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NEW TOOLS FOR ANALYZING THE THERMAL AND DAYLIGHTING PERFORMANCE OF FENESTRATION IN MULTISTORY BUILDINGS

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ABSTRACT

Accurately predicting the energy-related impact of fenestration is essential to the design of energy-efficient buildings. For complex nonresidential buildings, a complete understanding of fenestration performance requires not only thermal modeling but daylighting prediction as well. Multistory buildings tend to have higher skin-to-floor ratios than shorter, more compact structures of equal floor area and, thus, their performance is influenced to a greater extent by design decisions that affect the thermal and solar optical properties of the building skin. Despite the computational power of modeling programs, there are tradeoffs and limitations among accuracy, the cost of running the model, and the flexibility to model the large range of architectural solutions for high-rise buildings.

We recently completed the first phases of a project to add a daylight-modeling capability and related thermal algorithms to the DOE-2.1B energy analysis program. In order to provide accuracy and computational efficiency along with the ability to model geometrically complex buildings, we developed a family of supporting computational tools and experimental techniques. The next version of the DOE-2 program will have a daylighting model driven by a library of stored coefficients of utilization, which are either developed from scale model measurements in our sky simulator or calculated by a new daylighting illumination program, SUPERLITE. In addition, coefficients for unique designs can be determined from model measurements and

entered into the program. SUPERLITE provides detailed data on illuminance distribution in an interior space, but is too complex for use directly within the hour-by-hour model. Because the solar gains through sophisticated daylighting apertures are not adequately calculated in current models, our procedure will also use a library of coefficients stored in DOE-2. These coefficients will be determined from sun and sky simulator measurements of the solar optical properties of devices.

We describe our major experimental procedures and analytical models and present validation studies of DOE-2.1B and SUPERLITE. We illustrate the appliciability of these tools by showing results from a study of optimal fenestration performance as a function of climate and orientation.

1. INTRODUCTION

Lighting is a major end use of energy in most multistory nonresidential buildings. Design strategies that reduce electric lighting requirements should thereby reduce annual electrical consumption and peak electrical loads, and may also lower HVAC loads. Improved lighting design strategies, specification of new, efficient lighting hardware, and improved operation and maintenance of lighting systems all promise substantial energy savings. The impacts of these strategies can be estimated accurately using conventional energy analysis techniques. The use of natural lighting in buildings represents a more complex analytical problem because 1) daylight is a highly variable light source, 2) daylight is accompanied by solar gain that may increase cooling loads, and 3) there are many uncertainties in integrating lighting sensors and controls to utilize daylight properly. Single-story or low-rise buildings that incorporate simple skylights or other rooflight designs provide relatively uniform daylight over the majority of the floor area. However, most multistory daylighting solutions use sidelighting, which produces a non-uniform daylight contribution from the window-wall to the core, as well as a potential glare source directly in the field of view. Measured performance data from buildings could provide firm estimates of the real energy and load savings, but the existing performance data base is very small.

If experience with existing buildings cannot provide sufficient guidance to successful solutions, the designer must use analytical tools. Despite the proliferation of design tools for

building energy analysis, none currently in extensive use has demonstrated the capability for analyzing the energy-related impacts of daylighting strategies in multistory nonresidential buildings. This paper describes two new computer models--one for illuminance analysis and one for energy analysis--that show promise as powerful and flexible aids in understanding the role of daylighting in energy-efficient buildings.

The first of these tools, SUPERLITE, is a large computer model that predicts the spatial distribution of daylight illuminance in a building zone based on exterior sun and sky conditions, site obstructions, details of fenestration and shading devices, and interior room properties. We then utilize a second computer program, DOE-2, to estimate annual energy use and peak load impact. The DOE-2 model determines the energy impact of daylighting strategies based on hour-by-hour analysis of daylight availability, site conditions, window management in response to sun control and glare, and various lighting control strategies. The thermal interaction of daylight strategies is automatically accounted for within the DOE-2 program. Together these programs form the basis for improving our understanding of fenestration performance.

Figure 1 shows sample results from an extensive parametric analysis of fenestration performance in office buildings. The study was completed for a single floor that could be taken as typical of all floors in a multistory building, with the possible exception of the ground floor and the top floor. The study was the first in a series to examine variations in total energy consumption and component loads as a function of major glazing parameters (U-value, shading coefficient, window area, orientation, climate, lighting load, daylighting strategy, etc.)[1] Figure 2 shows the variation in peak electrical load and chiller size in response to fenestration parameters.[2] Peak electrical load and chiller size are plotted versus the "effective" aperture (the product of window area as a percentage of wall and the visible transmittance) for four cases: with and without daylight utilization; with and without window management to produce thermal comfort. The results shown are for a single intermediate floor of a prototypical multistory office building in Madison, Wisconsin. While the reductions in peak electrical load due to daylighting are substantial, the figure also illustrates the importance of understanding and controlling the contribution solar gain makes to cooling loads.

