

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, incorporates updated algorithms for modeling 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 a 30% difference in calculating peak solar heat gain between the detailed approach and a constant shading-coefficient approach. The modeling approach is adapted from a computer program that is used in the National Fenestration Rating Council's (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 a computer program (LBL 1992a) 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 computer 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. Included are single-, double-, triple-, and quadruple-pane windows with different tints, coatings, glass thickness, 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 and add it to the window library, which contains 200 entries representative of products available on the market today. Each library entry (Table 1) is listed with its thermal and optical properties and individual layer designations. The U-value and solar heat gain properties (SC and 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 ($R_{f_{sol}}$), the visible transmittance (T_{vis}), and the visible reflectance of the outside exposed surface ($R_{f_{vis}}$) 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 the computer program'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 computer program's output file, 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 degrees (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.

As mentioned, the window library entries represent products available on the market today. The total optical

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

ID	U-SI	U-IP	SC	SHGC	T_{sol}	Rf_{sol}	T_{vis}	Rf_{vis}	LAY 1		GAP 1		LAY 2	
									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

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.

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 (see the DOE-2.1E Reference Manual [LBL 1992a] for more information).

The thermal calculations in DOE-2.1E were adopted directly from the program, 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). Combined conduction, convection, and radiation are accounted for. From these results, the fraction of absorbed solar radiation flowing inward is found.

Given the inside and outside temperatures, the outside wind speed and direction, and the sky conditions and incident solar radiation, DOE-2.1E solves for the steady-state temperature distribution, U-value, and the solar heat gain for the center-of-glass area. Note that glazing temperatures can be accessed and used to study condensation and occupant thermal comfort. The glazing system can have up to six 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.

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 gains 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. For more information on total window U-values, solar heat gain, and optical properties, see LBL (1992b).

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 windows 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 and 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 1).

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

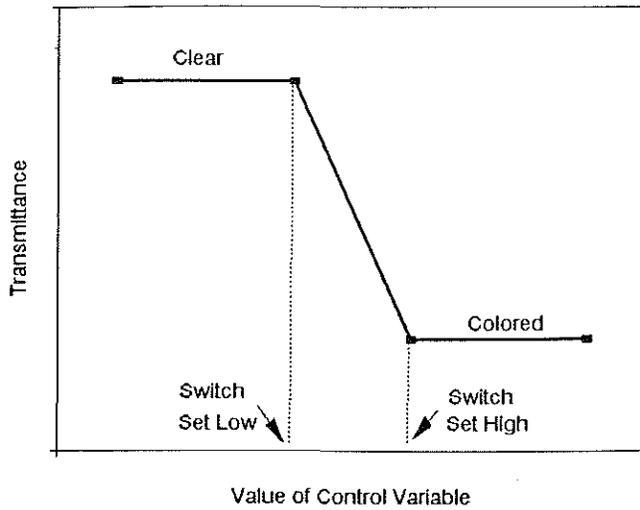


Figure 1 Control action for switchable glazing. Glass properties, such as solar transmittance, depend on the value of the user-specified control variable.

the results of calculating solar heat gain with a constant shading-coefficient approach versus a detailed approach with correct incident angle correlations. We also illustrate the switchable glazing simulation.

Figure 2 shows the hourly solar gain for clear days in January and July in Chicago for vertical glazing on south and west orientations. The glazing is either single-pane, reflective glass with a shading coefficient of 0.23 or double-pane, tinted, low-E insulating glass with a shading coefficient of 0.43. Monthly integrated solar gain values are shown in Figure 3 for all orientations for the double-pane, low-E window. In all cases, 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 and conducted into the room.

Two calculation methods are compared in these figures. The first is the ASHRAE shading-coefficient method (ASHRAE 1989). In this method, the solar gain is determined for standard 1/8-inch (3 mm) clear glass for the solar, temperature, and wind conditions and multiplied by the

