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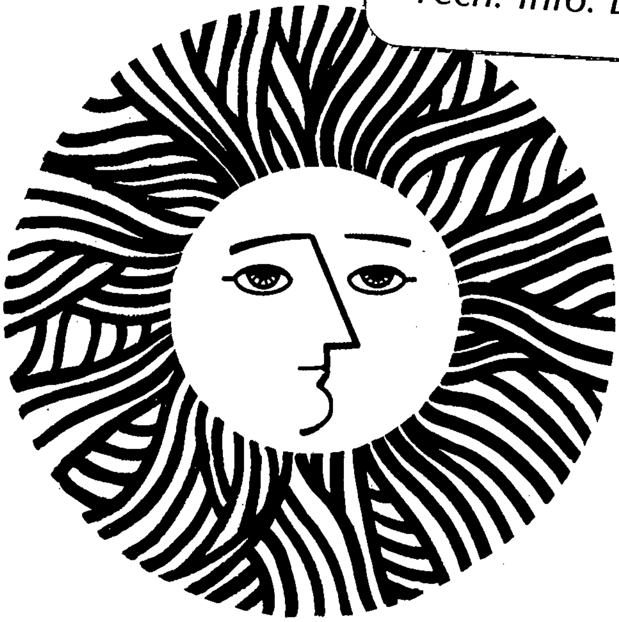

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ABSTRACT

We describe the capabilities and limitations of two daylighting computer programs, the algorithms used in each, results of validation studies, and sample results using each of these programs. We also describe features now under development for both programs which should further extend their usefulness as design tools.

1. INTRODUCTION

Lighting is a major end use of energy in most nonresidential buildings. Design strategies that reduce electric lighting requirements should thus reduce annual energy consumption, peak electrical loads, and may have beneficial effects on 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 with good accuracy using conventional analysis techniques. The use of natural lighting in buildings represents a more complex analytical problem because of the highly variable nature of the daylight resource, because of the coupling of daylight admittance to solar gain, and because of the uncertainties in the integration of electric lighting sensors and controls to properly utilize daylight. Measured performance data from buildings could provide a picture of the real energy and load savings but the existing performance database is very small. If we cannot turn to existing buildings to gain experience on successful solutions we invariably turn to analytical tools to assist in the design process. Despite the explosion of design tools for building energy analysis, there are none currently in extensive use with a demonstrated capability for analyzing the impact of daylighting strategies in nonresidential buildings. In this paper we describe two new computer models which show promise of being very powerful and flexible tools to assist 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 illuminance in a building based upon exterior sun and sky conditions, site obstructions, fenestration and shading device details, and interior room properties. To estimate annual energy use and peak load impact we utilize a second computer program, DOE-2.1B, which now contains a daylighting analysis model. The DOE-2 model determines the energy impact of daylighting strategies based upon 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.

2. CAPABILITIES OF THE SUPERLITE PROGRAM

The mathematical basis of the SUPERLITE algorithms has been described previously.(1) A uniform sky, CIE standard overcast sky, and CIE standard clear skies with or without direct sun can be modeled. Based upon the luminance distribution of a given sky, the luminances of the ground, adjacent buildings and other external obstructions are calculated. Then the luminances of each interior surface are determined. Since the luminance across an interior surface may vary significantly each surface can be divided into a number of sub-surfaces and the luminance of each sub-surface calculated separately. The angular dependence of transmittance through glazing materials is properly calculated. Once the luminance of all interior and external surfaces has been calculated, the work plane illuminance is determined by integrating the surface luminances over the appropriate solid angles.

In comparison to other daylighting computational models a major advantage in SUPERLITE is the ability to model nonrectangular surfaces and other complex geometries. The program will model arbitrary room shapes such as an L-shaped room (see Figure 2-G), a room with internal partitions, or rooms with external obstructions. Windows can be any generalized trapezoidal shape with arbitrary tilt angle. Various types of curtains and draperies can be modeled. Overhangs or fins with opaque, translucent, and semi-transmitting materials can also be modeled, thus permitting analysis of various types of light shelves (see Figure 2-H) or lightwells. We are adding a new capability to the program to allow modeling of complex sun shading systems, such as egg crate louvers, using optical properties determined from model measurements. We are also adding the capability of modeling electric lighting systems so that the combined illuminance from daylight and electric lighting can be studied.