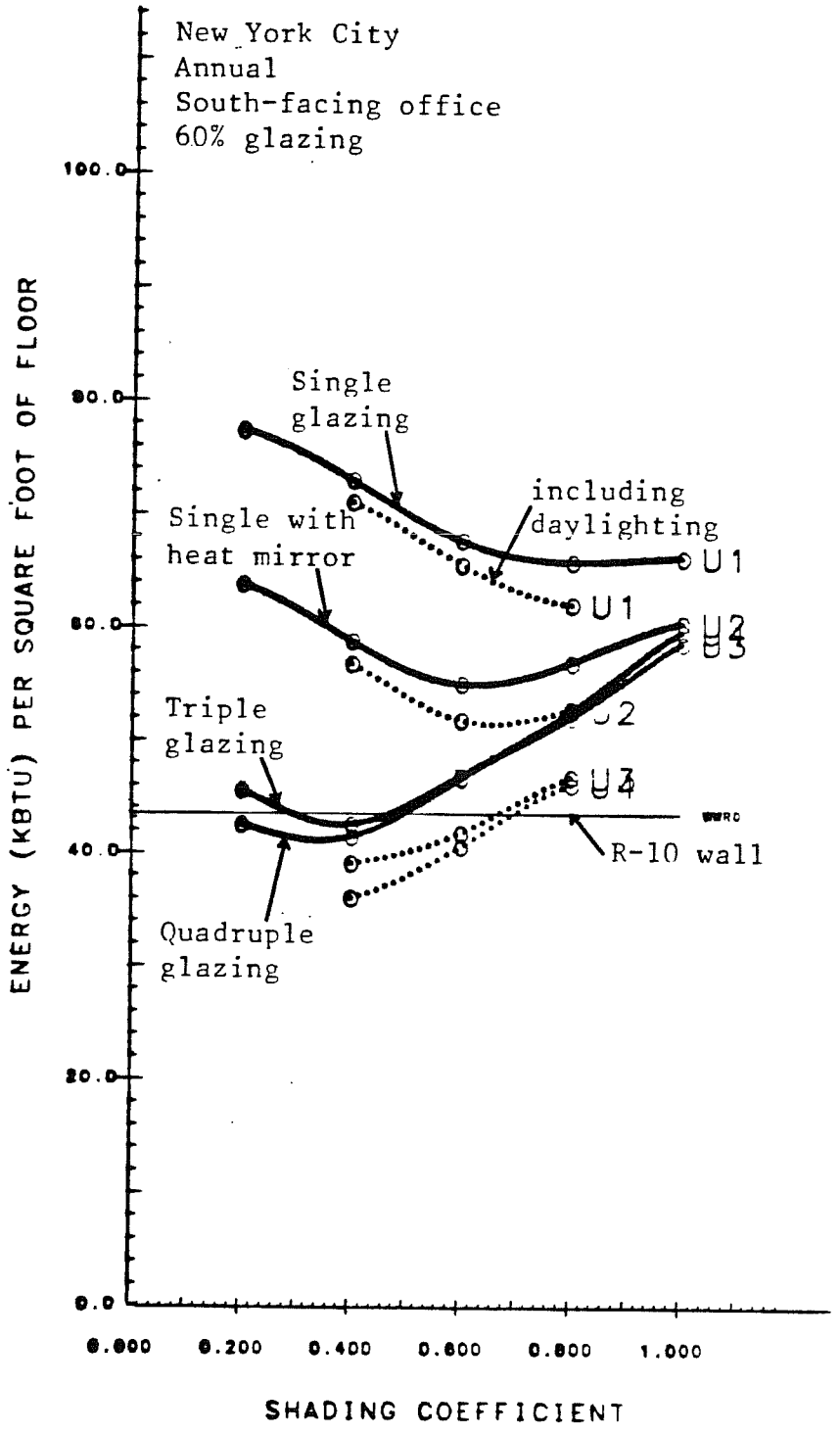


Fig. 1 Energy requirements for a south-oriented office module in New York City.

U1 = Normal single glazing, nominal 6.28 $W/m^{2o}C$.
U2 = Single glazing with low-emissivity coating, nominal 4.33 $W/m^{2o}C$.
U3 = Normal triple glazing, nominal 1.8 $W/m^{2o}C$.
U4 = Nominal 1.2 $W/m^{2o}C$.
Solid line = Energy use with no utilization of daylighting.
Broken line = Energy use with daylighting utilization.

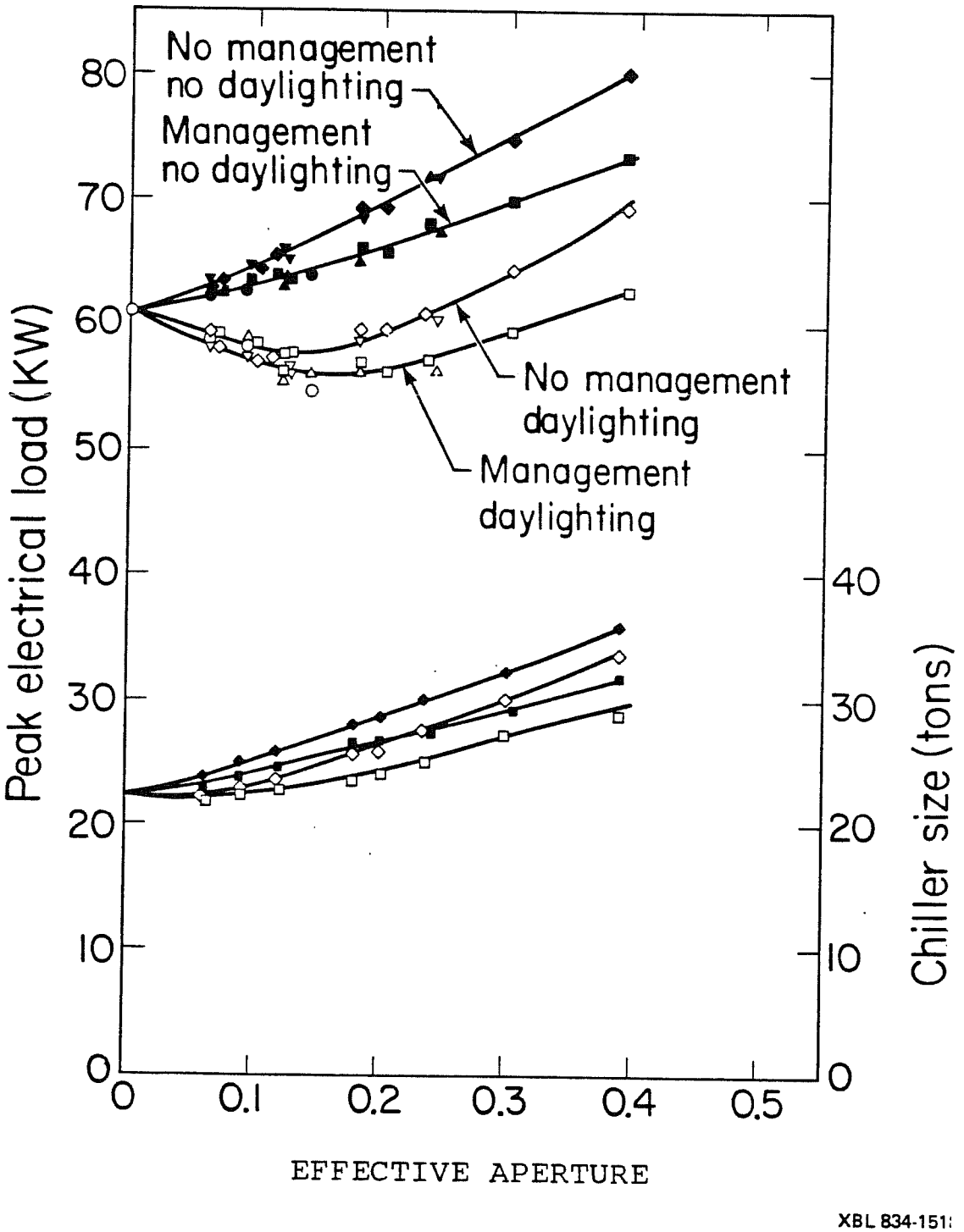


Fig. 2. Peak load and chiller size as a function of effective aperture for Madison, Wisconsin. Lighting power density is 1.7 W/ft^2.

2. REQUIREMENTS FOR FENESTRATION ANALYSIS

Even powerful computer models such as DOE-2 and SUPERLITE possess only some of the capabilities required to model fenestration systems accurately and efficiently. The tendency to expand computer models indefinitely by continuous accretion of new subroutines frequently creates models that are cumbersome and costly to debug, maintain, and use. The tradeoffs between increasing computational accuracy and complexity/cost are not easily resolved. Since there are a great number of possible fenestration designs and since many are geometrically complex, a purely computational approach to daylighting and thermal analysis was abandoned in favor of a primary computational package that utilizes precalculated and/or measured data. This reduces program complexity and cost without sacrificing modeling accuracy, and makes possible the analysis of some designs that would be mathematically intractable. The complete analysis package is shown schematically in Fig. 3.

DOE-2 is the primary computational tool used in parametric studies of glazing system energy performance. Major new capabilities are being added to the program to allow analysis of thermal and daylighting performance of complex fenestration systems.

The revised daylighting model planned for the next version of DOE-2.1 is based on a coefficient-of-utilization calculation. These coefficients are 1) calculated in a preprocessor for simple designs, 2) drawn from a library for more complex but standardized designs, or 3) input by the user for unique designs. The data for the DOE-2 library derive from 1) SUPERLITE calculations of illuminance distributions for simple and moderately complex designs or 2) measurements from scale models in a sun and sky simulator for mathematically intractable designs. When the number of optically active surfaces is not large and the surfaces are diffuse reflectors, SUPERLITE calculates interior illuminance directly from design parameters. When a daylighting element is geometrically complex (e.g., honeycomb) or has optically complex reflective or refractive surfaces, the program utilizes measured angular-dependent luminance data to describe the contribution of the device to room illuminance distribution.