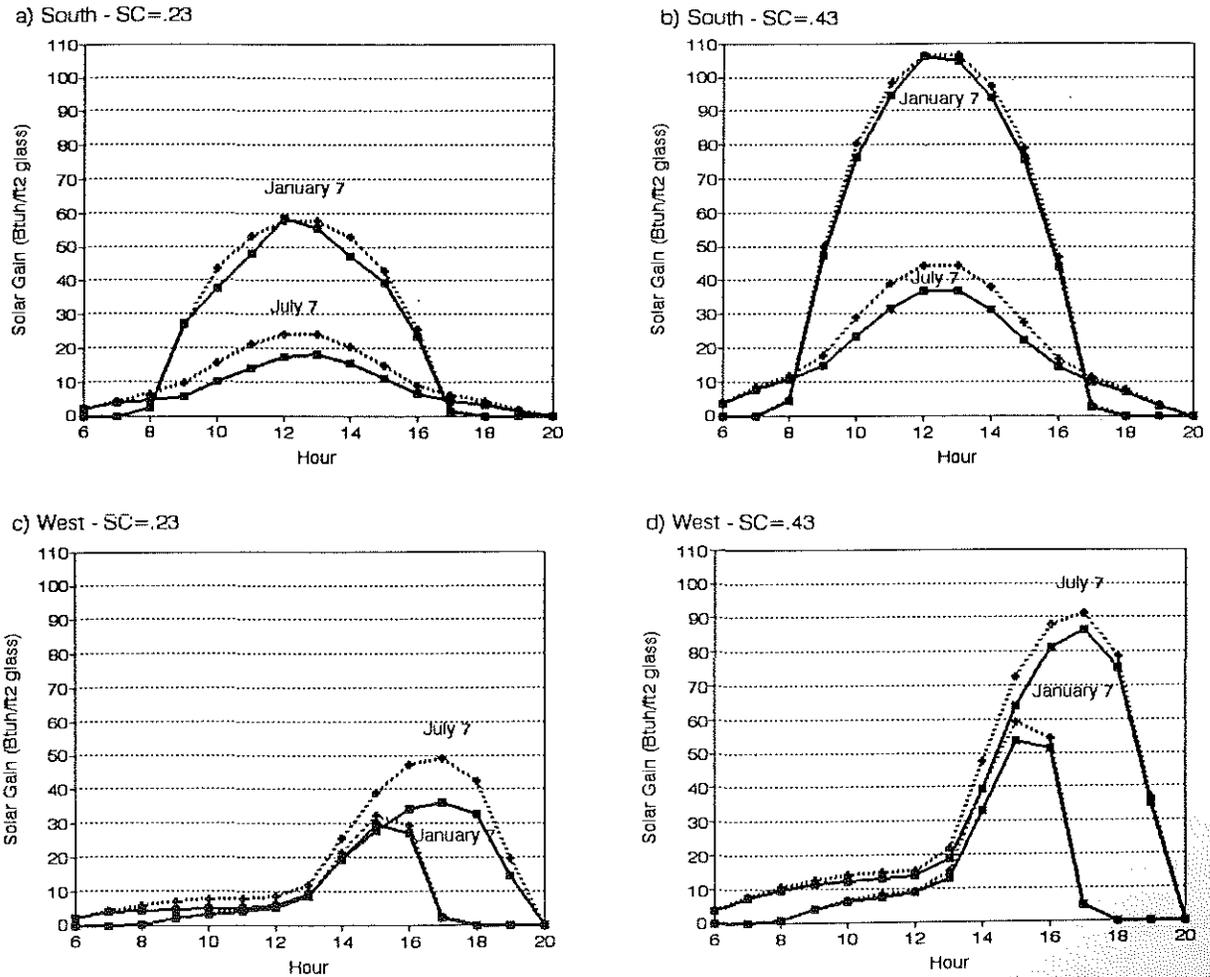


Figure 2 Hourly solar gain calculated by DOE-2.1E for south (a and b) and west (c and d) vertical glazing for clear Chicago days in January and July. The glazing with a shading coefficient of 0.23 is single pane with a highly reflective coating, and the glazing with a shading-coefficient of 0.43 is double-pane, tinted, low-E insulating glass. 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).

