.736   0.000
Total Height: 1828.8 mm
Total Width : 1219.2 mm
Glass Height: 1714.5 mm
Glass Width : 1104.9 mm
Mullion      : None
Gap          Thick    Cond  dCond     Vis    dVis    Dens    dDens      Pr     dPr
1 Argon       12.7 0.01620  5.000   2.110   6.300   1.700  -0.0060   0.680 0.00066
2 Air           0.      0.     0.      0.      0.      0.       0.      0.      0.
3 Air           0.      0.     0.      0.      0.      0.       0.      0.      0.
4 Air           0.      0.     0.      0.      0.      0.       0.      0.      0.
5 Air           0.      0.     0.      0.      0.      0.       0.      0.      0.
Angle     0.    10.    20.    30.    40.    50.    60.    70.    80.    90. Hemis
Tsol  0.624 0.624 0.619 0.612 0.602 0.576 0.513 0.385 0.186 0.000 0.533
Abs1  0.095 0.096 0.098 0.101 0.105 0.111 0.119 0.129 0.135 0.000 0.110
Abs2  0.135 0.136 0.138 0.138 0.137 0.133 0.126 0.109 0.064 0.000 0.126
Abs3     0.    0.    0.    0.    0.    0.    0.    0.    0.    0.    0.
Abs4     0.    0.    0.    0.    0.    0.    0.    0.    0.    0.    0.
Abs5     0.    0.    0.    0.    0.    0.    0.    0.    0.    0.    0.
Abs6     0.    0.    0.    0.    0.    0.    0.    0.    0.    0.    0.
Rfsol 0.146 0.145 0.146 0.149 0.157 0.180 0.241 0.377 0.615 1.000 0.221
Rbsol 0.131 0.131 0.132 0.135 0.143 0.166 0.226 0.360 0.609 1.000 0.207
Tvis  0.744 0.743 0.739 0.733 0.722 0.695 0.624 0.474 0.239 0.000 0.643
Rfvis 0.179 0.178 0.179 0.183 0.192 0.218 0.284 0.431 0.680 1.000 0.261
Rbvis 0.165 0.164 0.165 0.168 0.178 0.202 0.265 0.404 0.648 1.000 0.243
SHGC  0.736 0.736 0.733 0.727 0.716 0.688 0.621 0.479 0.246 0.000 0.640
SC: 0.86


Layer ID#              2      350F       0        0        0        0
Tir                0.000     0.000      0.       0.       0.       0.
Emis F             0.840     0.200      0.       0.       0.       0.
Emis B             0.840     0.840      0.       0.       0.       0.
Thickness(mm)        3.0       3.0      0.       0.       0.       0.
Cond(W/m2-C)       300.0     300.0      0.       0.       0.       0.
Spectral File       None      None    None     None     None     None

Overall and Center of Glass Window U-values (W/m2-C)
Outdoor Temperature                  -17.8 C       15.6 C       26.7 C       37.8 C
Solar      WdSpd  hcout hrout  hin
(W/m2)     (m/s)     (W/m2-C)
  0         0.00  12.25  3.25  7.65  2.10 1.61  2.09 1.59  2.13 1.64  2.21 1.74
  0         6.71  25.47  3.22  7.68  2.17 1.70  2.14 1.66  2.18 1.71  2.27 1.82
 783        0.00  12.25  3.36  7.30  2.17 1.69  2.20 1.73  2.25 1.80  2.30 1.86
 783        6.71  25.47  3.28  7.03  2.23 1.77  2.26 1.80  2.31 1.87  2.36 1.93
```

Figure 1. Sample window library entry showing solar-optical and thermal data used in the DOE-2.1E simulation. This file is produced by the WINDOW 4 calculation based on layer-by-layer input.