Each step leading to the energy analysis in DOE-2 (Fig. 3) utilizes a combination of direct computations and measurement-based calculations that are program-generated, predetermined,

and stored in program libraries or input by the user. This approach provides broad modeling flexibility and facilitates expansion of the program without incurring enormous cost. Daylighting illuminance normally is analyzed for specific well-defined room and fenestration designs that are frequently repeated throughout a multistoried building. It is also possible to model a multistory building having a different fenestration system and interior design on each floor, although the analysis cost will increase correspondingly.

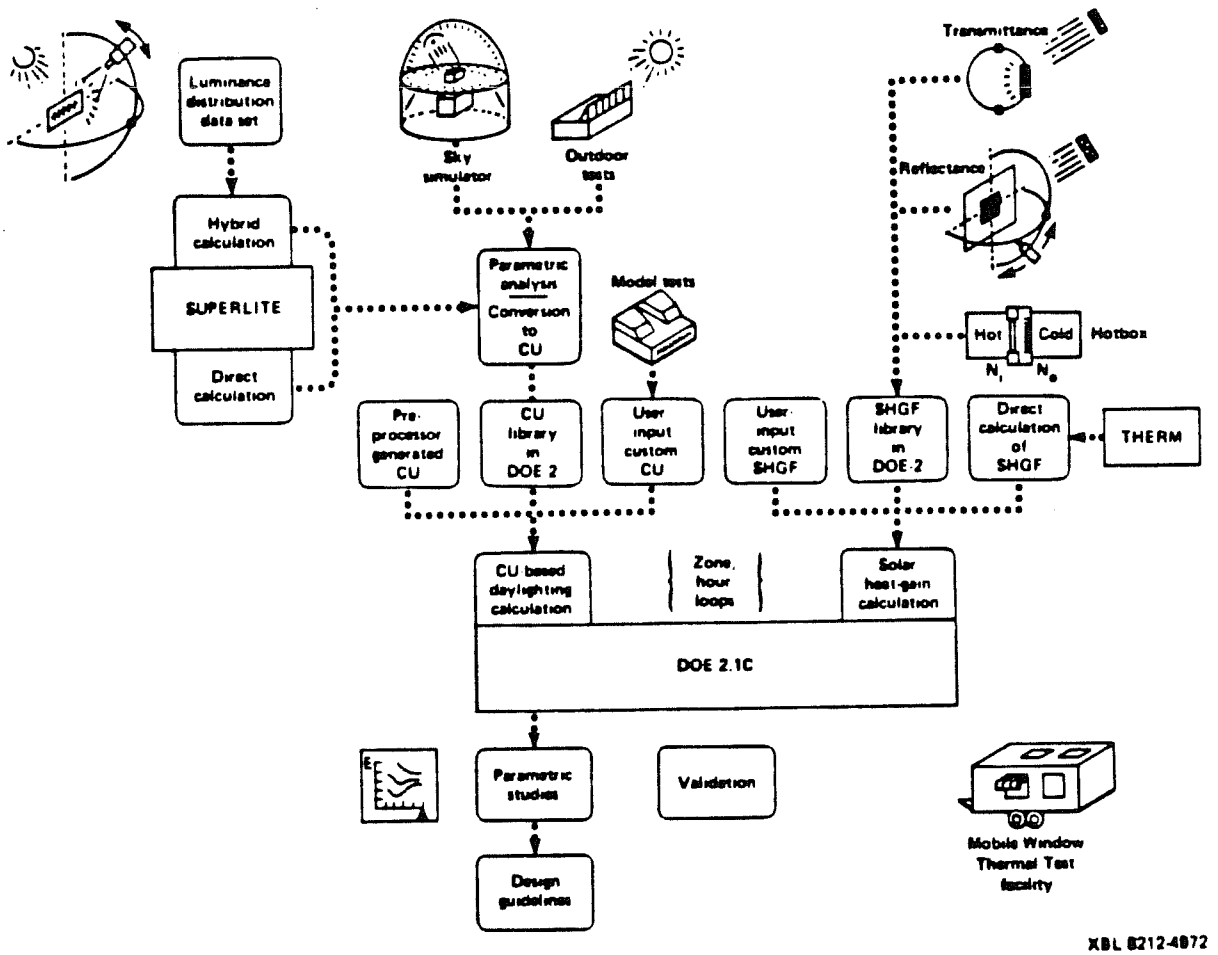


Fig. 3. Schematic diagram of DOE-2.1C planned fenestration modeling capabilities. Input is based on direct computation or calculations based on laboratory or field measurements, and is stored in DOE-2 or input by the user. Input is validated by model testing and in-situ testing by MoWiTT.

The new thermal models for analyzing complex fenestration systems in DOE-2 follow much the same philosophy. The necessity to accurately model complex systems requires a combination of new analytical models and new experimental procedures. The computational logic for modeling the control of operable insulating and shading systems has been added to the program. Work is in progress to improve the solar heat-gain calculations to enable analysis of geometrically complex architectural sun control and shading devices. The solar heat-gain calculation is based on measurement of optical and thermal properties of devices, as illustrated in Fig. 3. A sample device having small characteristic dimensions, such as a louvered shade screen, would be measured directly. Larger devices or architectural solutions would be reproduced and tested as scale models. The analytical solutions for multilayered homogeneous glazing materials are calculated directly in THERM and converted to the matrix formulation for DOE-2.

The Mobile Window Thermal Test (MoWiTT) facility will be used to validate net energy performance predictions from DOE-2 (Fig. 11). This facility has been designed to directly measure the component heat flows from fenestration systems and the interactions between fenestration systems and building HVAC systems.

A primary objective in developing this analytical approach has been to expand capabilities in order to model a broad range of design solutions without further modifying the structure of DOE-2. Embedding experimental measurements within a hierarchy of computational models appears to accomplish this goal.

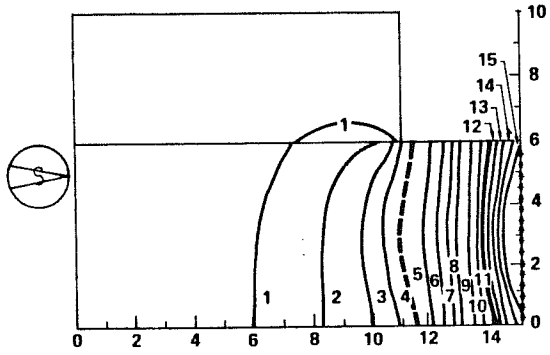
3. CAPABILITIES OF THE SUPERLITE PROGRAM

The mathematical basis of the SUPERLITE algorithms has been described previously.[3,4] This program can model a uniform sky, CIE standard overcast sky, and CIE standard clear sky with or without direct sun. Based on the luminance distribution of a given sky, the luminances of the ground, adjacent buildings, and other external obstructions are calculated. The angular dependence of transmittance through glazing materials is calculated, then the luminances of each interior surface are determined. Because the luminance across a surface may vary significantly, each surface can be divided into a number of subsurfaces having luminances that are calculated separately.

Once the luminances of all interior and external surfaces have been calculated, the work-plane illuminance is determined by integrating the surface luminances over the appropriate solid angles.

Compared to other daylighting computational models, a major advantage of SUPERLITE is its capability of modeling nonrectangular surfaces and other complex geometries. The program will model arbitrary room shapes such as an L-shaped room (see Fig. 4), a room with internal partitions, or rooms with external obstructions. Windows can be of any generalized trapezoidal shape with an arbitrary tilt angle. Various types of diffusing curtains and draperies can be modeled. Overhangs or fins with opaque, translucent, and semi-transmitting materials can also be modeled, permitting analysis of simple light shelves or lightwells. Optical properties determined from model measurements offer the new capability of modeling complex sunshading systems such as egg-crate louvers. Additional modifications will allow the modeling of electric lighting systems in combination with daylighting strategies.