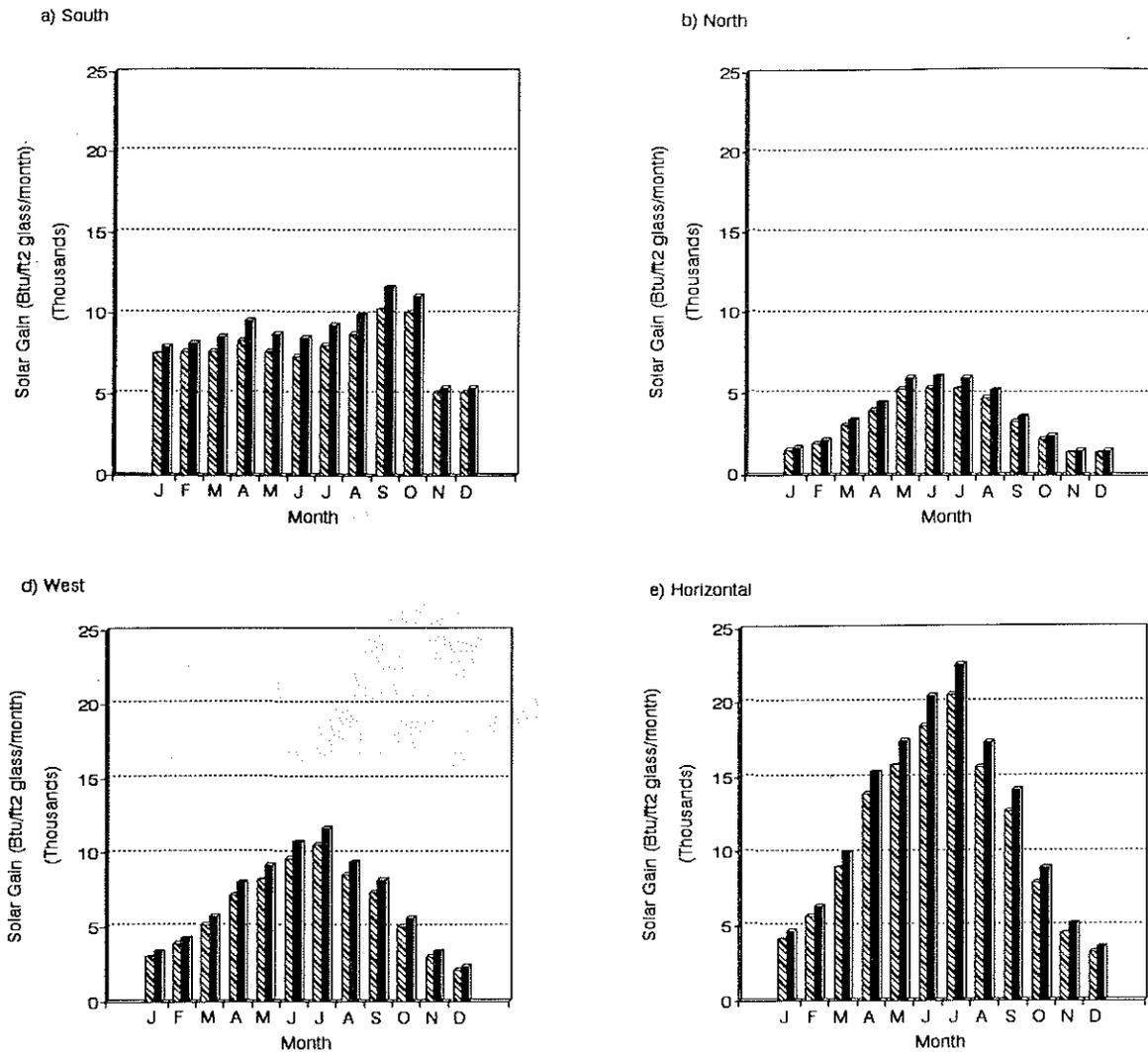


Figure 3 Monthly integrated solar gain calculated by DOE-2.1E for (a) south, (b) north, (c) west, and (d) horizontal glazing orientations for Chicago. The glazing is double-pane, tinted, low-E insulating glass with a shading coefficient of 0.43. Two calculation methods are compared: ASHRAE shading-coefficient method (solid bars) and detailed method using actual angular dependence of solar transmission and absorption (hatched bars).

shading coefficient of the selected glazing each hour. The second method employs the detailed approach in which 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.