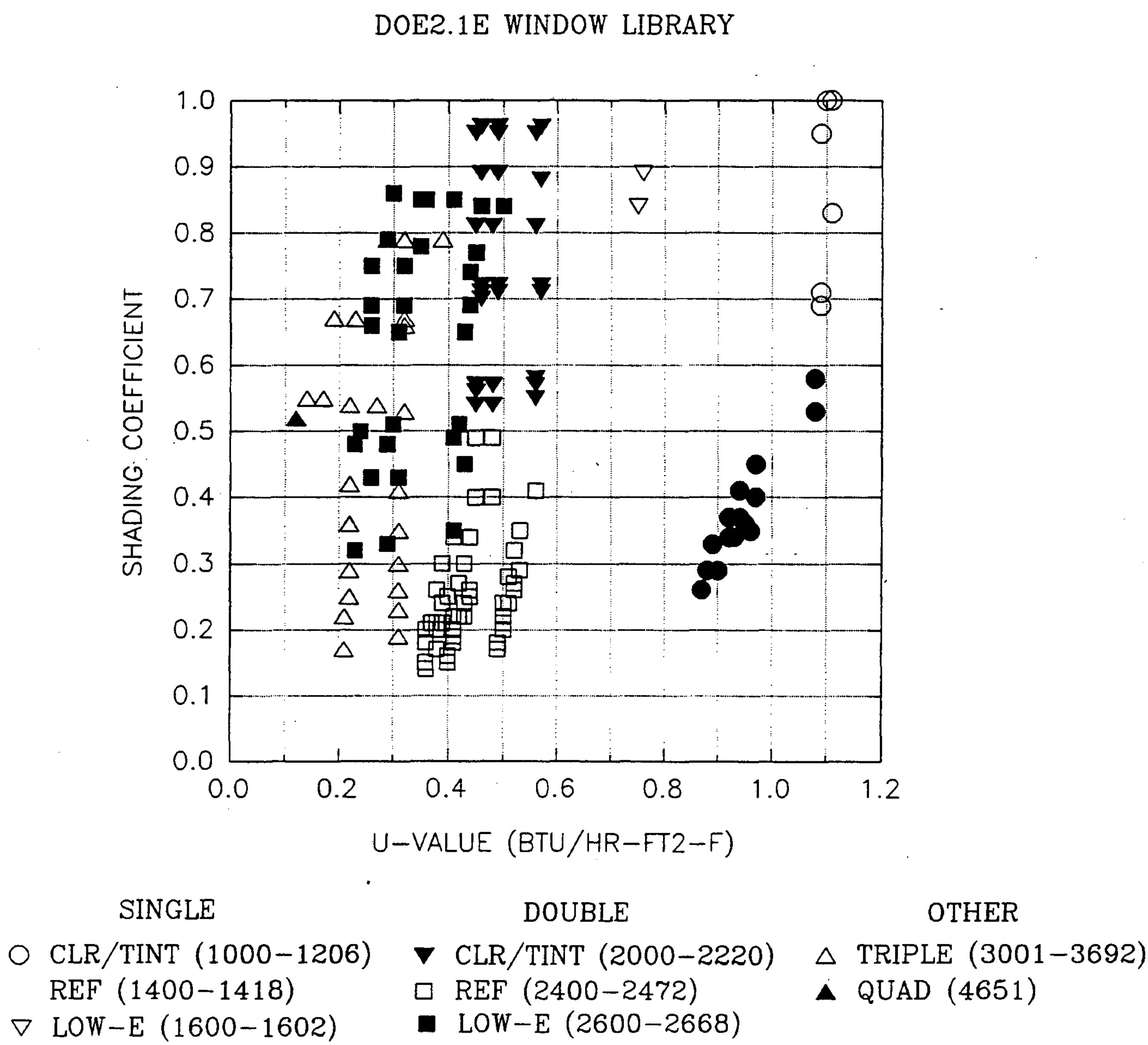

Figure 2. Center-of-glass shading coefficient vs. center-of-glass U-value for the conventional glazings in the window library. CLR/TINT is clear or tinted glass; REF is glass with a reflective coating; LOW-E is glass with a low-emissivity coating; SINGLE, DOUBLE, TRIPLE and QUAD refer to the number of panes. Numbers in parentheses give the GLASS-TYPE-CODE range.