Luminance and illuminance values for each room and sky condition studied can be output in tabular format or on contour plots generated by an auxiliary graphics program. Contour plots produced by SUPERLITE for an L-shaped room and for a large room with a light shelf are shown in Figs. 4 and 5 respectively.



Sky is clear
Sun position: 40° off zenith
0° off S to E

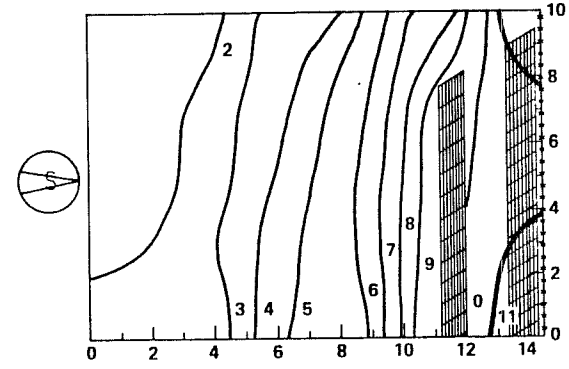
Horizontal illumination
Direct sun: 0 fc
Sky: 2083 fc

Contour Number	Illum. Level (Ft-candles)
1	20.0
2	40.0
3	60.0
4	80.0
5	100.0
6	150.0
7	200.0
8	250.0
9	300.0
10	400.0
11	500.0
12	600.0
13	700.0
14	800.0
15	900.0
16	1000.0

Windows marked by •••••
Sunny areas are hatched

XBL 831-1156

Fig. 4. SUPERLITE illuminance contour plot for an L-shaped room. 100-fc (dashed) and 500-fc (heavy) contours are highlighted.
Hatching shows where sunlight falls on floor.



Sky is clear
Sun position: 65° off zenith
30° off S to E

Horizontal illumination
Direct sun: 2407 fc
Sky: 1298 fc

Contour Number	Illum. Level (Ft-candles)
1	20.0
2	40.0
3	60.0
4	80.0
5	100.0
6	150.0
7	200.0
8	250.0
9	300.0
10	400.0
11	500.0

Windows marked by •••••
Sunny areas are hatched

XBL 831-1155

Fig. 5. SUPERLITE contour plot for a model having a clerestory and light shelf and with direct sun. 100 h-fc (dashed) and 500-fc (heavy) contours are highlighted.
Hatching shows where sunlight falls on floor.

4. DOE-2 DAYLIGHTING MODEL CAPABILITIES

DOE-2 daylighting simulation determines the hourly, monthly, and yearly impact of daylighting on electrical energy consumption and peak electrical demand, as well as the impact on cooling and heating requirements and on annual energy cost. The analysis for the total building is based on separate analysis of each of the identified thermal and/or daylighting zones. It accounts for daylight availability, site conditions, window management in response to sun control and glare, and various lighting control strategies. The development of a daylighting model for DOE-2 is based on a compromise between competing requirements for 1) maximizing accuracy, 2) minimizing computational time and cost, 3) minimizing input requirements, and 4) maximizing versatility. A primary concern has been to develop a model that can be expanded to study virtually any architectural daylight strategy. This is important because DOE-2 is used frequently to analyze large, complex multistory buildings that incorporate innovative designs. Because it is time-consuming to complete and debug major modifications to DOE-2, the daylighting model now running in DOE-2.1B was designed to accommodate future expansion without the need for major modifications. In Sections 4.1 and 4.2, the operation and capabilities of the DOE-2.1B daylighting model are described. Sections 4.3 and 4.4 describe work underway to expand the daylighting and thermal modeling capabilities for complex fenestration systems.

4.1 Daylight Calculation Model

The DOE-2.1B daylighting calculation has three major stages. First (Fig. 6), a preprocessor calculates daylight factors at specified lighting control locations for each window for various sun and sky conditions and stores them for later use in the hourly loads calculation. Luminance distribution of the sky, window size and orientation, glass transmittance, inside surface reflectances, sun control devices, and external obstructions are accounted for. The calculation is carried out for standard CIE overcast sky and for 20 different CIE clear skies with solar altitude and azimuth values covering the annual range of sun positions. Analogous factors for discomfort glare are also calculated and stored.

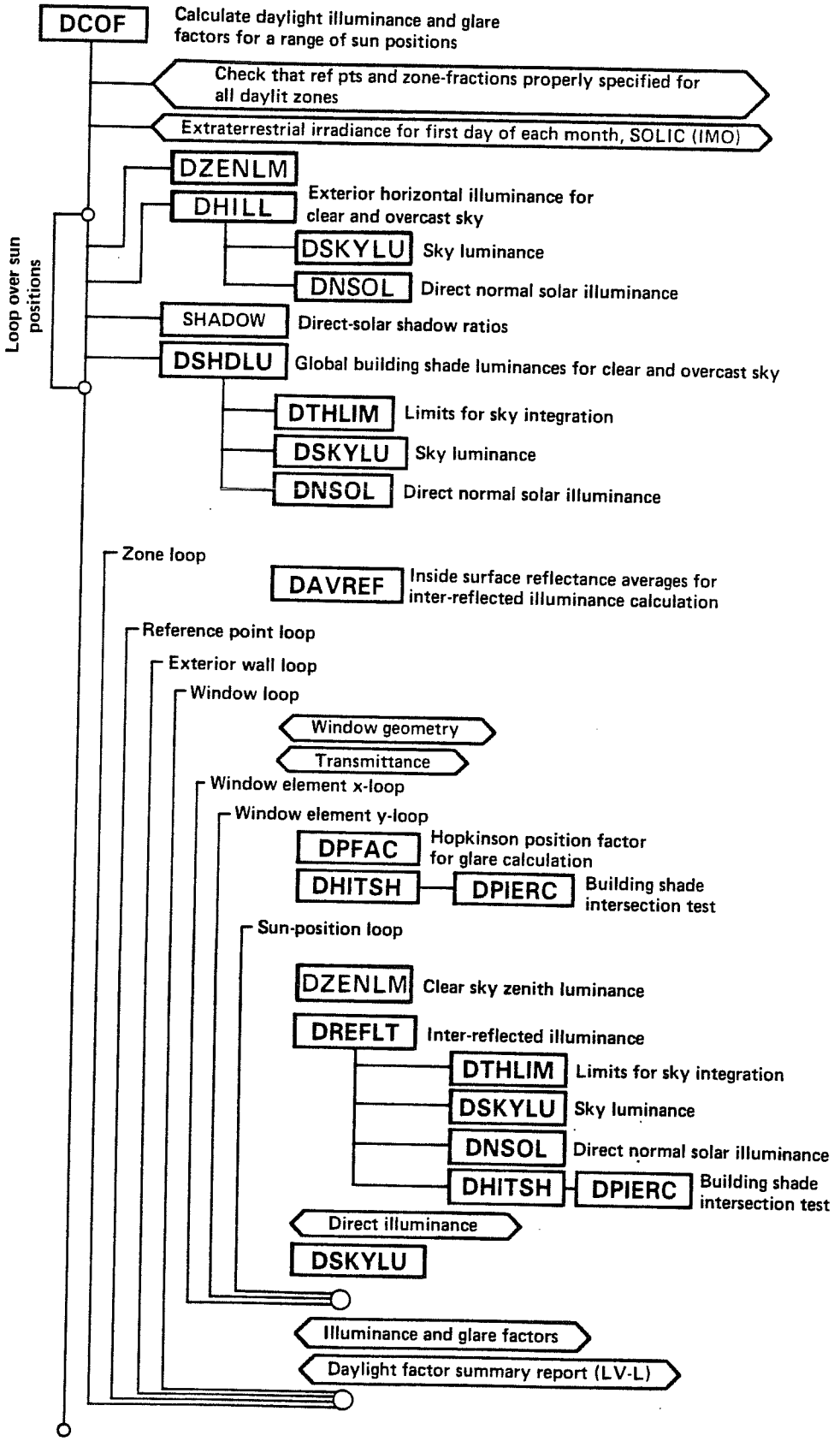


Fig. 6. Flowchart for DOE-2.1B daylighting preprocessor. Daylighting subroutines are in boldface.