Luminance and illuminance values from the program can be output in tabular format, or contour plots of illuminance levels or daylight factor can be generated by an auxiliary graphics program.

2.1 Contour Programming Features of SUPERLITE

Fig. 1 shows SUPERLITE contour plots for a room with two skylights under three sky conditions (overcast, clear without sun, and clear with direct sun) on March 21, June 21 and December 21, at noon. Contour plots produced by SUPERLITE for an L-shaped room and for a large room with a light shelf are shown in Figure 2G and 2H, respectively.

3. DOE-2 DAYLIGHTING MODEL CAPABILITIES

The 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 calculation has three main stages. In the first stage, a preprocessor calculates daylight factors for later use in the hourly loads calculation. The user specifies the coordinates of one or two reference points in a space. DOE-2 then integrates over the area of each window to obtain the contribution of direct light from the window to the illuminance at the reference points, and the contribution of light which reflects from the walls, floor, and ceiling before reaching the reference points. Taken into account are such factors as the luminance distribution of the sky, window size and orientation, glass transmittance, inside surface reflectances, sun control devices such as blinds and overhangs, and external obstructions. The calculation is carried out for standard CIE clear and overcast sky conditions for a series of 20 different solar altitude and azimuth values covering the annual range of sun positions. Analogous daylight factors for discomfort glare are also calculated and stored.

In stage two an hourly daylighting calculation is performed every hour of the year that the sun is up. The illuminance from each window is found by interpolating the stored daylight factors using the current-hour sun-position and cloud cover, then multiplying by the current-hour exterior horizontal illuminance. If the glare-control option has been specified, the program will automatically close window blinds or drapes in order to decrease glare below a predefined comfort level. A similar option is available to use window shading devices to automatically control solar gain.

In stage three the program simulates the lighting control system (which may be stepped or continuously dimming) to determine the electrical lighting energy needed to make up any difference between the daylighting level 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 electrical requirements are passed to the DOE-2 thermal calculation which determines hourly heating and cooling loads, and monthly and annual energy use.

3.1 DOE-2 Daylighting Output Reports

Table 1 shows three sample DOE-2 daylighting output reports for a south-facing office module in New York City. The module, which is 20´ wide, 30´ deep, and 10´ floor to ceiling, has a 5´ high strip window with 3´ sill height and 90% transmittance. Drapes with 35% transmittance are automatically closed if direct solar transmission exceeds 20 Btu/ft^2-hr or if glare is excessive. The module has two independently controlled lighting zones with reference points 10´ and 25´, respectively, from the window-wall, and with design illuminance of 50 fc. Each lighting zone has a continuously dimmable control system.

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

4. VALIDATION OF SUPERLITE AND DOE-2 DAYLIGHTING MODELS

Three types of validation studies have been undertaken for the computer models. First, we have tested the models by running series of parametric analyses to test the sensitivity of each calculation process to key design parameters. For example, we examine the influence of window size, window transmittance, and interior surface reflectance, under a variety of sun and sky conditions. Second, we compared the results of each of these programs to each other and to other detailed daylighting models and the QUICKLITE program,(2) a simplified daylighting analysis procedure. Finally, calculated results from both SUPERLITE and DOE-2 have been compared to an extensive series of measurements made in scale models in the LBL sky simulator.(3) This 24-foot diameter indoor facility allows us to test models under uniform, overcast, and clear sky conditions. The key 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 distribution, 2) the reflectance of the ground can be easily controlled, and 3) and most important, the sky luminance distributions are stable and reproducible at any time.

A small single-occupant office model and a large open landscaped office have been tested under a variety of conditions. The graphs in Figure 2 compare the daylight factors from SUPERLITE and DOE-2 calculations with measurements under the artificial sky along the centerline of the models. Results for clear and overcast conditions for both small and large models are shown in Figure 2A through 2F. The comparison shows good agreement throughout the room cross-section.

5. SUMMARY AND FUTURE DIRECTIONS

These two computer models represent powerful and complementary design tools that will assist us to better understand the role of daylighting in energy-efficient buildings. It is important to recognize the strengths, weaknesses and limitations of any design tool in order to use the tool properly. SUPERLITE calculates the detailed interior daylight distribution patterns resulting from both simple and complex fenestration designs under a variety of different climatic conditions. It is thus an illumination analysis tool, not an energy analysis tool. When we have completed the addition of an electric light modeling capability it will also allow us to examine the interaction and integration of daylight and electric lighting control strategies. The primary advantage of this model relative to existing computational models is its ability to accurately analyze geometrically complex but architecturally interesting design solutions. We are expanding this capability by adding the ability to model complex shading systems, specular reflectors, and other non-standard design alternatives.