Hourly results (Figure 2) show that the shading-coefficient method overpredicts the solar gain by up to 30%. The best agreement occurs for south glazing at noon in the January profiles. At this time, the angle of incidence (about 26°) is close to that for which the shading coefficient was calculated (0°). The worst agreement occurs for the absorbing glazing (shading coefficient = 0.23) on the west orientation at 5 p.m. in July. The angle of incidence is approximately 25° , so the difference is primarily attributable to the fact that the reference glazing used to calculate shading coefficients has a very low solar absorptance. For

the double-pane, low-E window, the largest difference occurs on the south orientation at 12 p.m. in July. At this time, the angle of incidence (about 70°) is furthest from the angle of incidence at which the shading coefficient was calculated.

Monthly results (Figure 3) show better agreement, but the shading coefficient method still overpredicts the solar gain by up to 15%. Further discussion of the limitations of the shading-coefficient approach can be found in McCluney (1991).

An example of switchable glazing simulation with daylighting control is shown in Figure 4 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 transmit-

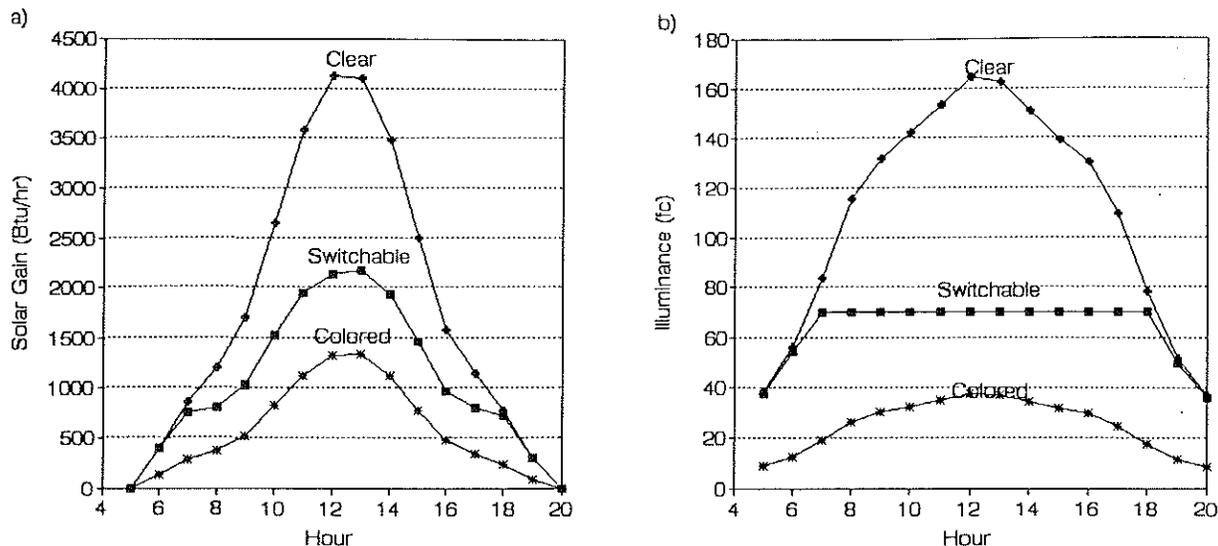


Figure 4 Hourly solar heat gain (a) and daylight illuminance (b) on a clear July day in Chicago calculated by DOE-2.1E for a south-facing 3 ft \times 20 ft window with switchable glazing. The clear state is double-pane clear insulating glass with a visible transmittance of 0.78 and shading coefficient 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).

tance (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 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 shading coefficient varies relative to the visible transmittance). For comparison, Figure 4 also shows two no-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 the shading-coefficient approach overestimates the solar heat gain by as much as 30% compared to the more detailed approach. The difference is most pronounced for low-transmitting, highly absorbing glass. With the shading-coefficient approach, the shading coefficient is multiplied by the solar heat gain through a reference glazing that has a solar absorptance of 0.05. So for highly absorbing glazing, the shading-coefficient approach overestimates the solar heat gain even at near-normal incidence. Note that this is not the case for the double-pane, low-E window, which also has a low solar

absorptance. The difference in results for this case occur at higher angles of incidence and are attributable to the fact that the shading coefficient is calculated at near-normal incidence. The optical properties of glazing materials significantly change at higher angles of incidence.

In terms of annual energy use, the two approaches are 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. A program for calculating the thermal performance of windows has updated algorithms for determining glazing optical properties between 0° and 90°.

We found that a constant shading-coefficient approach can overpredict the solar heat gain through a window at a given hour by as much as 30%. 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 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.

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