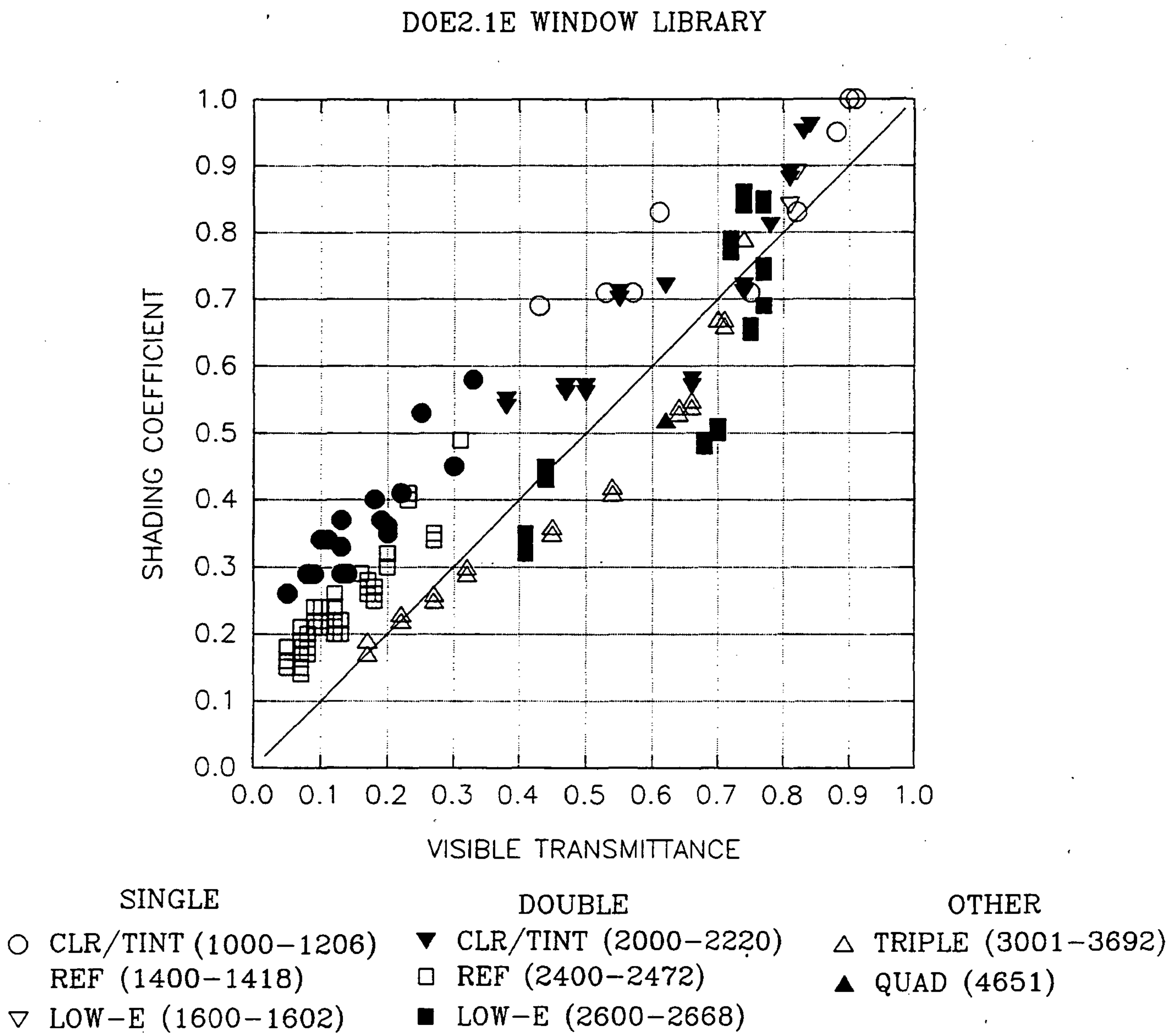

Figure 3. Center-of-glass shading coefficient vs. visible transmittance for the conventional glazings in the window library. CLR/TINT is clear or tinted glass; REF is glass with a reflective coating; LOW-E is glass with a low-emissivity coating; SINGLE, DOUBLE, TRIPLE and QUAD refer to the number of panes. Numbers in parentheses give the GLASS-TYPE-CODE range.

