



# Lawrence Berkeley Laboratory

UNIVERSITY OF CALIFORNIA

## APPLIED SCIENCE DIVISION

LAWRENCE  
BERKELEY LABORATORY

NOV 18 1988

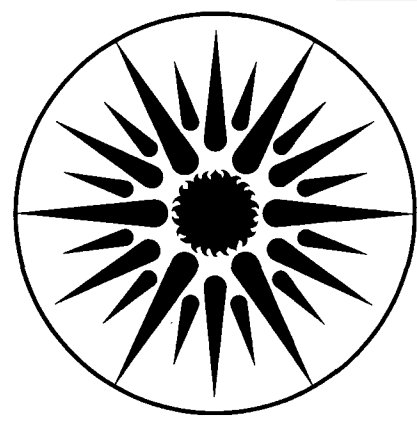
Presented at the ASHRAE Annual Meeting, Ottawa, Canada,  
June 26-29, 1988, and published in ASHRAE Transactions,  
Vol. 94, Part 2

### An Indices Approach for Evaluating the Performance of Fenestration Systems in Nonresidential Buildings

R. Sullivan, D. Arasteh, K. Papamichael, J.J. Kim,  
R. Johnson, S. Selkowitz, and R. McCluney

November 1987

**TWO-WEEK LOAN COPY**  
*This is a Library Circulating Copy  
which may be borrowed for two weeks.*



**APPLIED SCIENCE  
DIVISION**

LBL-23581  
e.2

## **DISCLAIMER**

This document was prepared as an account of work sponsored by the United States Government. While this document is believed to contain correct information, neither the United States Government nor any agency thereof, nor the Regents of the University of California, nor any of their employees, makes any warranty, express or implied, or assumes any legal responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by its trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof, or the Regents of the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof or the Regents of the University of California.

BS-251  
LBL-23581

Presented at the ASHRAE Annual Meeting, Ottawa, Ontario, Canada, June 26 - 29, 1988, and published in *ASHRAE Transactions*, Vol 94, Part 2.

**An Indices Approach for Evaluating the Performance of  
Fenestration Systems in Nonresidential Buildings**

R. Sullivan, D. Arasteh, K. Papamichael, J.J. Kim,  
R. Johnson, S. Selkowitz, R. McCluney

Applied Science Division  
Lawrence Berkeley Laboratory  
University of California  
Berkeley, CA 94720

November 1987

This work was supported by the Electric Power Research Institute and the New York State Energy Research and Development Administration. Project management was provided by the Lighting Research Institute. Additional support was provided by the Assistant Secretary for Conservation and Renewable Energy, Office of Buildings and Community Systems, Building Systems Division of the U. S. Department of Energy under Contract No. DE-AC03-76SF00098.

# An Indices Approach for Evaluating the Performance of Fenestration Systems in Nonresidential Buildings

R. Sullivan, D. Arasteh, K. Papamichael, J.J. Kim,  
R. Johnson, S. Selkowitz, R. McCluney

Applied Science Division  
Lawrence Berkeley Laboratory  
University of California  
Berkeley, CA 94720

## ABSTRACT

We present results from the first phase of a project to develop a fenestration performance design tool to be used by builders, designers, architects, utility auditors, etc. In phase 1 we defined the design tool concept and the experimental and analytical methodologies required to achieve the project goal. We defined five fenestration performance indices, which when combined with user-specified weighting factors yield a single figure of merit. Three of the indices are related to the effects of fenestration on building energy performance: fuel and electric use and peak electric demand. The other two are related to thermal and visual comfort. We derived index values and correlations to window design parameters by creating a data base consisting of a large number of building energy simulations for a prototypical office building module using the DOE-2 computer simulation program. Four glazing types and two shading devices were combined in several ways so that a representative sampling of realistic fenestration systems was analyzed.

## INTRODUCTION

Energy consumption as a major issue in the design of fenestration in today's office buildings brings about new complications and opportunities for lighting designers and architects. Daylighting can substantially reduce electric lighting requirements, but solar gains must be carefully controlled to avoid increasing cooling loads. Traditional design tools and approaches are inadequate for the complexity of the problem. The energy interactions of fenestration are complex and vary over time of day and time of year, often involving simultaneous beneficial and detrimental energy flows. Single-design-day methodologies may produce poorly performing solutions, and traditional design experience does not always provide an intuitive sense of correct solutions. New analytical tools, from simple nomographs to detailed computer energy simulation codes, also have shortcomings in practical design application. The simple tools, while convenient to use, do not account for all design parameters and generally provide rather crude answers. The more rigorous computer codes can account for all parameters and interactions, but their use is too time-consuming and costly to be practical in most situations for comparing a number of options during conceptual design. Also, many fenestration options cannot be properly treated by computer simulation because data on solar-optical performance is inadequate or nonexistent. Therefore, designers make decisions based on a mix of partial analysis, past experience, and guesswork. A design tool that offers simplicity, convenience, and flexibility in use is needed to allow the designer to compare a number of options at any stage of the design process with a high degree of predictive reliability.

We describe in this paper the first phase of a project whose objective is the development of a fenestration design tool. Phase 1 was conceived to develop a design tool concept and technical methodology. We were concerned with two primary issues: (1) that the design tool have a technical base that uses the most powerful analysis consistent with the problem, and (2) that its use be simple, straightforward, and easily accessible to designers. The design tool concept evolved to include five indices related to specific

---

R. Sullivan, D. Arasteh, R. Johnson, Staff Scientists; K. Papamichael, Graduate Student Res. Assoc.; J. Kim, Res. Assoc.; S. Selkowitz, Group Leader; Windows and Daylighting Group, Lawrence Berkeley Laboratory. R. McCluney, Principal Res. Sci., Florida Solar Energy Center.

issues of fenestration performance such as cooling load, daylighting contribution, and comfort. The basic indices are generated using results obtained from DOE-2 simulations. Since the project's first phase is limited to development and proof of concept, we chose a limited number of fenestration configurations, but ones sufficiently complex to prove the methodology.

The following sections describe the procedures and methodologies used in developing the fenestration performance evaluation technique, which required the resolution of a number of technical issues. We first discuss the measurement of the solar-optical properties of individual fenestration system layers, followed by the analytical development of the performance indices and an example of their use. In subsequent phases of this project, we will revise and refine the methods in response to users' reviews and comments and the data base will be expanded to include most fenestration configurations and products. This will require physical measurements of bidirectional transmittance/reflectance values for a large number of physical configurations, and subsequent DOE-2 simulations and regression analysis.

### MEASUREMENT SYSTEMS

A quantitative understanding of the solar-optical properties of fenestration systems is essential for accurate calculation of daylight illuminance levels, glare potential, solar heat gain and thermal comfort. For each direction of incoming radiation to clear, tinted, or reflective glass, there are two directions of outgoing radiant flux: the direction of the transmitted radiation and the direction of the specularly reflected radiation, with the solar-optical properties expressed as simple functions of the incident angle of the incoming radiation. However, very little is known about the properties of fenestration systems that are optically more complex, such as systems that incorporate diffusive glass, venetian blinds, horizontal or vertical louvers, or solar screens. Here, for each direction of incoming radiation, there is a particular  $4\pi$  distribution of outgoing radiant flux either transmitted or reflected by the fenestration system. It is necessary to express the solar-optical properties as functions of both the incoming and the outgoing directions of the radiant flux to obtain a complete description of the radiant behavior of such complex fenestration components.

A scanning radiometer was developed at the Lawrence Berkeley Laboratory to determine solar and visible bidirectional transmittance and reflectance of fenestration components and systems of arbitrary complexity (Spitzglas 1986). Determining the bidirectional properties of actual fenestration systems through direct measurement allows us to avoid the assumptions about the geometry and texture of fenestration components that are commonly used in mathematical modeling. However, various combinations of even the most common fenestration components can produce thousands of optically different fenestration systems. Measuring all such combinations is impossible; moreover, the scanning radiometer provides no information about the net absorptance of individual layers as they perform as parts of fenestration systems. The layer-by-layer absorption of solar radiation, which ultimately contributes to solar heat gain through re-conduction, is a complicated function of the distribution of the incident radiation and the nature of the interreflections between the fenestration layers.