The daylighting model in DOE-2.1B has also been designed with flexibility and future expansion in mind. At the present time the program calculates interior illuminance for conventional window designs using a preprocessor calculation and sun control systems such as shades, drapes and blinds that are assumed to be ideal diffusers. We are currently expanding the program to allow modeling of more geometrically complex sunshading solutions such as horizontal or vertical louvers based upon results calculated in the SUPERLITE program or determined by model measurements. These results would be stored in a library within the DOE-2 program and could be specified by the user. For one-of-a-kind building designs we will allow a program user to input his or her own daylight coefficients based upon model tests made on that unique design. We are thus working towards an energy analysis model that has a very high degree of flexibility and should be responsive to the latest in architectural design strategies. In addition we are currently upgrading the thermal and sun control modeling capabilities of DOE-2 so that they are consistent with the improved daylight modeling and allow accurate trade-offs to be made between heat loss, heat gain and daylighting benefits.

DOE-2.1B should become publicly available late this summer. Earlier versions of DOE-2(4) have been extensively used by larger architectural and engineering firms. The SUPERLITE program will also be made available when validation studies have been completed. However, both programs are large computer models that require a substantial investment in training to properly utilize them. We recognize that the majority of buildings are designed using much simpler and more accessible design tools. We expect to use these powerful new computer models to develop simplified design tools that reproduce most of the accuracy and analytical power of the more complex tools while lowering cost and providing easier use.