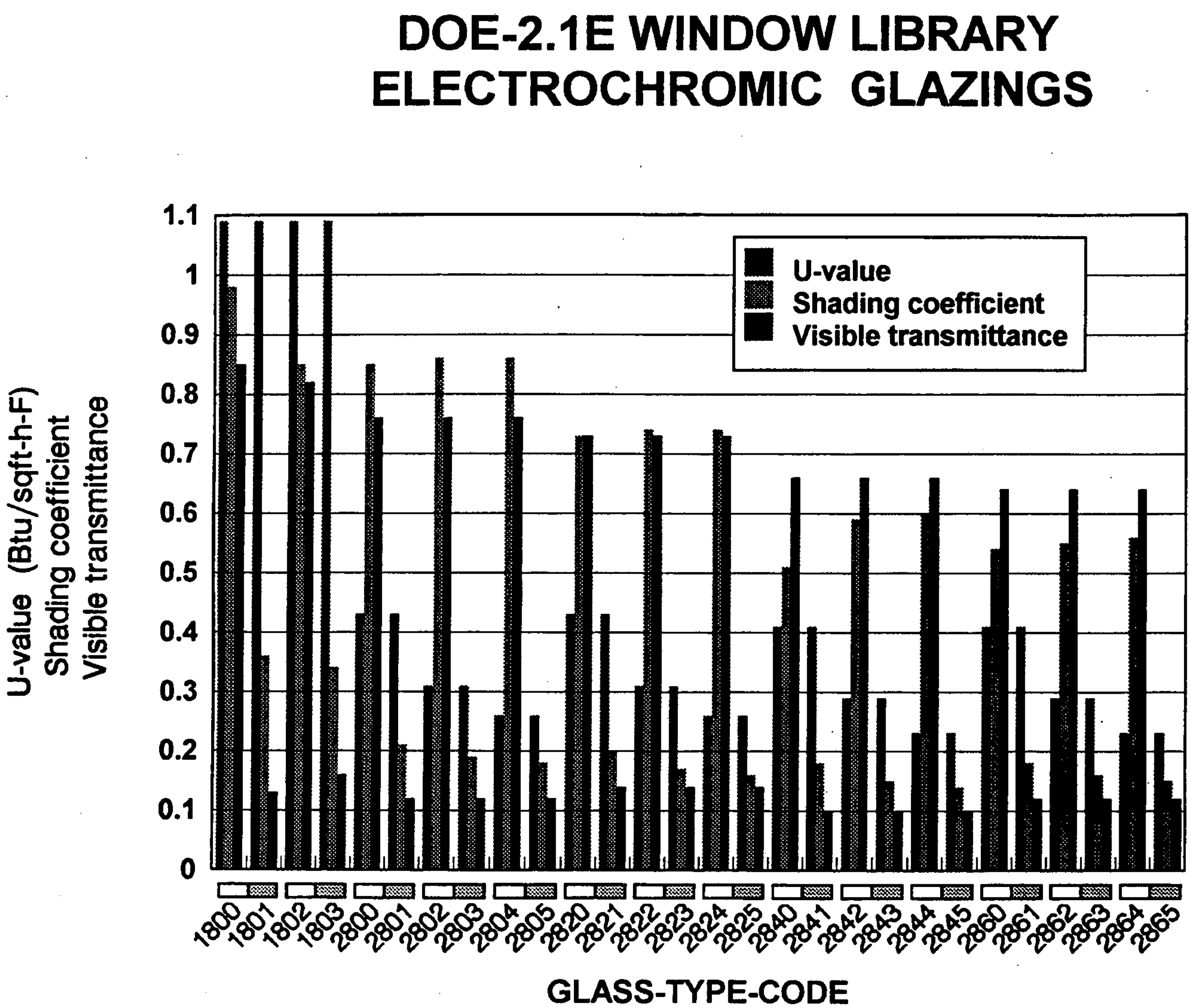

Figure 4. U-value, shading coefficient, and visible transmittance for the electrochromic glazings in the DOE-2.1E window library. For each GLASS-TYPE-CODE pair, such as (1800,1801), the left-hand group of three bars corresponds to the unswitched, bleached state and the right-hand group corresponds to the fully-switched, colored state.The choices shown are single-pane absorbing (1800-1801), single-pane reflecting (1802-1803), double-pane absorbing (2800-2805), double-pane reflecting (2820-2825), low-E double-pane absorbing (2840-2845), and low-E double-pane reflecting (2860-2865). "Absorbing" means that the electrochromic switches from transmitting to absorbing, while "reflecting" means that the electrochromic switches from transmitting to reflecting.

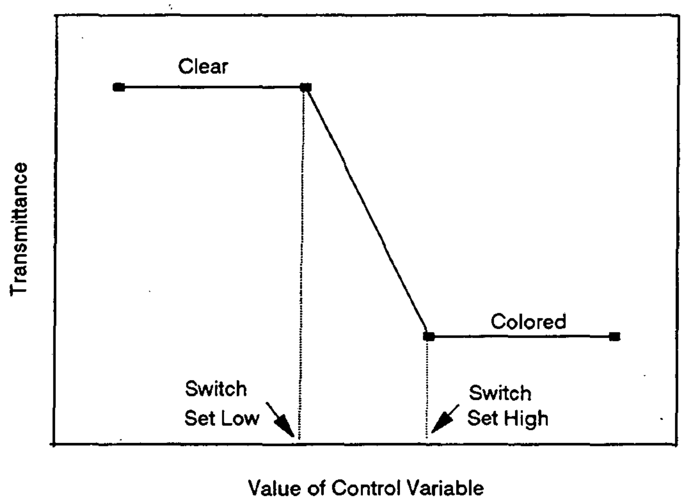

Figure 5. Control action for switchable glazing. Glass properties, such as solar transmittance, depend on the value of the user-specified control variable.