A mathematical procedure was therefore required to determine the overall optical properties of a fenestration system from the properties of each individual layer. Papamichael (1986) describes such a procedure based on a matrix representation of the bidirectional properties of fenestration layers and systems. A computer program named TRA (Transmittance-Reflectance-Absorptance) was developed as an application of the method. The output of TRA serves as input to the daylighting calculation model SUPERLITE (Selkowitz 1982) for determining daylight illuminance and luminance distributions and as input to a heat transfer calculation program called WINDOW-2.0 (Rubin 1986). Outputs from these two programs are then used within DOE-2 (Simulation Research Group 1985) for determining solar heat gain and daylighting characteristics. This approach, presented schematically in Figure 1, can accurately and consistently determine the hourly, seasonal, or annual luminous and thermal performance of fenestration systems of arbitrary complexity under varying environmental conditions.

## DATA BASE CONSTRUCTION

The foundation of the performance index concept is a large data base of DOE-2 annual simulations of a prototypical single-story commercial office module, seen in Figure 2. The module has four perimeter zones consisting of ten offices, each 4.57 m (15 ft) deep by 3.05 m (10 ft) wide, surrounding a central core zone of 929 m<sup>2</sup> (10,000 ft<sup>2</sup>) floor area. Floor-to-ceiling height is 2.6 m (8.5 ft) with a plenum of 1.07 m (3.5 ft) height. Thermal transfers were selectively constrained in order to isolate the energy effects of interest, i.e., the floor and ceiling as well as the walls at each end of the perimeter zones were modeled as adiabatic surfaces (i.e., having no heat transfer). The envelope effects can thus be considered analogous to those in an individual office in a series of contiguous offices. Normal building thermal interactions included heat capacity effects and small convective/conductive transfers between core and perimeter. The exterior wall U-value was fixed at 0.28 W/m<sup>2</sup>·C (0.05 Btu/hr-ft<sup>2</sup>·F).

Continuous-strip windows were used in the exterior wall of each perimeter zone. Four glazing types and two shading devices were combined in several ways to simulate a representative sampling of realistic fenestration systems. Glazing area was parametrically varied at 0, 15%, 30%, 45%, and 60% of the wall area. The glazing types were clear, bronze-tinted absorptive, reflective, and clear low-E. Results were obtained for single-, double-, and triple-pane units. Shading devices included a diffusing shade and a venetian blind. The scanning radiometer described above was used to measure the solar-optical properties of these shading systems. Experimental data were collected and then put in a form that was used by the DOE-2 program during the simulation process.

Lighting characteristics included the simulation of varying lighting power densities and daylighting with continuous dimming controls for varying lighting levels. The continuously dimmable system linearly varied the lighting output with input power. The illuminance setpoint was varied from 323 lux (30 fc) to 753 lux (70 fc) and the installed power from 7.5 W/m<sup>2</sup> (0.7 W/ft<sup>2</sup>) to 29 W/m<sup>2</sup> (2.7 W/ft<sup>2</sup>). Daylighting levels were calculated at two reference points in each perimeter zone at a height above the floor of 0.76 m (2.5 ft) and at depths of 1.52 m (5 ft) and 3.05 m (10 ft).

System coil loads were calculated for each perimeter zone. To isolate zone loads from the building system interactions, a separate single-zone constant-volume system was assigned to each zone. A constant furnace efficiency and chiller coefficient of performance converted these loads to energy usage values that formed the data base of energy usage (electric and fuel) and peak electric demand. Our future work will include the use of other HVAC systems. We also developed special outputs from each DOE-2 simulation that assisted in determining the thermal and visual comfort aspects of each configuration. These are discussed in the next section.

## COMFORT EVALUATION

Specific studies relating commercial building fenestration system parameters to levels of thermal comfort have been performed only incidentally to the more general concerns of what defines thermal comfort in different environments. Lacking explicit studies of windows, we developed a new technique using past experimental evidence to give an indication of expected comfort as a function of various window parameters. A report by LBL and FSEC (1987) contains a more exhaustive treatment of thermal comfort that includes an examination of the literature and a description of the technique used in the DOE-2 simulation program to calculate a thermal comfort index.

The LBL and FSEC report shows that the primary thermal comfort issue in commercial buildings is high-intensity direct solar radiation from windows. Windows become a source of cold discomfort in our office module only when they comprise more than 60% of the wall area. Since 60% is the upper limit of window size in this study, we have not developed a comfort index for cold discomfort. However, the procedures outlined below to derive a comfort index for a high-intensity source could also be used for a cold window. The same is true for warm windows. Experimental evidence on these configurations indicates that further investigations are necessary to verify the extreme temperature asymmetries currently deemed acceptable. This is particularly true because of the increased use of heat absorbing glass in some geographic locations.

For the high-intensity source, we correlated the magnitude of direct solar radiation coming through a window with the percentage of people dissatisfied, calculated in accordance with methods developed by Fanger (1970). The amount of solar radiation was binned for the occupied hours during each DOE-2

simulation run. These values were then related to level of dissatisfaction. Table 1 shows the relationship between the particular bin and the percent dissatisfied. A comfort index was calculated using the following expression:

$$TC = \sum_{i=1}^{NB} X_i (1 - PPD_i) \quad (1)$$

where X is the percent hours at a solar level divided by a hundred and PPD is the percent dissatisfied at that level divided by a hundred. Subscript i represents a summation over the number bins (NB). The highest or best index value for thermal comfort is 0.95 since a 5% level of dissatisfaction is always apparent according to Fanger's studies. However, to simplify the analysis, for TCs greater than or equal to 0.95, we use the value 1.0. The lowest or worst index is 0.0 for the case where 100% of the occupied hours have a solar radiation greater than 473 W/m<sup>2</sup> (150 Btu/hr-ft<sup>2</sup>). This condition never occurs and is only mentioned to illuminate the index concept.

A proportional relationship is used to account for window area variations under the assumption that the largest window corresponds to the largest level of discomfort. A relative comparison between fenestration systems is obtained using the minimum TC value and maximum window area as follows:

$$TC_n = 1.0 - \{ [(1-TC)/(1-TC_{min})] [A_g/A_{gmax}] \} \quad (2)$$

where A<sub>g</sub> is the window area and where TC<sub>n</sub> is the normalized comfort index and its value varies between 0.0 and 1.0. The calculated thermal comfort index was subsequently correlated with the solar heat gain coefficient.

It was not necessary to perform as detailed an analysis for visual comfort as was done for thermal comfort. This is because the DOE-2 simulation program, as part of its daylighting calculation, already defines a glare index, and it was not the intent of this study to develop new methodologies for evaluating glare. However, certain revisions were made to the DOE-2 program to facilitate the derivation of a weighted index similar to the above thermal-comfort index. The indices were binned during the occupied hours and subsequently used to determine an overall glare index, which was then defined as a function of fenestration system parameters. Table 2 shows the glare index bins and degrees of discomfort. DOE-2 currently uses the Cornell method (Winkelmann, 1983), which is expressed as:

$$GI = 10 \log H \quad (3)$$

where

$$H = \frac{L_s^{1.6} \Omega^8}{L_b + 0.07 \omega^5 L_s} \quad (4)$$

L<sub>s</sub> is the source luminance; Ω is the solid angle of the source modified for the position of its elements in the field of view; L<sub>b</sub> is the luminance of the surroundings; and ω is the solid angular subtense of the source at the eye. The overall glare index was calculated as follows:

$$G = \sum_{i=1}^{NB} X_i (GI_i) \quad (5)$$

where X is the percent hours at a glare index level, GI. Subscript i represents a summation over the number of bins (NB). The glare index was subsequently correlated with the effective aperture of the window.

## PERFORMANCE INDICES

We developed five performance indices, each being a function of several fenestration system configuration variables. A regression analysis was performed on the DOE-2 parametric simulation data base, and simplified algebraic expressions were derived that accurately reproduced the simulation results. Multiple regression is an analytical technique for determining the best mathematical fit for a dependent variable as a function of many independent variables. The performance indices or dependent variables included three energy-related indices and two that dealt with thermal and visual comfort criteria. We envision the use of two indices: one directly related to the actual energy usage or comfort indicator and the other a nondimensional index that varies between the values of 0 and 1 and represents the worst and best performers, respectively. Such a nondimensional scheme facilitates a more direct comparison of fenestration systems without regard to specific energy usage or comfort indicator amounts.