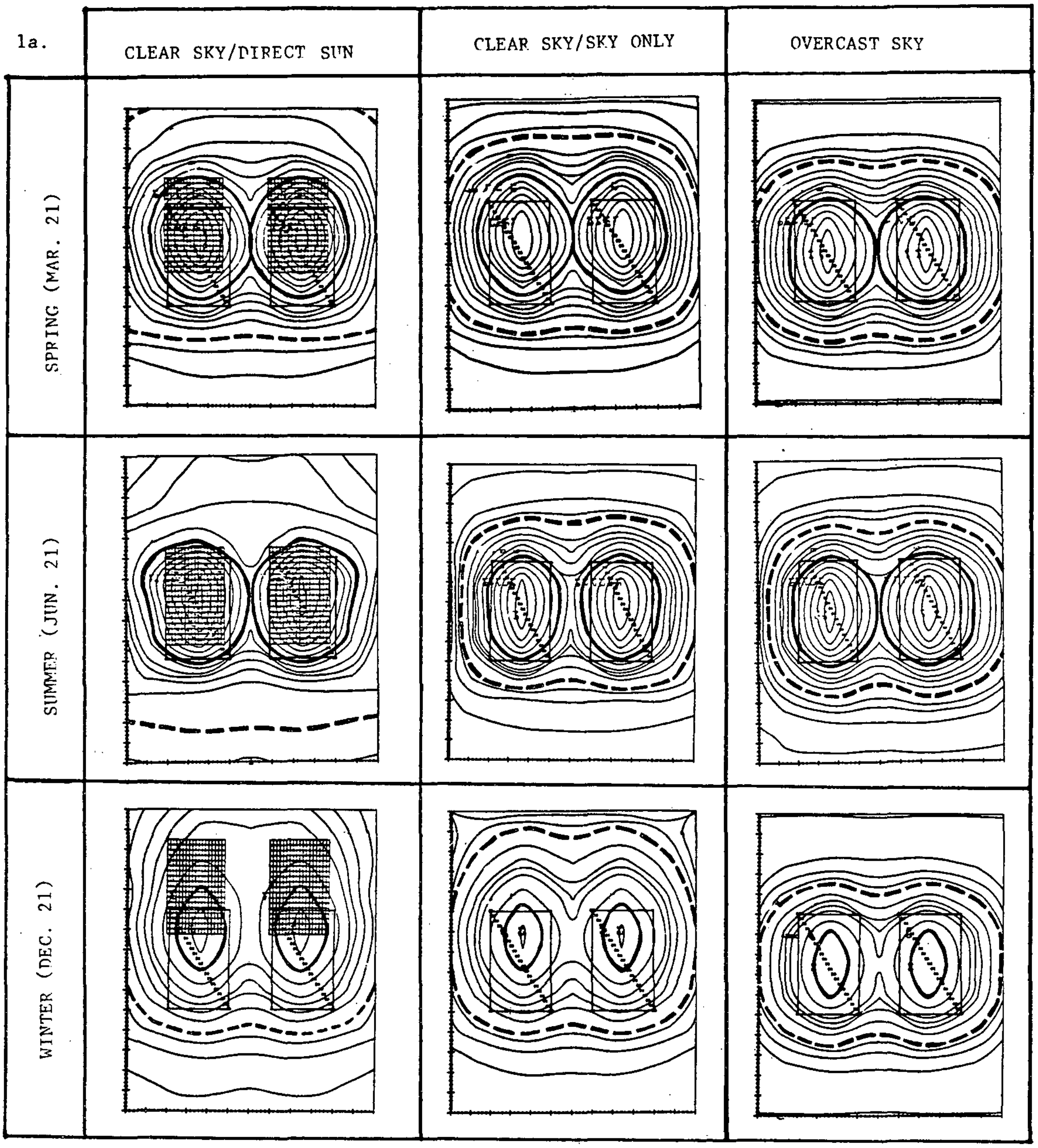
6. ACKNOWLEDGEMENT

This work was supported by the Assistant Secretary for Conservation and Renewable Energy, Office of Buildings and Community Systems, Building Division of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

7. REFERENCES

1. Michael F. Modest, "Daylighting Calculations for Non-Rectangular Interior Spaces with Shading Devices", LBL Report 12599, June 1981.
2. H. Bryan et al., "QUICKLITE1: A Daylighting Program for the TI-59 Calculator", Lighting Design and Application June 1981, pp.28-36.
3. S. Selkowitz, "A Hemispherical Sky Simulator for Daylighting Model Studies", Proc. of the 6th National Passive Solar Conference, J. Hayes and W. Kolar, eds., 1982, pp. 850-854.
4. DOE-2 Reference Manual, Los Alamos National Laboratory Report LA-7689-M, Ver. 2.1 and Lawrence Berkeley Laboratory Report LBL -8706 Rev. 1, May 1980.

1a.



1b.

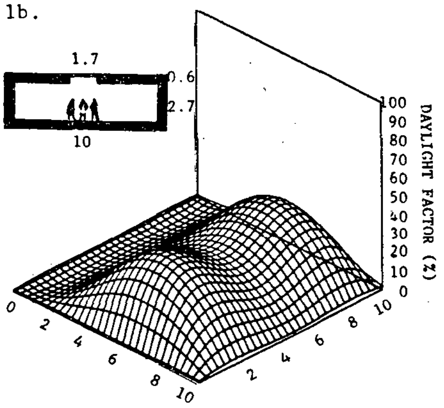


Figure 1a. Example of SUPERLITE illuminance contour plots for a room with two skylights under three sky conditions (time: noon; latitude: 38°N). The 100-fc level (dashed contour) and the 500-fc level (solid contour) are highlighted. The hatched rectangles on the clear sky/direct sun plots show where sunlight falls on the floor of the room.

Figure 1b. The 3-D graph for the same room shows the illuminance levels as measured in the sky simulator under conditions of spring, clear sky only.

1a.

REPORT- LS-G SPACE DAYLIGHTING SUMMARY

SPACE SOUTHZONE

	PERCENT LIGHTING ENERGY REDUCTION BY DAYLIGHTING (ALL HOURS)			PERCENT LIGHTING ENERGY REDUCTION BY DAYLIGHTING (REPORT SCHEDULE HOURS)			REPORT SCHEDULE HOURS WITH SUN UP: AVERAGE DAYLIGHT ILLUMINANCE (FOOTCANDLES)		PERCENT HOURS DAYLIGHT ILLUMINANCE ABOVE SETPOINT		AVERAGE GLARE INDEX		PERCENT HOURS GLARE TOO HIGH	
MONTH	TOTAL ZONE	REF PT 1	REF PT 2	TOTAL ZONE	REF PT 1	REF PT 2	REF PT 1	REF PT 2	REF PT 1	REF PT 2	REF PT 1	REF PT 2	REF PT 1	REF PT 2
JAN	33.7	38.6	28.7	44.1	50.5	37.8	70.4	35.9	44.4	26.9	19.6	17.8	25.4	21.9
FEB	38.6	43.2	34.0	49.8	55.4	44.2	79.1	40.7	59.5	37.3	20.3	18.9	31.3	24.2
MAR	43.5	48.3	38.8	54.5	59.8	49.2	84.2	43.5	65.6	45.9	21.3	19.9	40.9	21.9
JUN	53.7	59.7	47.8	63.2	68.7	57.6	70.0	36.7	77.8	14.8	22.1	20.9	1.5	0.
SEP	50.5	54.2	46.7	61.0	64.5	57.4	87.4	45.8	75.9	46.7	21.9	20.6	37.0	18.9
DEC	30.0	34.7	25.2	39.3	45.4	33.2	63.0	31.7	40.9	25.4	18.0	16.5	22.6	16.1
ANNUAL	44.8	49.9	39.7	55.3	60.8	49.7	74.0	38.2	65.0	29.7	21.0	19.7	20.8	11.5