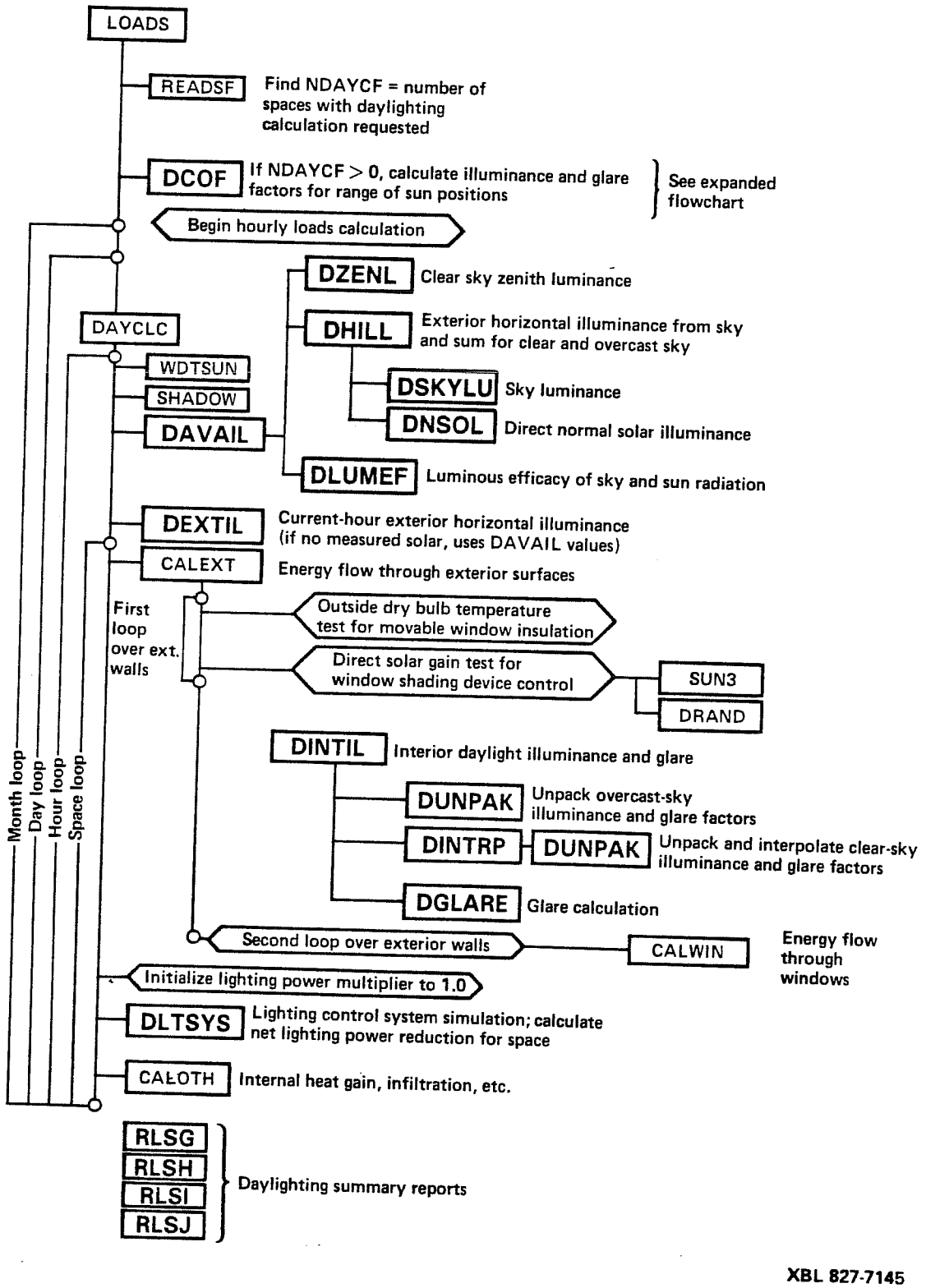


Fig. 7. Flowchart for DOE-2.1B daylighting calculation. Daylighting subroutines are in boldface. Some nondaylighting LOADS subroutines are also shown.

In stage two a daylighting calculation is performed each hour of the year that the sun is up (Fig. 7). The illuminance through each window is found by interpolating the stored daylight factors using the current-hour sun position and cloud cover and then multiplying by the current-hour exterior horizontal illuminance. If the glare-control option has been specified, the program will assume that window blinds or drapes are closed to lessen glare below a pre-defined comfort level. A similar option assumes that window shading devices are operated manually or automatically to control solar gain.

In stage three (Fig. 7) the program simulates the operation of the lighting control system (which may be stepped or continuously dimmed) to determine the energy needed to make up any difference between the daylight illuminance and the design illuminance. Each thermal zone can be divided into two independently controlled lighting zones. Both uniform lighting and task-ambient systems can be modeled. Finally, the zone lighting requirements are transferred to the DOE-2 thermal calculation, which determines hourly heating and cooling loads as well as monthly and annual energy use. Additional details of the calculation procedures can be found in Ref. 5.

4.2 DOE-2.1B Daylighting Output Reports

Tables 1A through 1C show sample DOE-2 daylighting reports for a south-facing office module from a prototypical high-rise building in New York City. The module, which is approximately 6.2 m (20 ft) wide, 9.2 m (30 ft) deep, and 3.1 m (10 ft) floor to ceiling, has a 1.5-m (5-ft) high strip window with 0.9-m (3-ft) sill height and 90% transmittance. Drapes with 35% transmittance are automatically closed if direct solar transmission exceeds 6.4 W/m^2 (20 Btu/ft^2-hr) or if glare is excessive. The module has two independently controlled lighting zones with reference points 3.1 m (10 ft) and 7.7 m (25 ft), respectively, from the window wall, and with design illuminance of 538 lux (50 fc). Each lighting zone has a continuously dimmable control system that dims linearly from 100% light/100% power to 20% light/30% power.

TABLE 1a Sample DOE-2.1B Daylighting Report LS-G--Space Daylighting Summary--for the South-Facing Office Module Described in Fig. 1. Times under "report schedule hours" are restricted to the period 8 am to 5 pm, the hours of major occupancy.