Energy-related indices are representative of annual fuel use (heating), annual electricity use (cooling, lighting, fan), and peak electrical demand. The fuel usage was obtained by applying a fixed furnace efficiency of 0.6 to the perimeter zone heating coil loads calculated by DOE-2. Electricity usage and peak electric demand used a COP of 3.0 for calculating the cooling energy from the loads. Eventually, we plan on utilizing efficiency and COP as variables in our final design tool concept. The resultant regression expression used to predict these quantities was:

$$\Delta E_i = \beta_{1i} U_g A_g + \beta_{2i} S_g A_g + \beta_{3i} k_d L A_f \quad (6)$$

where  $\Delta E$  is the incremental effect due to the fenestration system and subscript  $i$  refers to the particular energy-related index: fuel (therms), electricity (kWh), and peak electric demand (W). The regression coefficients are denoted by  $\beta$ , and the equation has three components chosen to contain the energy effects from a particular building component: conduction ( $U_g A_g$ ), solar radiation ( $S_g A_g$ ), and lighting ( $k_d L A_f$ ), where  $U_g$  is the overall conductance of the glazing,  $S_g$  is the solar heat gain coefficient,  $k_d$  is a daylighting correction term, which is discussed below, and  $L$  is the lighting power density in watts per square meter. Non-dimensional indices are obtained by using the following equation:

$$I_{\Delta E_i} = 1.0 - [(\Delta E_i - \Delta E_{i\min}) / (\Delta E_{i\max} - \Delta E_{i\min})] \quad (7)$$

where  $\Delta E_{i\max}$  and  $\Delta E_{i\min}$  are the maximum and minimum values of the incremental energy quantities.

The quantity ( $k$ ) is the daylighting factor that is an exponential and varies between 0 and 1. It also was determined by a regression analysis and was found to be a function of visible transmittance ( $\nu$ ), desired lighting level ( $C$ ), and effective aperture ( $A_e$ ), which is the product of window-to-wall ratio and visible transmittance. The following expression was used:

$$k_d = 1.0 - [\phi_{1i} + \phi_{2i} (C/\nu)] [1.0 - e^{-(\phi_{3i} + \phi_{4i} C) A_e}] \quad (8)$$

where  $\phi$  represents regression coefficients.

In the comfort section, we present a normalized thermal-comfort index that was calculated using the following:

$$I_{TC} = TC_n = 1.0 - \{ [(1-TC)/(1-TC_{\min})] [A_g/A_{g\max}] \} \quad (9)$$



The DOE-2 calculated value of TC was predicted by using the solar heat gain coefficient,  $S_g$ , since this was a good measure of the amount of transmitted solar radiation, and the TC index was generated using such bin data. An exponential was derived so that at a solar heat gain of zero, the index was at its maximum or most comfortable level of 1.0, and at large values of solar heat gain, the index was at its lowest level or most uncomfortable, i.e.,

$$TC = \alpha_1 e^{\alpha_2 S_g} \quad (10)$$

The weighted annual glare indices for the DOE-2 simulation runs were correlated with the effective aperture. This seems reasonable since the glare index is a function of luminance and solid-angle values that are indirectly related to glazing transmittance and area. The following exponential expression yields the lowest or best glare index at zero effective aperture and its highest or worst index at large aperture values:

$$G = \delta_1 [1 - e^{\delta_2 A_e}] \quad (11)$$

The normalized glare index was calculated in a manner similar to the energy-related indices:

$$I_G = G_n = 1.0 - [(G - G_{\min}) / (G_{\max} - G_{\min})] \quad (12)$$

These equations show the feasibility of condensing DOE-2 results to relatively simple, compact expressions, i.e., indices that express performance relative to glazing properties. Other forms of equations might also be used to achieve the same results. However, the intent has been to define the process and not necessarily to derive an exact form. Additional analysis and alternative suggestions by potential users may affect the final form selected for development.

### FIGURE OF MERIT

The final step in the task to evaluate the performance of fenestration systems and to establish a ranking procedure was to develop a figure of merit that combines all the index values into one number. The user can then directly compare the relative performance of the options being considered. We propose a procedure that gives the user the option of customizing the figures of merit for specific applications by assigning a weighting factor to each index. The figure of merit,  $F$ , would thus be derived from:

$$F = \sum w_i I_i \quad (13)$$

where  $w_i$  represents the weighting factors assigned to the performance indices,  $I_i$  (fuel, electric, peak electric, thermal and visual comfort). By making the sum of the weighting factors be equal to one--since the indices are expressed as values between zero and one--we also set the value of the figure of merit between zero and one. The system that best satisfies the design criteria is the system with the highest figure of merit. Other types of index value limits and types of weighting can be used; however, this very simplified nondimensional technique illustrates the concept.

The procedure's versatility can be observed by considering an example. We desire to compare the performance of four glazings, two sizes, with and without daylighting, for an east-facing perimeter zone fenestration system in Madison, WI. First we shall present the calculated performance indices, then show a series of figures of merit for various types of weighting. Information needed for this evaluation is as follows:

1. Glazing types: Clear, bronze-tinted, reflective, low-E (all double-pane).
2. Area:  $50 \text{ m}^2$  ( $540 \text{ ft}^2$ ) and  $25 \text{ m}^2$  ( $270 \text{ ft}^2$ ).
3. Lighting power density:  $18.3 \text{ W/m}^2$  ( $1.7 \text{ W/ft}^2$ ).
4. Lighting level: 538 lux (50 fc).

The resultant performance indices which were calculated using the above expressions and appropriate regression coefficients are shown in Figures 3 through 6. We present on a dual scale the actual energy and comfort levels as well as the nondimensional values between zero and one. The maximum and minimum values were determined by defining the best and worst performers for all module configurations used in the study. The analysis includes variations due to orientation, window size, window type, use of daylighting, lighting power, density, and lighting level, and is specific to the local climate.

The energy-related index values in Figures 3 to 5 are inversely related to actual usage or electrical peak demand quantities, since an index of one is best, corresponding to lowest energy use. Comfort indices in Figure 6 are proportional to the calculated annual average comfort levels. In viewing the indicated comfort values, one should note the extremely small range of variation. Thermal comfort varies between a low of 84.7% satisfaction level and an upper value of 95%. The annual average glare index varies between the value zero, which occurs for no window, and 12.74, which is a degree of discomfort that is just perceptible. For both comfort indices, therefore, the performance range is quite small. We plan to refine this methodology in Phase 2 and develop comfort-related indices that may be more indicative of a comparative performance appraisal.

Figure 7 shows results that use equal weighting for the performance indicators. A 20% weighting factor was applied to each of the five indices. Figure 8 shows evenly distributed weighting for only the energy-related indices. Here, the fuel index variation with glazing type is somewhat opposite to the electric and peak variation, resulting in an almost constant figure of merit for each condition for the glazing types analyzed. Figures 9 and 10 are cost-based weighting results. The three energy-related indices have been weighted by maintaining a fixed ratio of the cost of electricity to gas (\$0.07/kWh for electricity and \$0.60/therm for gas results in a ratio of 3.5) and then varying the magnitude of the peak demand index between two extremes (10% and 70%). Since fuel costs are lowest, the figures of merit tend to approach the electric index and peak index values, respectively, shown in the two figures.

## CONCLUSIONS

Building designers, utility auditors, and others are constantly required to compare and evaluate the performance of alternative fenestration systems. To properly address the energy-related impacts of fenestration, one must be able to quantify the energy performance for all systems in a systematic and reproducible way. The objective of this study was to develop numerical indicators for comparing fenestration system performance on the basis of annual energy consumption, peak electrical demand, illumination performance, and thermal and visual comfort. These indicators are to be used as guides in evaluating and selecting alternative fenestration products and systems for use in various building types and climates.

The project consists of two phases. In Phase 1, the subject of this report, we developed the basic methodology for determining the performance indicators and tested the techniques for a few sample fenestration systems. Phase 2 will support the measuring and analytical tasks required to construct a large data base of indices for most of the common generic fenestration systems. We will also develop a microcomputer-based design tool to embody the projects' results.

We utilized various experimental devices to measure the solar-optical properties and daylight transmittance/distribution functions of the sample systems, since the performance of several classes of fenestration products cannot readily be characterized using conventional analytical techniques. The integrating sphere and the luminance/radiance scanner were instrumented, calibrated, and used in this experimental work. In addition, several data-reduction computer programs were written that converted the raw data from the scanner and sphere into expressions that the DOE-2 program used to simulate transmission characteristics.

A major revision was made to the DOE-2 energy analysis simulation program to incorporate new algorithms for calculating solar transmission and optical properties. The algorithms use the same approach as previous DOE-2 methodology, but have more accurate polynomial coefficients to define system performance. In conjunction with these revisions to DOE-2, we also introduced a number of bin-type reports that tabulate U-value, solar heat gain, visible transmittance, etc., over the course of the year for each hour of the day. These reports were used in the performance evaluation of the different fenestration systems.