1b.

REPORT- LS-H PERCENT LIGHTING ENERGY REDUCTION BY DAYLIGHTING VS HR OF DAY

SPACE SOUTHZONE

HOUR OF DAY

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	ALL HOURS
JAN	0	0	0	0	0	0	0	10	24	46	55	58	56	52	47	37	22	0	0	0	0	0	0	0	34
FEB	0	0	0	0	0	0	0	16	36	45	55	59	61	58	55	50	29	12	0	0	0	0	0	0	39
MAR	0	0	0	0	0	0	20	34	50	55	58	61	59	59	57	52	40	25	0	0	0	0	0	0	44
JUN	0	0	0	0	2	26	44	56	62	65	65	66	66	65	63	61	51	42	27	2	0	0	0	0	54
SEP	0	0	0	0	0	6	36	55	59	60	62	65	66	64	62	58	51	27	3	0	0	0	0	0	50
DEC	0	0	0	0	0	0	0	10	31	42	48	51	51	50	41	31	9	0	0	0	0	0	0	0	30
ANNUAL	0	0	0	0	0	9	29	46	51	57	60	61	62	60	57	51	34	19	6	0	0	0	0	0	45

1c.

REPORT- LS-J DAYLIGHT ILLUMINANCE FREQUENCY OF OCCURRENCE

SPACE SOUTHZONE

		PERCENT OF HOURS IN ILLUMINANCE RANGE: ILLUMINANCE RANGE (FOOTCANDLES)									PERCENT OF HOURS ILLUMINANCE LEVEL EXCEEDED: 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-	13	15	11	10	6	4	4	4	33	100	87	72	61	51	44	41	37	33
	-2-	32	20	9	5	8	1	3	4	19	100	68	48	39	34	27	25	23	19
FEB	-1-	11	7	9	10	4	7	5	5	42	100	89	83	73	63	60	53	48	42
	-2-	21	17	12	8	6	6	6	8	17	100	79	62	50	43	37	31	25	17
MAR	-1-	7	8	6	6	7	5	6	3	51	100	93	85	79	72	66	61	54	51
	-2-	17	12	11	10	4	10	13	10	13	100	83	71	59	43	46	35	23	13
JUN	-1-	0	0	4	11	7	14	10	20	34	100	100	100	96	85	78	64	54	34
	-2-	1	15	18	23	29	10	1	3	1	100	99	84	66	43	15	5	4	1
SEP	-1-	6	6	4	5	3	6	7	7	56	100	94	88	84	79	76	70	63	56
	-2-	14	7	9	11	11	14	11	9	13	100	86	79	70	58	47	33	21	13
DEC	-1-	21	11	8	13	6	5	4	4	28	100	79	67	59	47	41	36	32	28
	-2-	36	19	11	5	3	5	4	1	15	100	64	45	34	29	25	20	16	15
ANNUAL	-1-	6	6	7	9	7	8	7	10	40	100	94	87	80	72	65	57	50	40
	-2-	15	14	14	13	14	10	6	4	9	100	85	70	56	43	30	20	13	9

Table 1 (a)-(c): Sample DOE-2.1B daylighting program reports for selected months for the south-facing office module described in text. Quantities under "report schedule hours" in 1 (a) are restricted to the time period 8 am to 5 pm, the hours of major occupancy.