							REPORT SCHEDULE HOURS WITH SUN UP							
	Percent Lighting Energy Reduction By Daylighting (All Hours)			Percent Lighting Energy Reduction By Daylighting Report Schedule Hours)			Average Daylight Illuminance (Footcandles)		Percent Hours Daylight Illuminance Above Setpoint		Average Glare Index		Percent Hours Glare Too High	
	Total	REF PT	REF PT	Total	REF PT	REF PT	REF PT	REF PT	REF PT	REF PT	REF PT	REF PT	REF PT	REF PT
Month	Zone	1	2	Zone	1	2	1	2	1	2	1	2	1	2
JAN	17.1	34.3	0.	22.1	44.1	0.	40.3	0.	34.8	0.	8.7	0.	0.	0.
FEB	20.1	40.2	0.	25.3	50.7	0.	46.9	0.	44.8	0.	9.9	0.	0.	0.
MAR	22.5	45.0	0.	27.5	55.0	0.	50.6	0.	57.0	0.	10.4	0.	0.	0.
APR	25.3	50.6	0.	30.2	60.4	0.	55.8	0.	59.3	0.	11.3	0.	0.	0.
MAY	27.6	55.2	0.	32.2	64.4	0.	54.4	0.	45.5	0.	11.4	0.	0.	0.
JUN	28.8	57.6	0.	33.2	66.4	0.	66.5	0.	58.5	0.	12.4	0.	0.	0.
JUL	27.0	54.0	0.	31.2	62.4	0.	65.5	0.	58.4	0.	12.2	0.	0.	0.
AUG	28.6	57.3	0.	33.7	67.5	0.	69.3	0.	71.3	0.	12.9	0.	0.	0.
SEPT	25.9	51.7	0.	30.5	61.0	0.	53.6	0.	56.7	0.	10.9	0.	0.	0.
OCT	24.7	49.3	0.	30.4	60.7	0.	58.6	0.	58.4	0.	11.2	0.	0.	0.
NOV	19.3	38.6	0.	24.6	49.2	0.	45.6	0.	43.3	0.	9.6	0.	0.	0.
DEC	15.5	31.0	0.	19.9	39.8	0.	39.3	0.	36.9	0.	8.5	0.	0.	0.
ANNUAL	23.6	47.2	0.	28.4	56.9	0.	53.9	0.	52.1	0.	10.8	0.	0.	0.

NOTE: 1 fc = 10.76 lux.

TABLE 1b Sample DOE-2.1B Daylighting Report LS-H--Percent of Lighting Energy Reduction by Daylighting vs Hour of the Day for the South-Facing Office Module Described in Fig. 1.

Month	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	Hours
JAN	0	0	0	0	0	0	0	4	16	23	25	28	26	24	22	20	14	10	0	0	0	0	0	0	17
FEB	0	0	0	0	0	0	0	8	19	24	27	29	30	29	28	25	18	9	0	0	0	0	0	0	20
MAR	0	0	0	0	0	0	9	21	25	27	29	30	29	30	29	27	22	15	0	0	0	0	0	0	23
APR	0	0	0	0	0	3	21	28	29	30	32	32	33	31	30	29	25	21	2	0	0	0	0	0	25
MAY	0	0	0	0	0	10	26	30	32	31	32	33	33	33	34	32	29	26	5	0	0	0	0	0	28
JUN	0	0	0	0	1	10	26	30	33	34	33	35	34	32	34	34	31	24	13	1	0	0	0	0	29
JUL	0	0	0	0	0	7	24	30	31	31	32	32	31	32	33	30	30	27	6	1	0	0	0	0	27
AUG	0	0	0	0	0	0	23	31	33	34	39	35	35	35	34	33	31	22	3	0	0	0	0	0	29
SEP	0	0	0	0	0	3	17	29	29	30	31	32	33	31	30	30	29	18	1	0	0	0	0	0	26
OCT	0	0	0	0	0	0	8	26	28	31	33	34	33	32	30	27	24	2	0	0	0	0	0	0	25
NOV	0	0	0	0	0	0	5	16	26	28	28	30	29	27	25	24	4	0	0	0	0	0	0	0	19
DEC	0	0	0	0	0	0	0	4	16	21	23	25	25	24	22	19	4	0	0	0	0	0	0	0	15
ANNUAL	0	0	0	0	0	4	17	26	26	29	30	31	31	30	29	28	20	12	3	0	0	0	0	0	24

NOTE-The Entries in This Report Are Not
Subject To The Daylighting Report Schedule

TABLE 1C

Frequency of Interior Daylight Illuminance

Sample DOE-2.1B daylighting program Report LS-J--Daylight Illuminance Frequency of Occurence--for the south-facing office module described in Fig. 1.

		Percent of Hours In Illuminance Range									Percent of Hours Illuminance Level Exceeded								
		Illuminance Range (Footcandles)									Illuminance Level (Footcandles)								
Month	REF PT	0 -- 10	10 -- 20	20 -- 30	30 -- 40	40 -- 50	50 -- 60	60 -- 70	70-- 80	80 -Above	0	10	20	30	40	50	60	70	80
JAN	-1-	28	11	6	9	11	5	8	4	18	100	72	61	55	46	35	30	22	18
	-2-	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FEB	-1-	17	12	5	9	13	7	11	10	17	100	83	71	66	58	45	38	27	17
	-2-	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MAR	-1-	15	8	5	5	10	17	15	11	14	100	85	77	72	67	57	40	25	14
	-2-	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
APR	-1-	7	10	4	7	13	16	16	13	15	100	93	83	80	72	59	44	28	15
	-2-	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MAY	-1-	4	5	8	13	25	14	8	7	16	100	96	90	83	70	46	32	23	16
	-2-	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
JUN	-1-	0	6	4	13	18	13	7	8	31	100	100	94	90	77	59	46	39	31
	-2-	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
JUL	-1-	3	5	5	8	20	11	8	9	30	100	97	92	87	78	58	47	39	30
	-2-	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
AUG	-1-	0	1	3	9	15	21	16	7	27	100	100	99	95	87	71	50	34	27
	-2-	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SEPT	-1-	12	5	5	8	13	20	13	9	16	100	88	83	78	70	57	37	24	16
	-2-	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
OCT	-1-	8	11	4	8	11	9	8	11	30	100	92	81	77	70	58	49	41	30
	-2-	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
NOV	-1-	22	13	6	7	9	8	7	8	20	100	78	64	59	52	43	35	28	20
	-2-	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
DEC	-1-	29	13	8	9	4	10	5	3	19	100	71	58	50	41	37	27	22	19
	-2-	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ANNUAL	-1-	12	8	5	9	14	13	10	8	21	100	88	80	74	66	52	40	29	21
	-2-	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

NOTE: 1 fc = 10.76 lux.
The hours considered in this report are those with sun up and daylighting report schedule on.

The data provided in these reports give a detailed description of the role of daylighting in the building. Table 1A shows the type of monthly and annual summary data useful for estimating the savings and cost-effectiveness of a daylighting strategy. The hourly average energy savings in Table 1B provide more detailed data on the hourly/monthly pattern of daylight savings. A frequently observed pattern is one in which midday savings reach a maximum but early morning and late afternoon values are well below maximum. Adding glazing in these cases will save little extra lighting energy but may significantly increase cooling loads. These results can be viewed on a zone-by-zone basis and for the entire building. The two sections of Table 1C provide detailed statistics on the frequency of occurrence of various interior daylight illuminance values and the cumulative probability of exceeding each value. A user can quickly estimate the change in daylighting savings if a design illuminance value is changed or if the lighting control strategy is altered, without rerunning the DOE-2 program.

Other DOE-2 daylighting reports (not shown) give hourly values for exterior and interior daylight illuminance and reductions in lighting power for user-specified time periods.

4.3 Daylighting Model for New Versions of DOE-2.1

The program currently calculates interior illuminance for conventional window designs using a preprocessor calculation and assuming that sun control systems such as shades, drapes, and blinds are ideal diffusers. The program is being expanded to model geometrically complex sunshading solutions such as horizontal and vertical louvers or light shelves and to model unique architectural spaces such as atrium spaces that are more routinely being incorporated into large multistory buildings.