A methodology was developed to define the relationship between fenestration characteristics, direct solar radiation, and comfort so that annual thermal and visual comfort indices could be calculated. The thermal-comfort index is the summed product of the percent hours at a particular solar radiation level and percent dissatisfaction determined by the increase in mean radiant temperature within the space. The visual comfort index is the number of occupied hours of the year during which glare reached uncomfortable levels.

Numerous DOE-2 parametric runs were completed for the prototypical configuration in Madison and Lake Charles, and multiple regression coefficients were obtained and used in developing performance indicators. An overall fenestration performance figure of merit was defined from the calculated performance indicators and a user-defined weighting function. Phase 1 objectives have been attained. We have shown that the techniques developed to evaluate and categorize fenestration system performance do work and that the basic figure-of-merit concept has been proven. Remaining tasks associated with Phase 2 include field testing and user review, completion of a data base containing results for many fenestration systems, and development and creation of a working microcomputer design tool.

## REFERENCES

- Fanger, P.O. 1970. *Thermal comfort*. New York: McGraw-Hill.
- Johnson, R.; Sullivan, R.; Nozaki, S.; Selkowitz, S.; Conner, C.; and Arasteh, D. 1983. "Building envelope thermal and daylighting analysis in support of recommendations to upgrade ASHRAE/IES Standard 90, final report." Lawrence Berkeley Laboratory, Report LBL-16770.
- Lawrence Berkeley Laboratory and Florida Solar Energy Center. 1987. "Commercial building fenestration performance indices project, Phase 1: Development of Methodology." Lawrence Berkeley Laboratory Report LBL-23385.
- Papamichael, K.M., and Winkelmann, F. 1986. "Solar-optical properties of multilayer fenestration systems." Lawrence Berkeley Laboratory, Report LBL-20543.
- Rubin, M.; Arasteh, D.; and Hartman, J. 1986. "WINDOW: A computer program for calculating U-values and shading coefficients of windows." Lawrence Berkeley Laboratory Report, LBL-20212.
- Selkowitz, S.; Kim, J.J.; Navvab, M.; and Winkelmann, F. 1982. "The DOE-2 and SUPERLITE daylighting programs." Proceedings of the 7th National Passive Solar Conference, Knoxville, TN.
- Simulation Research Group. 1985. "DOE-2 supplement: Version 2.1C." Lawrence Berkeley Laboratory, Report LBL-8706, Rev. 4 Suppl.
- Spitzglas, M. 1986. "A new bidirectional scanner for testing building fenestration systems." Lawrence Berkeley Laboratory, Report LBL-21353.
- Winkelmann, K. 1983. "Daylighting calculation in DOE-2." Lawrence Berkeley Laboratory, Report LBL-11353.

**ACKNOWLEDGEMENT**

This work was supported by the Electric Power Research Institute and the New York State Energy Research and Development Administration. Project management was provided by the Lighting Research Institute. Additional support was provided by the Assistant Secretary for Conservation and Renewable Energy, Office of Buildings and Community Systems, Building Systems Division of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

TABLE 1

Transmitted Direct Solar Radiation Bin Data and Corresponding Level of Dissatisfaction

Solar Bin W/m <sup>2</sup> (Btu/hr-ft <sup>2</sup> )	Percent Dissatisfied	Percent Dissatisfied *
567- (180- )	>76	100
473-567(150-180)	59-76	100
378-473(120-150)	43-59	70
284-378( 90-120)	28-43	50
189-284( 60-90 )	16-28	40
95-189( 30-60 )	7-16	20
63-95 ( 20-30 )	6- 7	10
32-63 ( 10-20 )	5- 6	10
3-32 ( 1-10 )	5	5
Less Than 3(1)	5	5

\* This column represents a more conservative estimate of the correlation between transmitted solar radiation and percent dissatisfied and was used in the analysis.

TABLE 2

Glare Index Bin Data and Level of Dissatisfaction

Glare Index Bin	Degree of Discomfort
28-	Just intolerable
25-28	
22-25	Just uncomfortable
19-22	
16-19	Just acceptable
13-16	
10-13	Just perceptible
Below 10	