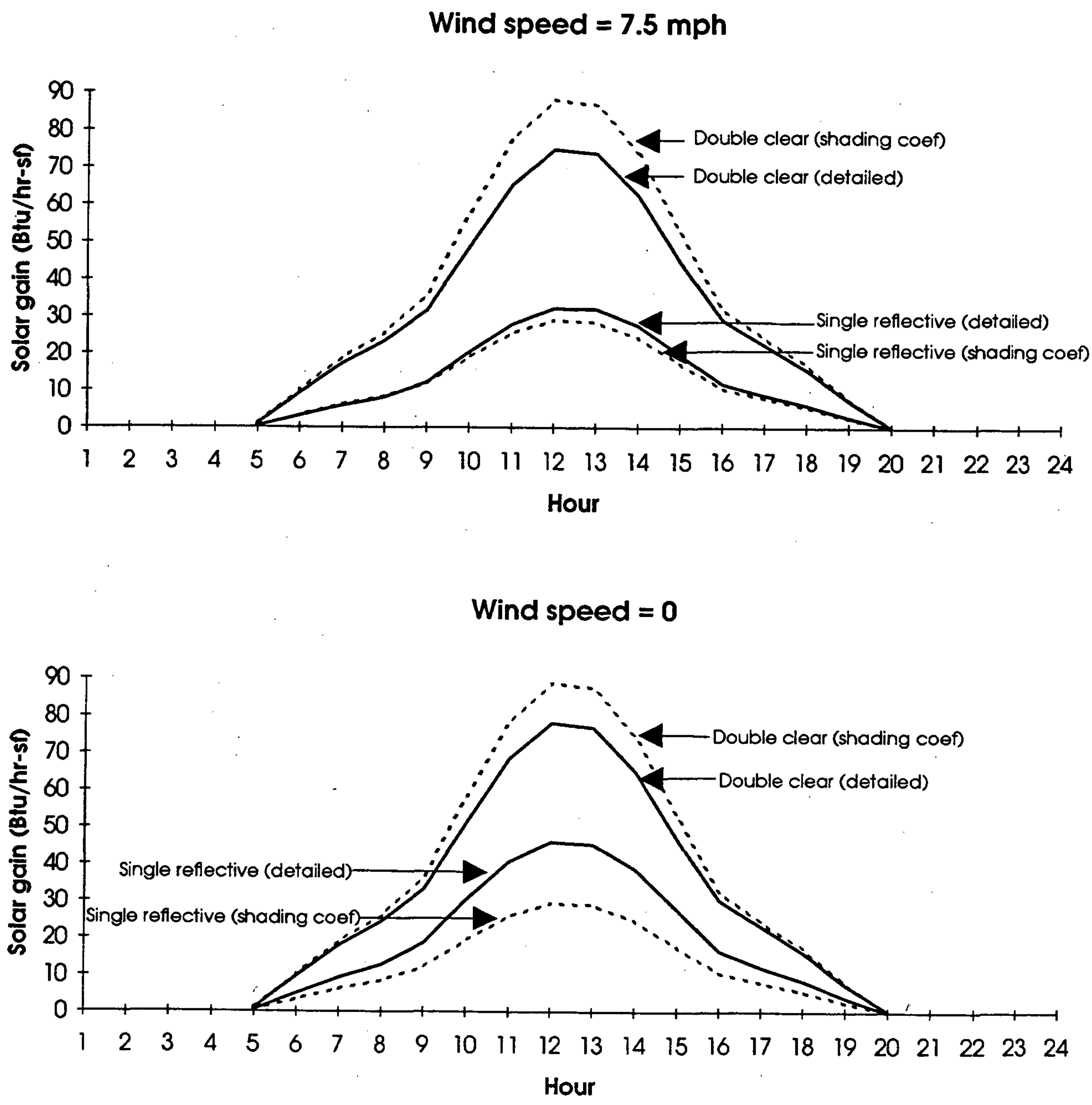

Figure 6. Hourly solar gain calculated by DOE-2.1E for south vertical glazing for a clear June day in Chicago for two wind speeds. The glazings shown are *single-pane reflective* (7% transmittance, 80% absorptance, 0.29 shading coefficient) and *double-pane clear* (70% transmittance, 17% absorptance, 0.89 shading coefficient). Two calculation methods are compared: ASHRAE shading coefficient method (dashed line) and detailed method using actual angular dependence of solar transmission and absorption (solid line).