Because direct calculation of interior illuminance from complex sunshading systems is computationally difficult (and in some cases impossible), a new coefficient-of-utilization model was developed based on data calculated or measured outside the DOE-2 program. There are several ways in which this new model can be implemented. Some designs can be standardized (e.g., horizontal flat louver system) but may be too complex to calculate in DOE-2. These are precalculated using SUPERLITE (for a range of louver reflectance values, width/spacing ratios, etc.) and stored in DOE-2.

When it is important to generate values for specific products rather than generic designs, SUPERLITE will serve as a "preprocessor" to DOE-2 and will generate the coefficients directly.

A second category includes daylighting designs that can be standardized but may be too complex to calculate using an existing computational model (e.g., complex curved, semi-specular light shelves). In this instance the required illuminance data will be generated from scale models in a large hemispherical sky simulator at Lawrence Berkeley Laboratory (LBL) (Fig. 8); results will be converted to coefficients that are stored in the DOE-2 library.

A third category includes unique designs not found in the DOE-2 library. In this case a user can develop the required data from model studies, convert these data into a format compatible with the coefficient-of-utilization calculation, and input the results directly into the program library. Each user thus can create his/her own library of custom designs for evaluation.

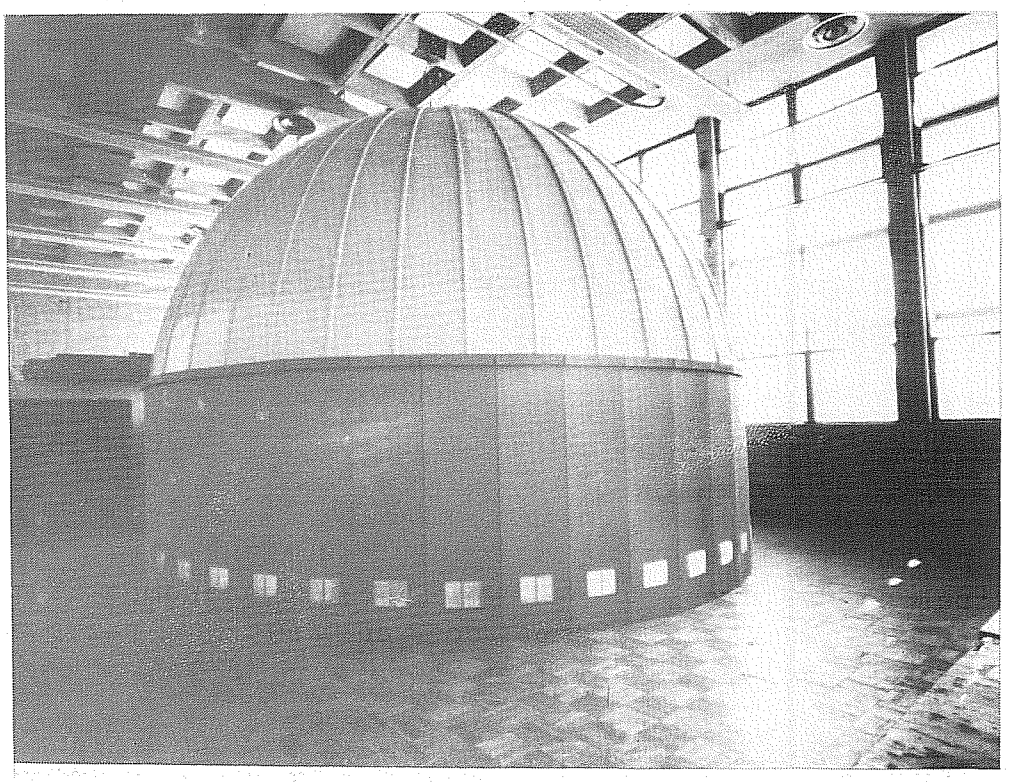


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Fig. 8. Exterior view of 7.4-m (24-ft) diameter hemispherical sky simulator.

Each of these options requires a systematic series of calculations and/or measurements under a full range of overcast and clear skies and direct sun conditions. The coefficient-of-utilization model extends the calculation method now used by the Illuminating Engineering Society (U.S.) for daylighting calculations,[6] but includes five coefficients that are sensitive to illumination from the ground, sky, and sun. Basic data for the standard DOE-2 library are being developed from an extensive series of parametric analyses using SUPERLITE and from systematic model tests in the LBL sky simulator.

4.4 Fenestration Thermal Model for New Versions of DOE-2.1

If the energy and load impacts of complex fenestration systems are to be adequately analyzed, not only must the daylight contribution be properly modeled but also the thermal loads must be accurately analyzed. None of the major hour-by-hour energy analysis programs account for solar gain through geometrically complex fenestration. It is therefore necessary to develop a new computational model to determine solar heat gain from complex fenestration systems. This heat-gain model is similar to the new coefficient-of-utilization daylighting model described in the previous section.

Solar heat gain will be calculated by splitting the incident solar energy into three components: direct solar radiation, sky diffuse radiation, and ground diffuse radiation. This differentiation is important if systems such as operable louvers are to be modeled accurately. A separate solar heat-gain factor will be developed for each component of each fenestration system. Because multiple fenestration devices may be used on a single aperture (e.g., exterior fins, heat-absorbing glass, interior drapes), the approach must predict the performance of individual devices in series. Solar heat gain through a complex fenestration system at a given time will thus be the sum of three transmitted components (direct, sky diffuse, ground diffuse) plus the net inward-flowing fraction of all absorbed energy. All transmitted components are calculated from optical properties of the devices using a matrix computation that accounts for the interreflectance between glazing layers and/or shading devices in series.

Because it is impractical to determine the optical properties for separate solar components in an outdoor calorimeter and it is impossible to calculate many of the values directly, a laboratory measurement will be used. Each of the three

incident solar components can reach the interior by two pathways: it can be transmitted directly through the aperture or can be absorbed in the fenestration system and then re-radiated and convected to the interior. The transmitted components are determined by a series of optical measurements. Transmission measurements for beam radiation as a function of angle of incidence will be made by mounting the device in an opening in a large, 2.2-m (7-ft) diameter integrating sphere and illuminating it with an exterior radiant source. The transmittance of the device is the ratio of two signals from a set of detectors in the sphere: the signal with the device in place divided by the signal with an empty opening. Reflectance measurements from both sides of the device will be made by illuminating the device, scanning the radiance over a hemisphere, and integrating the resulting values. Both sets of measurements will be made using a sun simulator with a collimated beam at varying incident angles and with a diffuse source in the sky simulator. The integrating sphere may also be used outdoors with the sun as a source.

The absorbed component can be calculated directly if the transmittance and reflectance are known. Part of the absorbed component will be transferred to the interior space, while the remainder will be rejected to the outdoors. This rejected fraction will be determined using a calibrated hotbox that measures the thermal conductance of window systems. The device to be tested will be mounted in the proper location relative to the glazing and the entire assembly installed in a hotbox. First the hotbox will be operated normally to establish a base case; the shading device will then be electrically heated to simulate the absorbed solar component. The resulting reduction in heater power to the hotbox, relative to the total input power to the shading device, is the inward-flowing fraction of absorbed energy. The accuracy limitations of summing contributions from absorbing layers in series require additional study.

5. MODEL VALIDATION

Extensive validation studies are required to build confidence in the predictions from these analytical tools. Ideally, one would like comparisons to measured energy consumption in multistoried buildings, but for practical reasons the performance of fenestration components and systems normally would be studied at a smaller, but more detailed, level. Each of the major

computational modules has been or is being tested by comparison to more detailed computer models and to experimental data. Validation of total fenestration performance predictions awaits calibration of the Mobile Window Thermal Test facility described in Section 5.2.