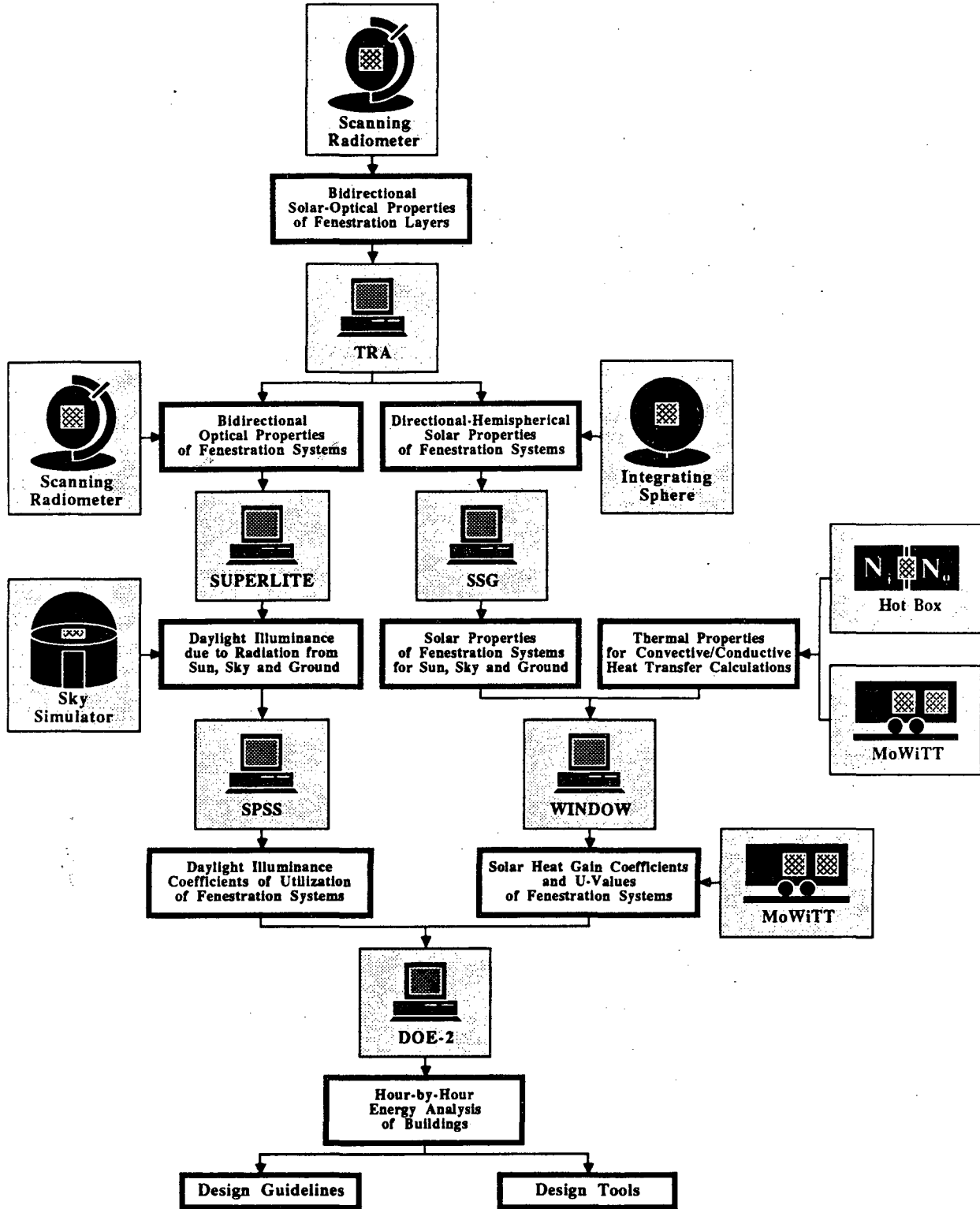


Figure 1. Information Flow

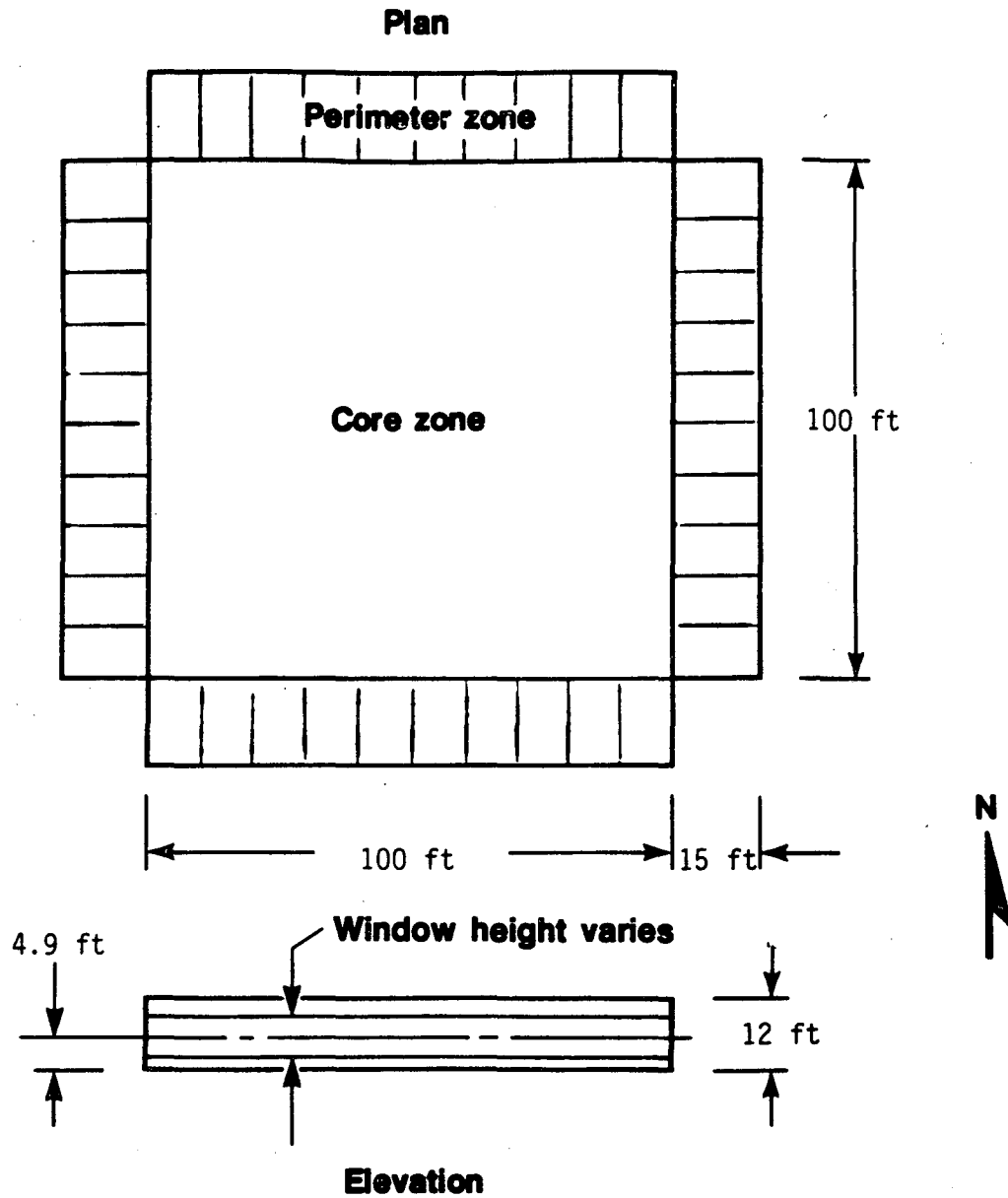


Figure 2. Module Description

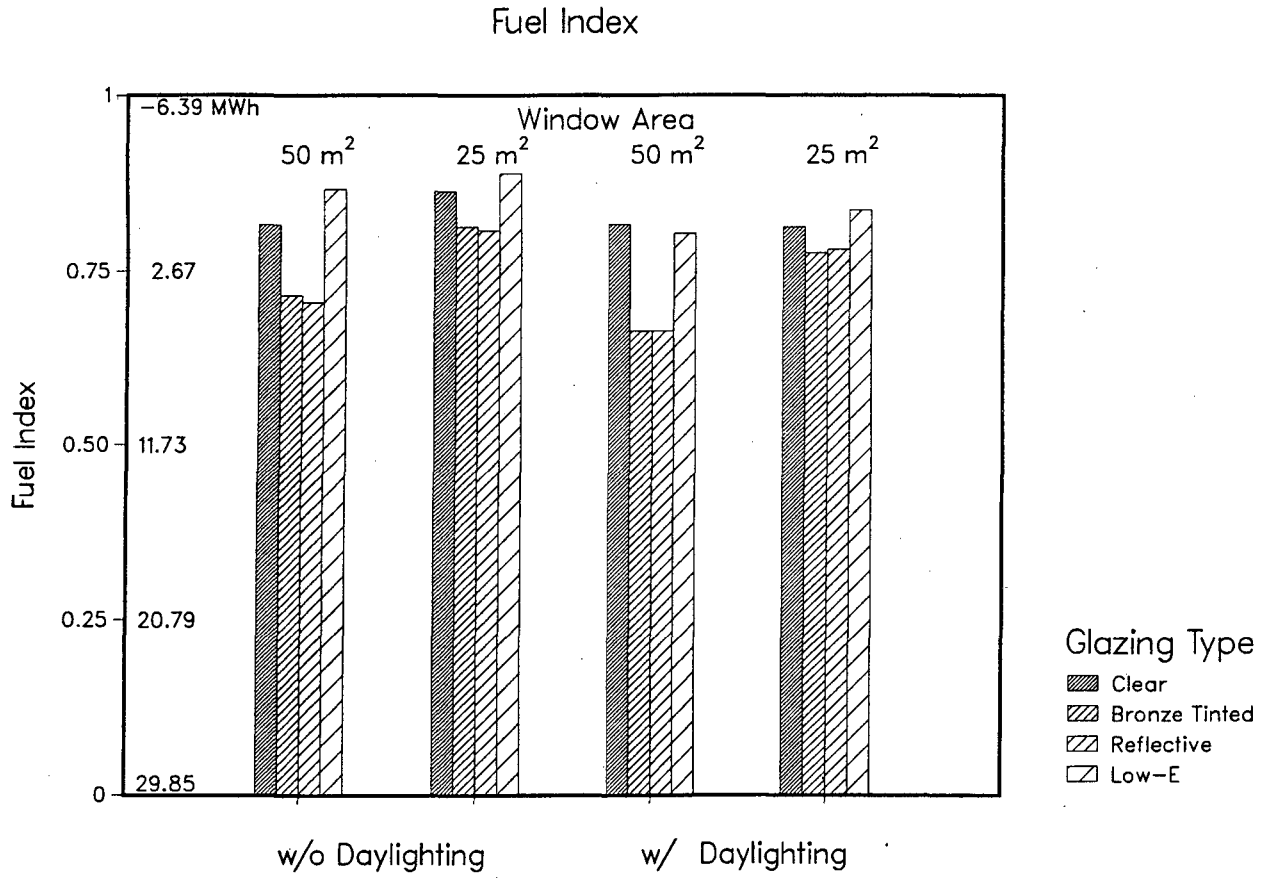


Figure 3. Fenestration performance indicators for annual fuel consumption for an office building module with windows facing east and a lighting power density of 18.3 W/m<sup>2</sup> and lighting level of 538 lux. Index values vary between zero and one and are inversely related to energy usage. Results are shown for four glazing types and two window sizes, with and without the use of continuous dimming lighting controls.