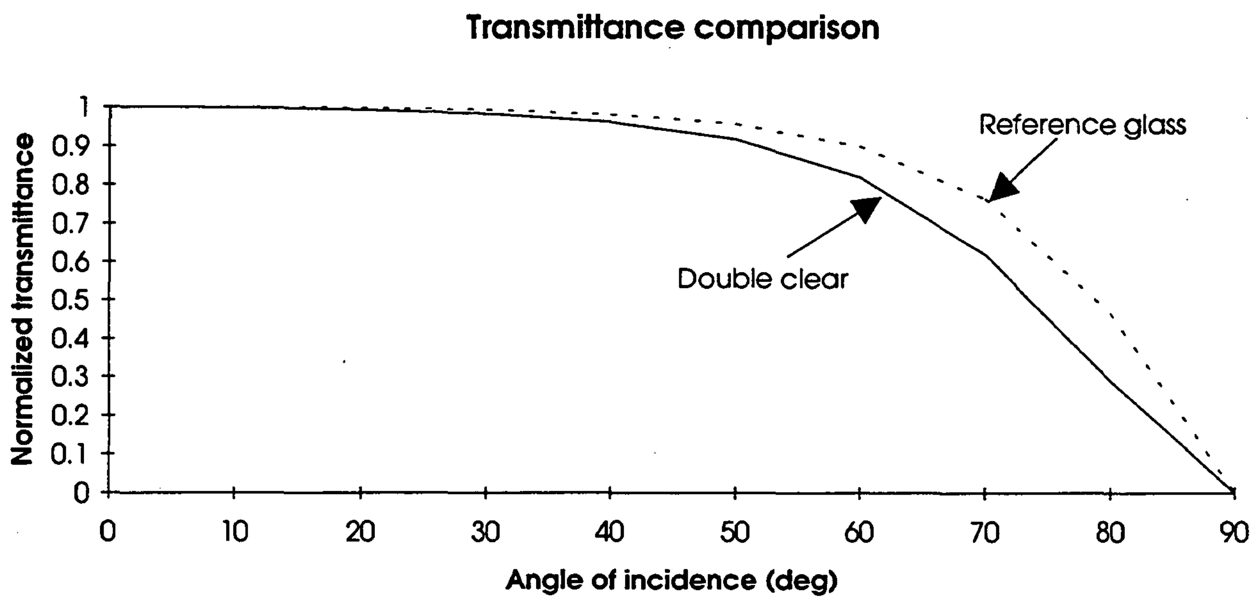

Figure 7. Normalized solar transmittance (transmittance divided by transmittance at 0°) vs. angle of incidence. "Reference glass" is the 1/8-inch clear glass used as the basis of the ASHRAE shading coefficient method of calculating solar heat gain. "Double clear" is a commonly used double-pane clear insulating glass from the DOE-2.1E window library.

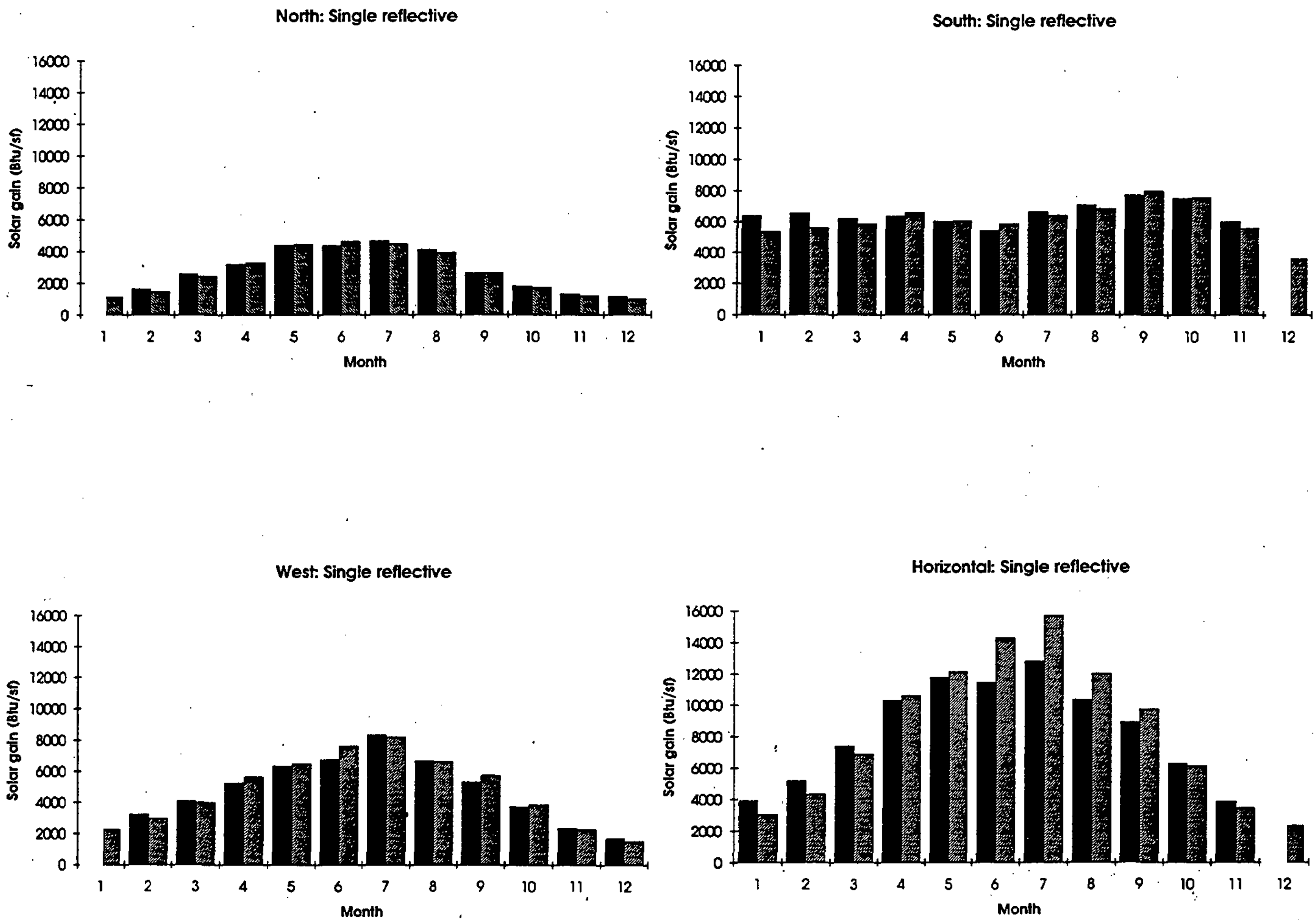

Figure 8. Monthly integrated solar gain calculated by DOE-2.1E for north, south, and west vertical glazing and for horizontal glazing in Chicago. The glazing is single-pane reflective glass (7% transmittance, 80% absorptance, 0.29 shading coefficient). Two calculation methods are compared: detailed method using actual angular