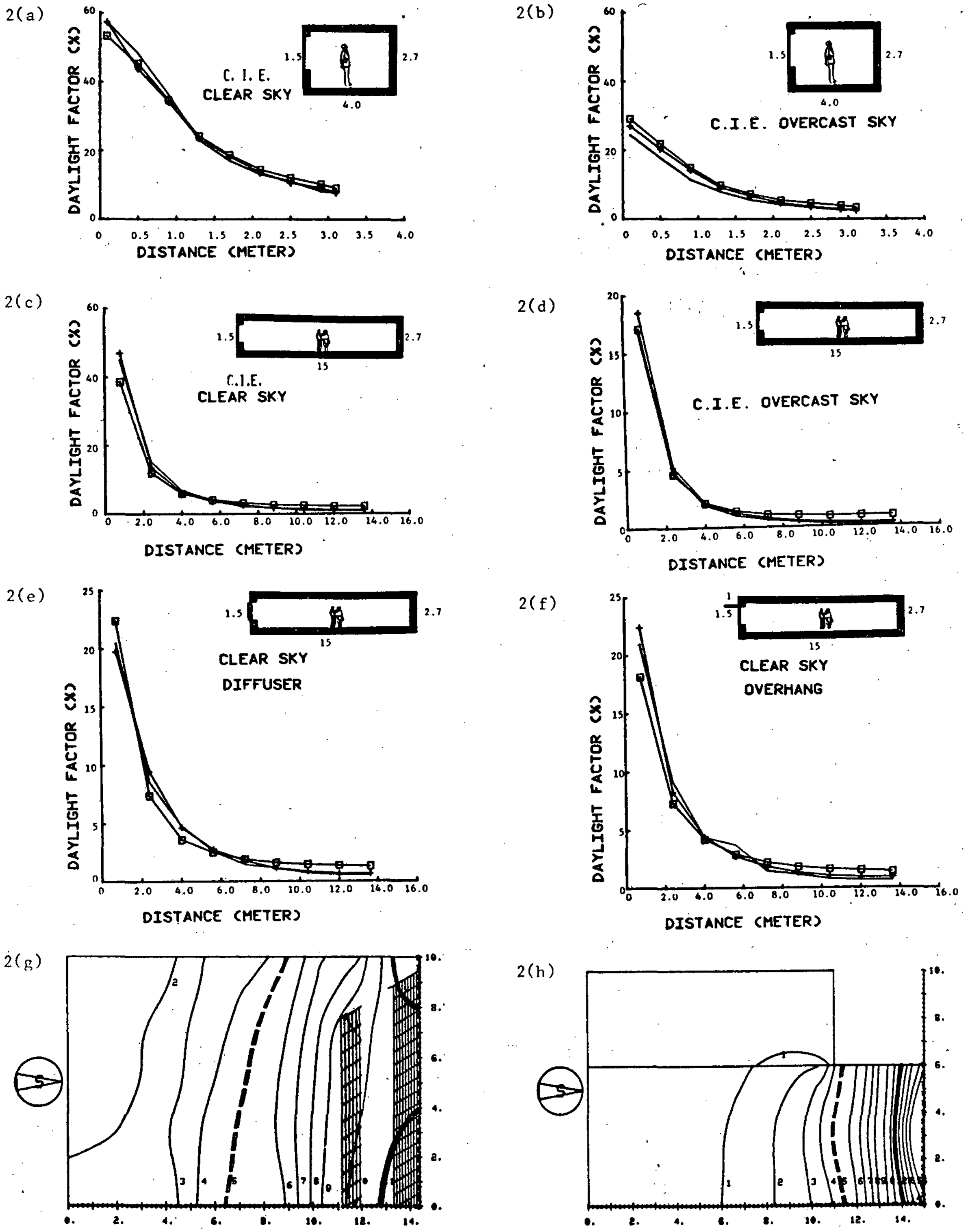


Figure 2 (a)-(f): SUPERLITE (+) and DOE-2 (☐) predictions compared with sky-simulator measurements (-). Cases of clear sky have solar altitude 50°, azimuth 0°, but exclude direct sun. Ground reflectance is zero. Interior reflectances are 25% for floor, 60% for walls, 80% for ceiling. Glass transmittance is 90%; diffuser transmittance in (e) is 60%.
Figure 2 (g): SUPERLITE contour plot for model (c) with a clerestory and light shelf added and with direct sun. 100-fc (dashed) and 500-fc (heavy) contours are highlighted. Hatching shows where sunlight falls on floor.
Figure 2 (h): SUPERLITE contour plot for an L-shaped version of model (c).

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