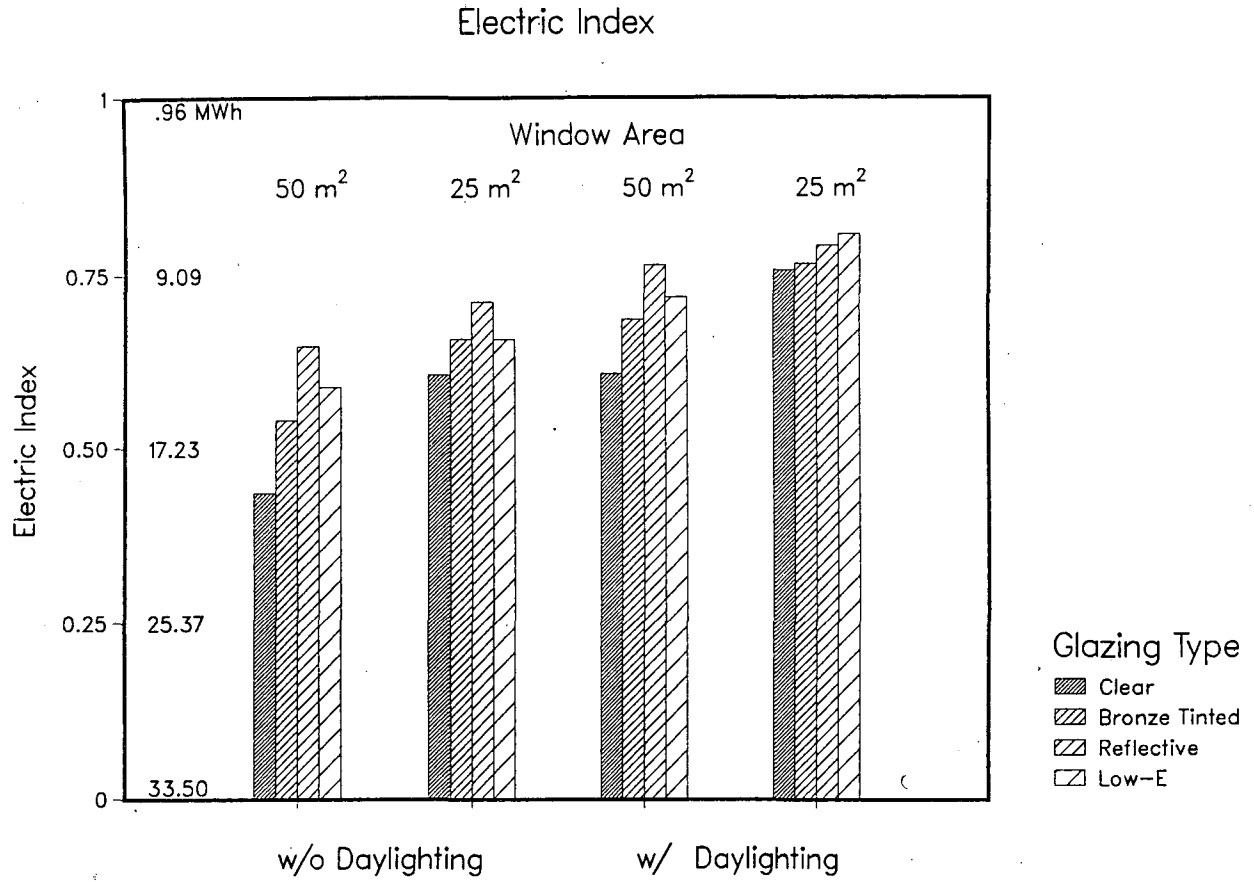


Figure 4. Fenestration performance indicators for annual electric consumption for an office building module with windows facing east and a lighting power density of 18.3 W/m<sup>2</sup> and lighting level of 538 lux. Index values vary between zero and one and are inversely related to energy usage. Results are shown for four glazing types and two window sizes, with and without the use of continuous dimming lighting controls.



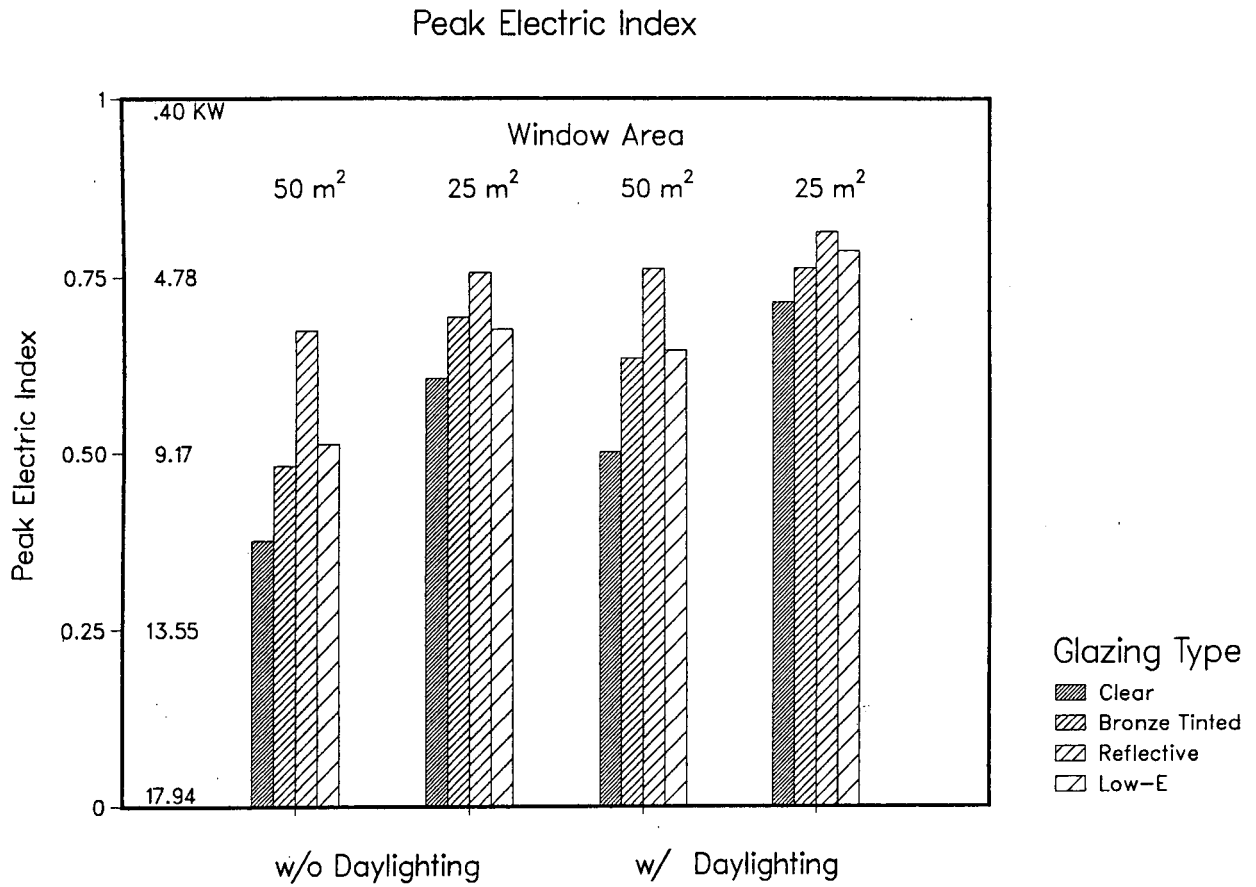


Figure 5. Fenestration performance indicators for peak electrical demand for an office building module with windows facing east and a lighting power density of 18.3 W/m<sup>2</sup> and lighting level of 538 lux. Index values vary between zero and one and are inversely related to energy usage. Results are shown for four glazing types, two window sizes, with and without the use of continuous dimming lighting controls.