dependence of solar transmission and absorption (solid bars) and ASHRAE shading coefficient method (hatched bars).

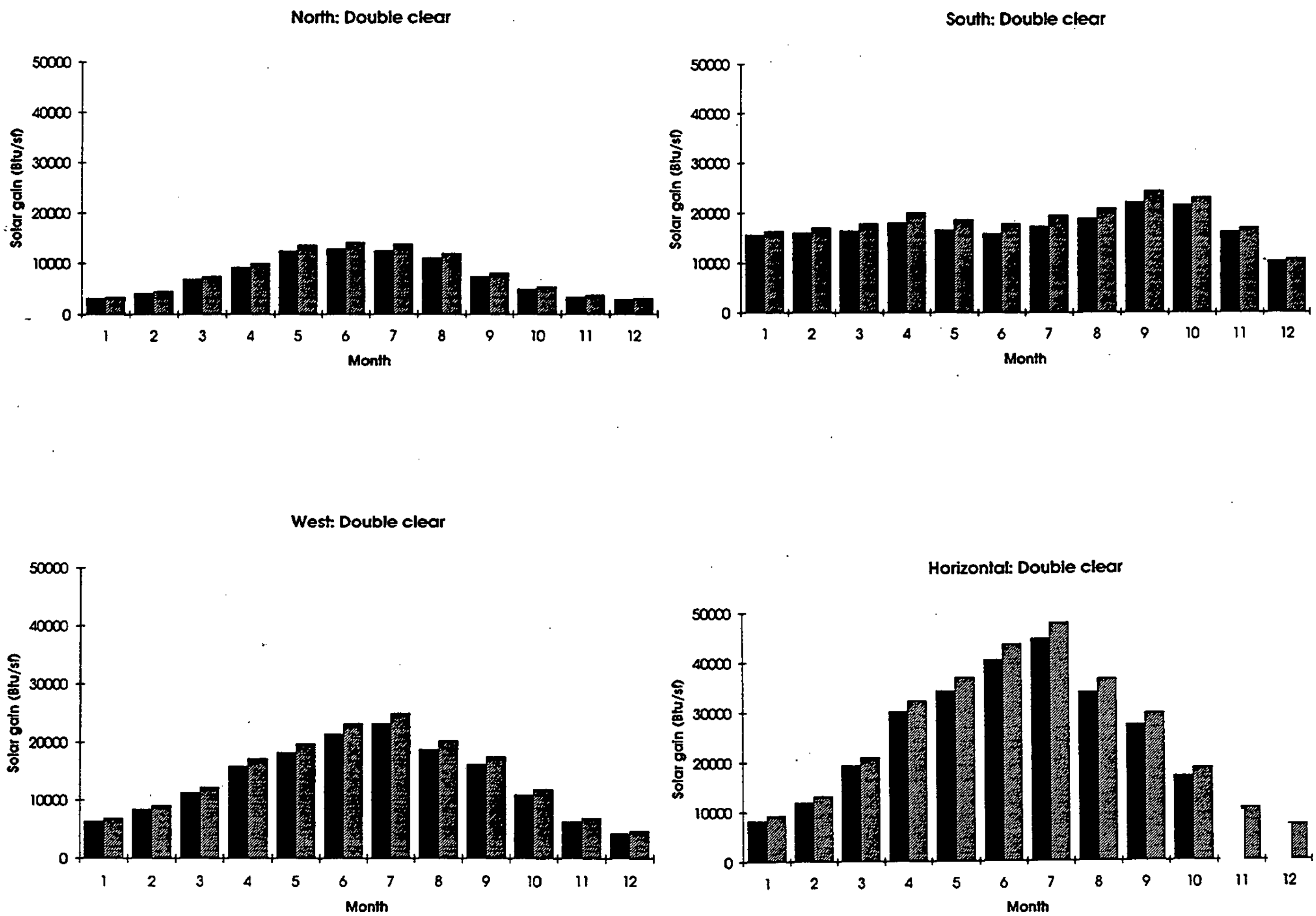

Figure 9. Monthly integrated solar gain calculated by DOE-2.1E for north, south, and west vertical glazing and for horizontal glazing in Chicago. The glazing is double-pane clear insulating glass (70% transmittance, 17% absorptance, 0.89 shading coefficient). Two calculation methods are compared: detailed method using actual angular dependence of solar transmission and absorption (solid bars) and ASHRAE shading coefficient method (hatched bars).

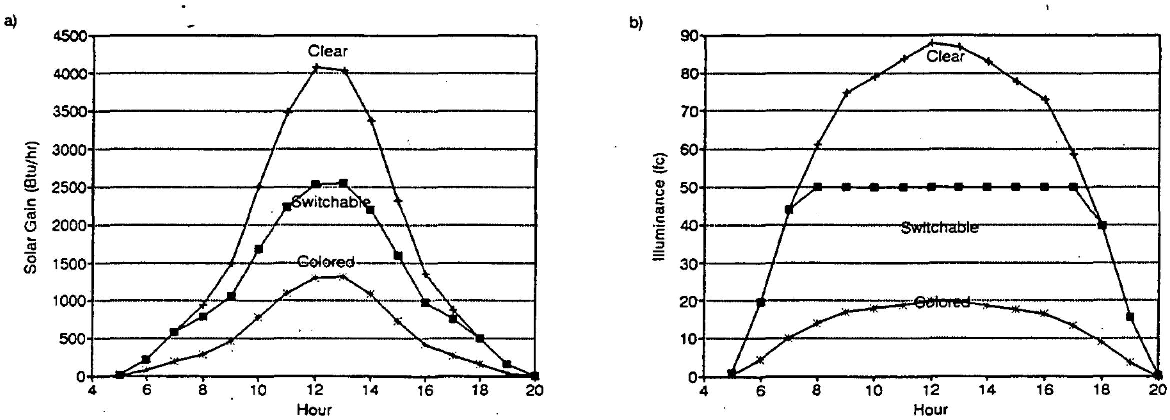

Figure 10. Switchable glazing example: hourly solar heat gain (a) and daylight illuminance (b) on a clear July day in Chicago calculated by DOE-2.1E for a south-facing 3 ft x 20 ft window with switchable glazing. The clear state is double-pane clear insulating glass with a visible transmittance of 0.78 and shading coefficient of 0.81. The colored state is reflective insulating glass with a visible transmittance of 0.18 and shading coefficient of 0.26. Three cases are shown: the visible transmittance of the glass is adjusted continuously between 0.78 and 0.18 each hour so that the daylight illuminance at a reference point 10 ft from the window is as close as possible to the 50 footcandle setpoint (switchable); the glass is fixed at its clear state (clear); the glass is fixed at its colored state (colored).

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