5.1 Daylighting Models

Several types of validation studies have been undertaken for the computer models. First, the models are tested by running a series of parametric analyzes to test the sensitivity of each calculation process to key design parameters. For example, one test series might examine the influence of window size, window transmittance, and interior surface reflectance under a variety of sun and sky conditions. Second, the results of each program are compared to each other and to other daylighting models. Finally, calculated results from both SUPERLITE and DOE-2 have been compared with a series of measurements made on scale models in the LBL sky simulator.[7] This 7.4-m (24-ft) diameter indoor facility enables testing under uniform, overcast, and clear sky conditions (Fig. 8). The advantages of using this artificial sky compared to outdoor tests are 1) the direct illuminance from the sun can be separated from the clear sky contribution, 2) the reflectance of the ground can be easily controlled, and most importantly 3) the sky luminance distributions are stable and reproducible.

A small single-occupant office model and a large open-landscaped office have been tested under a variety of sky conditions. The graphs in Figs. 9 and 10 compare the daylight factors from SUPERLITE and DOE-2 calculations with measurements under the artificial sky along the centerline of the models. Results are shown for clear sky conditions for both small and large office models. These methods compare well throughout the cross section of the room. Additional comparisons to outdoor model tests are in progress.

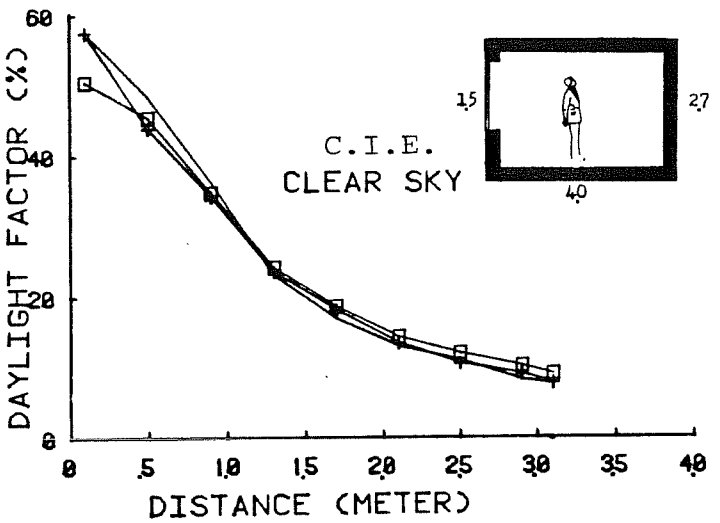

Fig. 9. SUPERLITE (+) and DOE-2 (□) predictions compared with sky-simulator measurements (-). CIE clear sky with solar altitude 50°, azimuth 0°; direct sun is excluded. Ground reflectance is zero. Interior reflectances are 25% for floor, 60% for walls, and 80% for ceiling. Glass transmittance is 90%.

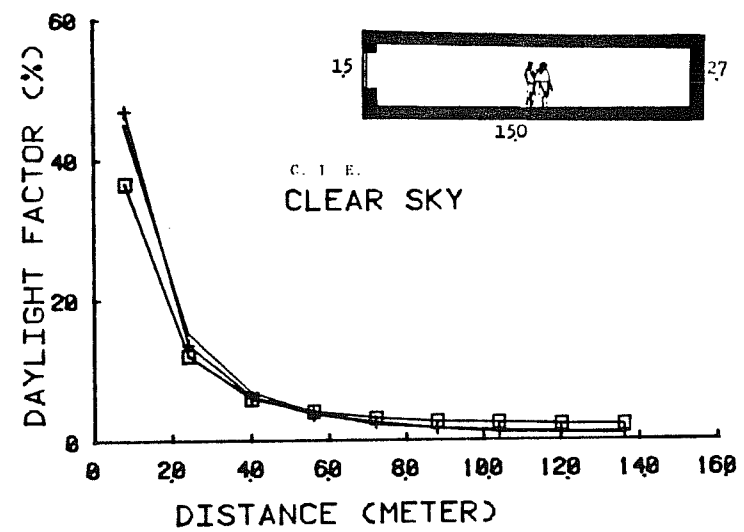

Fig. 10. SUPERLITE (+) and DOE-2 (□) predictions compared with sky-simulator measurements (-). CIE clear sky with solar altitude 50°, azimuth 0°; direct sun is excluded. Ground reflectance is zero. Interior reflectances are 25% for floor, 60% for walls, and 80% for ceiling. Glass transmittance is 90%.

5.2 Thermal Models

The thermal models in DOE-2 must accurately predict performance for a broad range of new window systems. Some of these new systems employ multiple glass and plastic layers, transparent low-emittance coatings, and low-conductance gas fills. These can be modeled using an extension of existing algorithms and are validated by comparison to heat-transfer predictions from THERM. THERM is a detailed window heat-transfer model based upon the algorithms described in Ref. 8. Heat-transfer predictions from THERM have been validated by comparison to results from a calibrated hotbox.[9]

The performance of complex window systems under incident sunlight must be validated in an outdoor facility that accounts for solar gain, temperature effects, and other energy-related interactions. A Mobile Window Thermal Test (MoWiTT) facility has been built for this purpose.[10] The facility contains two highly instrumented, side-by-side test chambers, the thermal properties of which can be altered to simulate a range of building conditions. This facility permits direct measurement of the thermal impact of fenestration on HVAC systems and will enable the thermal impact of daylighting strategies to be measured. The primary objective is to develop a data base on fenestration performance at a level of detail that allows hour-by-hour energy analysis programs such as DOE-2 to be validated at the algorithm level. Field calibration of the unit is in progress (Fig. 11).

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Fig. 11. Exterior view of Mobile Window Thermal Test (MoWiTT) facility showing the side-by-side test chambers.

8. SUMMARY AND FUTURE DIRECTIONS

The SUPERLITE and DOE-2 computer models represent powerful and complementary design tools that will improve our understanding of the role of daylighting in energy-efficient multistory buildings. It is important to recognize the strengths, weaknesses, and limitations of any design tool in order to use it properly. SUPERLITE is a lighting design tool that calculates the detailed interior daylight distribution patterns resulting from both simple and complex fenestration designs under a variety of climatic conditions. When the capability for modeling electric lighting is added, examination of the interaction and integration of daylight and electric lighting

control strategies will be possible. The primary advantage of this model compared to other computational models is its ability to accurately analyze geometrically complex but architecturally interesting concepts. This capability is being expanded to model complex shading systems, specular reflectors, and other non-standard design alternatives based on measurements of device luminance distributions.

The daylighting model in DOE-2.1B has been designed for flexibility and future expansion. Currently the program calculates interior illuminance for conventional window designs based on a preprocessor calculation and sun control systems that are assumed to be ideal diffusers. The program is being expanded to model more geometrically complex sunshading solutions (such as horizontal or vertical louvers) based on results calculated by the SUPERLITE program or determined from model measurements. These results will be stored in a library within the DOE-2 program or could be specified by the user. For unique building designs a user can input his or her own daylight coefficients based on model tests of that design. The goal is an energy analysis model that is highly flexible and responsive to the latest design strategies. In addition, DOE-2's thermal and sun control modeling capabilities are being expanded to be consistent with the improved daylighting modeling and to accurately model tradeoffs among heat loss, heat gain, and daylighting benefits.

Any large computer model requires a substantial investment in training before it can be utilized effectively. Most multistory buildings are designed using much simpler and more accessible design tools. Thus these powerful new computer models are being used to develop the technical basis for simplified design tools that reproduce most of the accuracy and analytical power of more complex tools but are less costly and easier to access and use.

7. ACKNOWLEDGEMENT

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