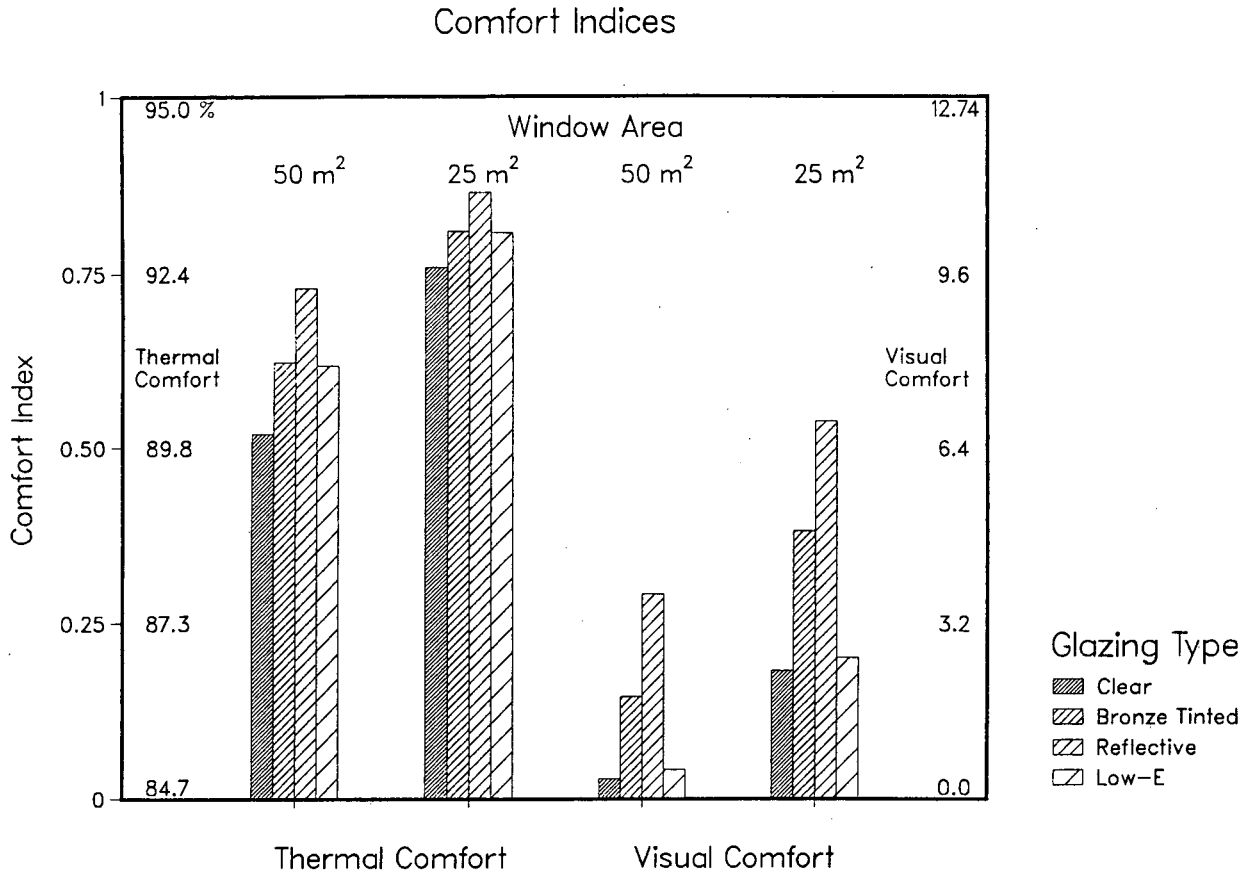


Figure 6. Fenestration performance indicators for thermal and visual comfort for an office building module with windows facing east and a lighting power density of 18.3 W/m<sup>2</sup> and lighting level of 538 lux. Index values vary between zero and one and are directly proportional to the comfort parameters. Results are shown for four glazing types and two window sizes.

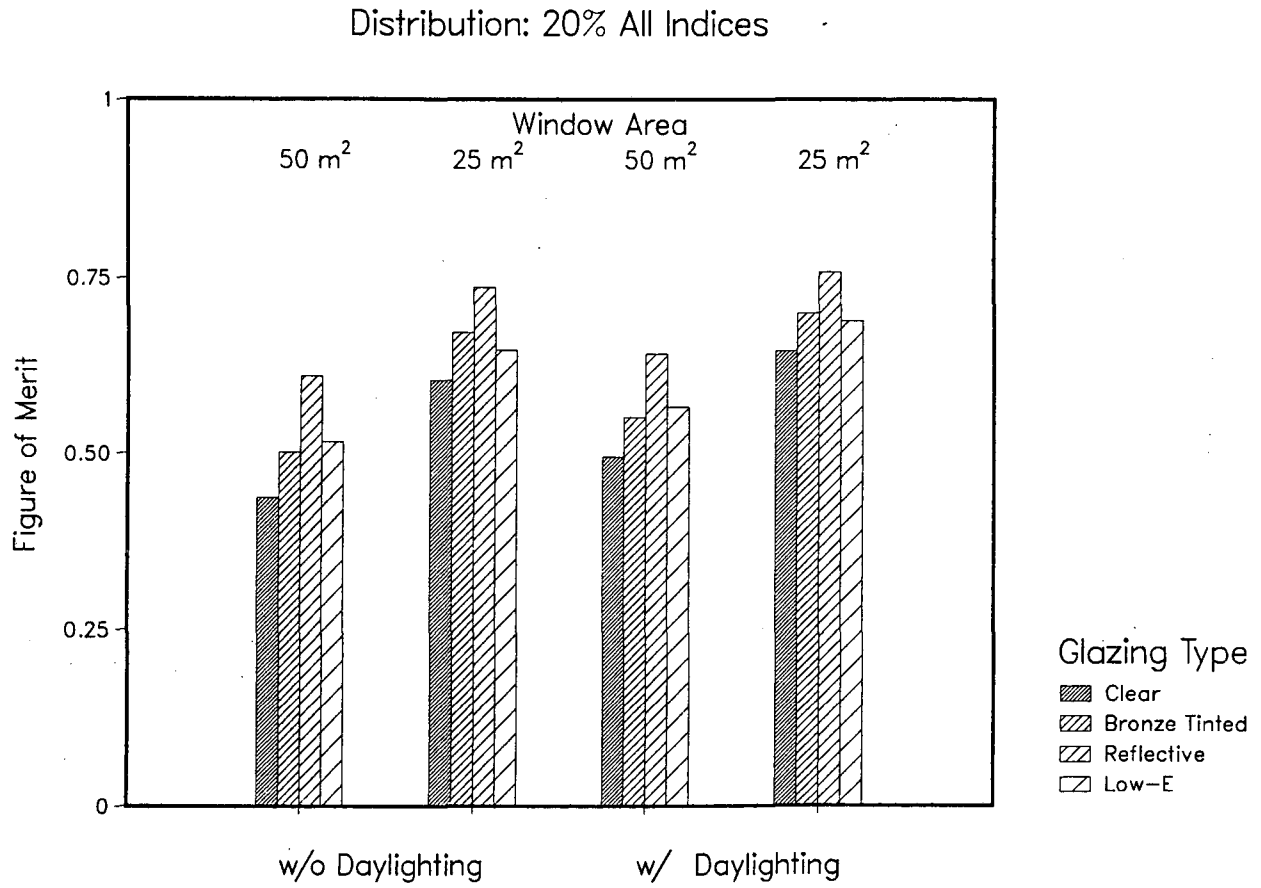


Figure 7. Example of the use of the figure of merit for comparing fenestration system performance. Shown is a distribution in which the five performance indices are equally weighted (20% each). Results are shown for four glazing types, two window sizes, with and without the use of continuous dimming lighting controls.

Distribution: Fuel=33.3%, Elec=33.3%, Peak=33.3%, Comfort=0%

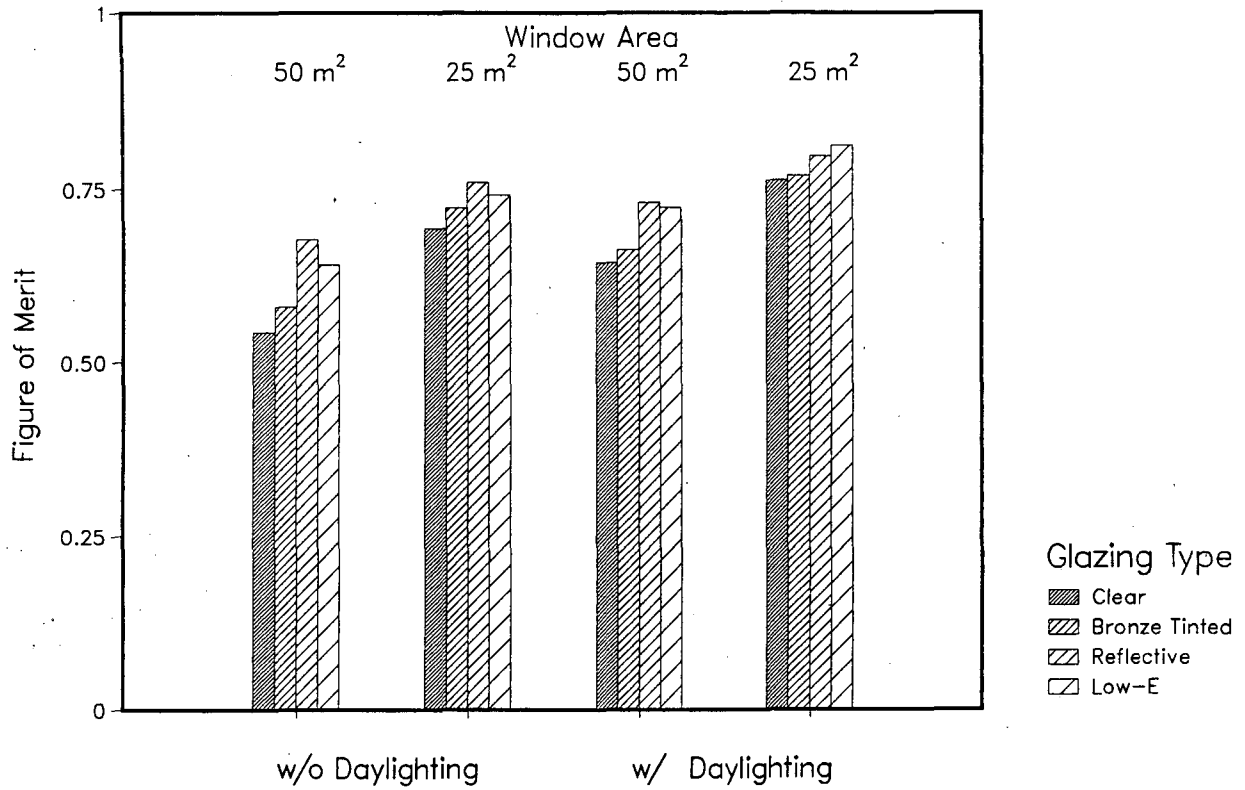


Figure 8. Example of the use of the figure of merit for comparing fenestration system performance. Shown is a distribution in which the three energy related performance indices are equally weighted (33.3% each). Results are shown for four glazing types, two window sizes, with and without the use of continuous dimming lighting controls.

Distribution: Fuel=20%, Elec=70%, Peak=10%, Comfort=0%

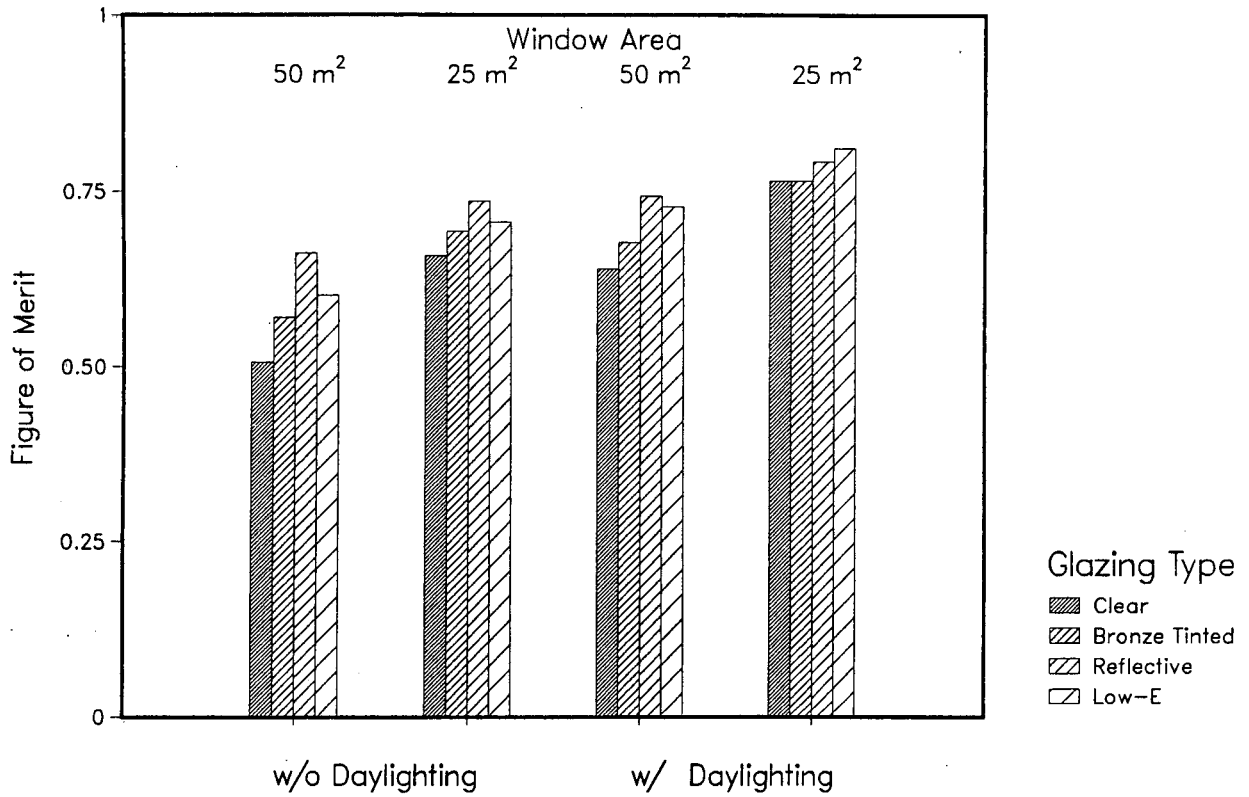


Figure 9. Example of the use of the figure of merit for comparing fenestration system performance. Shown is a cost based distribution in which the three energy related performance indices are weighted by relative costs (20% fuel, 70% electricity, 10% peak electrical demand). Results are shown for four glazing types, two window sizes, with and without the use of continuous dimming lighting controls.

Distribution: Fuel=7%, Elec=23%, Peak=70%, Comfort=0%

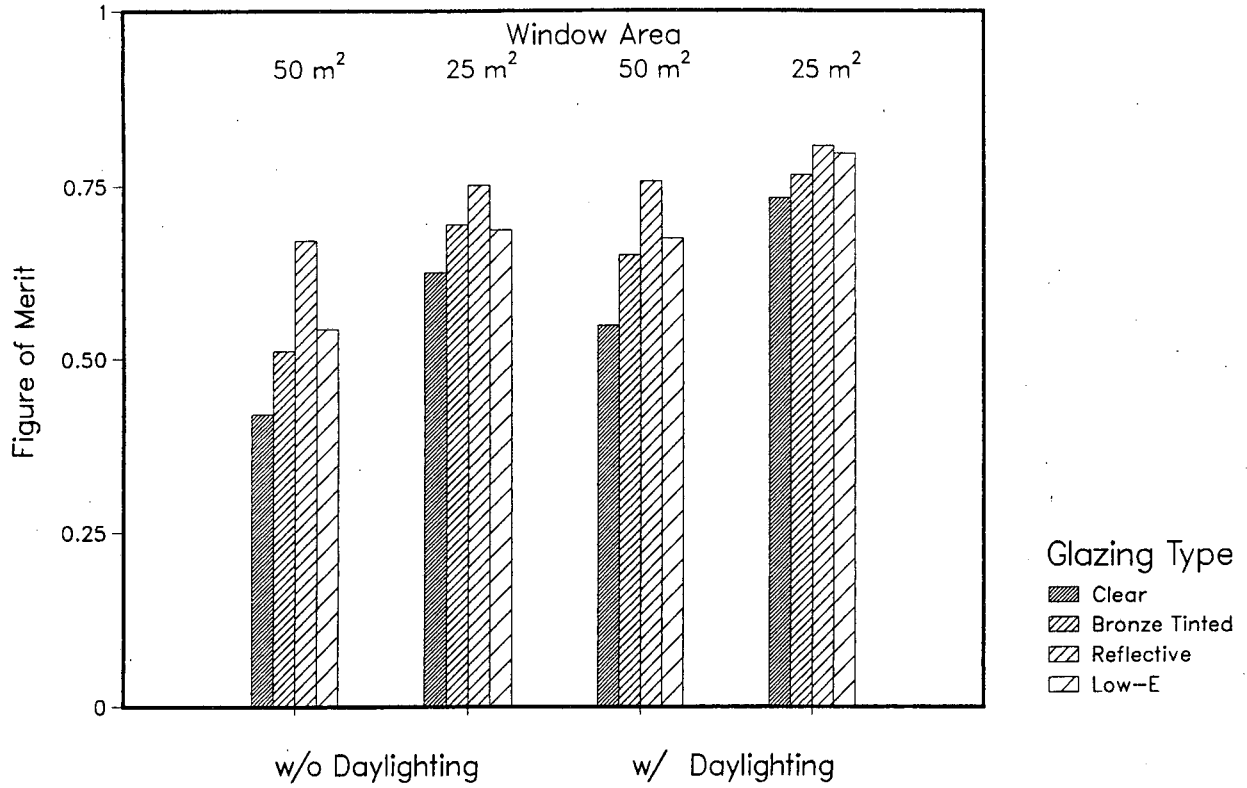


Figure 10. Example of the use of the figure of merit for comparing fenestration system performance. Shown is a cost based distribution in which the three energy related performance indices are weighted by relative costs (7% fuel, 23% electricity, 70% peak electrical demand). Results are shown for four glazing types, two window sizes, with and without the use of continuous dimming lighting controls.

*LAWRENCE BERKELEY LABORATORY  
TECHNICAL INFORMATION DEPARTMENT  
UNIVERSITY OF CALIFORNIA  
BERKELEY, CALIFORNIA 94720*