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February 1984

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AN ENERGY-BASED ANALYSIS OF INTERIOR ILLUMINATION SYSTEMS IN OFFICE BUILDINGS*

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ABSTRACT

Various interior electric lighting system designs are evaluated in terms of power demand and illumination capability. The primary objectives of the work described were to: 1. identify practical, energy-efficient approaches to providing quality illumination, addressing the specific issues of illuminance requirements, interior design, and electric lighting hardware and 2. provide fundamental background in establishing base conditions for ongoing parametric energy analyses of daylighting in office buildings.

INTRODUCTION

Approximately one-quarter of the energy used to operate commercial and industrial buildings in the United States is expended for lighting.(1) Recent building energy performance studies suggest that this fraction may be closer to one-half for new buildings constructed with current-practice thermal envelope integrity and HVAC efficiency.(2) At Lawrence Berkeley Laboratory, parametric energy analyses have been performed on prototypical commercial buildings to assess the potential benefits of various kinds of building apertures, such as windows and roof monitors.(3,4) The potential energy savings attributable to roof aperture daylighting systems has been shown to be quite sensitive to the type of electric lighting system employed and to the amount of electric lighting power that potentially can be displaced by daylighting.

Establishing efficient and well-planned electric lighting base conditions for parametric energy analyses is therefore of prime importance if accurate assessments are to be made of the daylighting potential associated with roof apertures. Establishing base operating conditions for the prototypical office building model was the original motivation for this research. However, in the process of performing this work, a number of important insights emerged regarding the design of electric lighting systems. This paper describes the work performed, discusses the electric lighting design implications, and describes the base conditions selected for the prototypical office building model.

For the purposes of this study, lighting systems were classified into two broad categories. One category, referred to as "General Lighting," relies exclusively on ceiling-mounted luminaires to provide illumination which is adequate everywhere in the space for the most demanding task to be performed. The other category, referred to as "Task-Ambient Lighting," uses ceiling-mounted luminaires to provide a moderate level of ambient lighting in the space and user-controlled desk lamps to provide more intense, localized illumination where critical tasks are being performed.

RESEARCH OBJECTIVES:

1. To identify and evaluate efficient electric lighting systems appropriate to the illumination demands of office buildings.

2. To compare the performance of general and task/ambient lighting as measured by power density and illumination capability.

3. To develop a prototypical office building model for computer-based, parametric, energy analyses of roof aperture daylighting systems.

METHODOLOGY

The electric lighting systems examined in this paper have been evaluated in terms of energy expenditure, as measured by power density, and in terms of the ability to provide a specified level of design illuminance under representative room space conditions. This evaluation procedure involved both analytic and experimental methods. The analytic portion used IES design procedures to estimate the power density as a function of the occupancy density, for both general and task/ambient systems.(5) The experimental procedure used scale models to evaluate the ability of general lighting systems to provide a specified design illuminance in the task area under a range of realistic room space conditions. This procedure was undertaken in recognition of the inherent deficiencies associated with existing design procedures that assume an

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unobstructed room cavity. The objective in these modeling experiments was to understand the effects of various obstructions, such as partitions, furniture, and the human body and hand, on the illumination potential associated with overhead general lighting systems.

ANALYTIC PROCEDURE (Power Density Analysis)

Power densities were calculated for both general and task/ambient electric lighting for a range of representative interior room space conditions, in order to illustrate the potential energy differences.

General Lighting Power Density

The power density calculation for the general lighting system was based on the zonal-cavity, average-illuminance procedure in conjunction with the power requirements for the specific lamp/ballast circuit employed. The power density was calculated for an efficient, 2-lamp luminaire of dimension 2 feet by 4 feet with a coefficient of utilization of .70. A high-frequency, solid-state, 2-lamp ballast was used to drive two low-wattage, F40T12 Lite White lamps with an initial rated output of 2925 lumens per lamp.(6) Solid state ballasts were employed in this analysis to allow continuous dimming of the lights in response to daylight entering the building. The solid-state ballasts also have the advantage of being inherently more efficient than core ballasts.(7) For this lamp/ballast combination, the power requirement is 71 watts per luminaire.(7) The general lighting power density has been calculated using the following assumptions:

1. Room Area = 10,000 square feet
2. Coefficient of utilization = 0.70
3. Light loss factor = 0.70
4. Initial rated lumens = 2925/lamp
5. System power requirements = 71 watts/luminaire
6. Illuminance requirements = 50 F.C. and 70 F.C. (consistent with I.E.S. recommendations for office tasks)

Table 1
GENERAL LIGHTING POWER DENSITIES

ILLUMINANCE (Footcandles)	POWER DENSITY (Watts/ft^2)
50 F.C.	1.23 w/ft^2
70 F.C.	1.73 w/ft^2

Task/Ambient Lighting Power Density

The power density for task/ambient lighting systems is the sum of the power densities for the task component and for the ambient component.

Ambient component power density. The power density for the ambient component was determined by using the same lamp/ballast system and calculation procedure as was used for the general lighting system; however, horizontal illuminance was set at 20 F.C. (consistent with I.E.S. recommendations), yielding a power density of .49 watts/ft^2.

Task component power density. Power density for the task component is the product of: 1) the power assignment per task station (i.e., per person), which is a function of the particular lamp/ballast circuit employed in the task light and 2) the density of task stations in the space (i.e., the occupancy density).

In determining the appropriate task power assignment, a detailed task lighting design was not generated. The approach used in this study was to assume a range for the task power assignment, based on a range of realistic task lamp designs. In this manner, it is possible to establish the sensitivity of the overall power density to the task power assignment. The range of task power assignments examined was 20 to 80 watts/station. Twenty watts is considered optimistic and eighty watts is considered representative of current practice. Forty watts is considered reasonably efficient and clearly achievable. The approximate area that could be maintained at 50 F.C. using 40 watts of power is in the range of 30 square feet, assuming that 70 percent of the luminous output of the lamp system will strike the work plane. Thirty square feet of horizontal plane is considered a work area sufficient to define a majority of task applications. (This would be independent of the potential ambient component contribution.)

Three levels of occupancy density were established corresponding to high-, medium-, and low-density office buildings. Data from a detailed interior space analysis was used to provide space utilization information for a representative, high-density office situation.(8) Seventy percent of the floor area was designated as office space requiring illumination appropriate to the most demanding office tasks and thirty percent was used for circulation and other tasks requiring less illumination than the office space. For the prototype office building model having 10,000 gross square feet of floor area, the area designated as office space would be 7000 ft^2 and area designated for visually less demanding functions (corridors, mechanical, etc.) would be 3000 ft^2. The space analysis also indicated that a high occupancy density within the 7000 ft^2 of usable office space would be 100 ft^2 per person; medium density would be 150 ft^2 per person and low density would be 200 ft^2 per person. For the prototype office building model having 10,000 gross square feet of floor area, the number of occupants corresponding to high, medium, and low occupancy densities would be 70, 46.6, and 35 people respectively.

TASK POWER	POWER DENSITY (WATTS/FT^2) (No. of People/10,000 Ft^2) 70	46.6	35	COMPONENT
20W	.14	.09	.07	Task
	.49	.49	.49	Ambient
	.63	.58	.56	Total
40W	.28	.18	.14	Task
	.49	.49	.49	Ambient
	.77	.67	.63	Total
60W	.42	.27	.21	Task
	.49	.49	.49	Ambient
	.91	.76	.70	Total
80W	.56	.36	.28	Task
	.49	.49	.49	Ambient
	1.05	.85	.77	Total

Table 2 TASK/AMBIENT POWER DENSITITES

Table 2 lists the task/ambient power density as a function of task power allocation and the number of occupants in the 10,000 ft^2 office building, assuming an ambient illuminance of 20 foot-candles.

Figure 1 shows the variations in power density for both the general and task/ambient systems. Power density, as measured in watts/square foot, is plotted versus the number of occupants in the 10,000 ft^2 office building. Two levels of general illumination are plotted, corresponding to 50 footcandles and 70 footcandles. Four levels of task/ambient lighting are plotted, corresponding to 20, 40, 60, and 80 watts per task station. For all the task/ambient lighting, the ambient component is assumed to be 20 footcandles. It is apparent that task/ambient systems offer substantial energy savings relative to general lighting, particularly at low occupancy densities. With increasing occupancy density, there is a decrease in the power density differential between the two approaches.

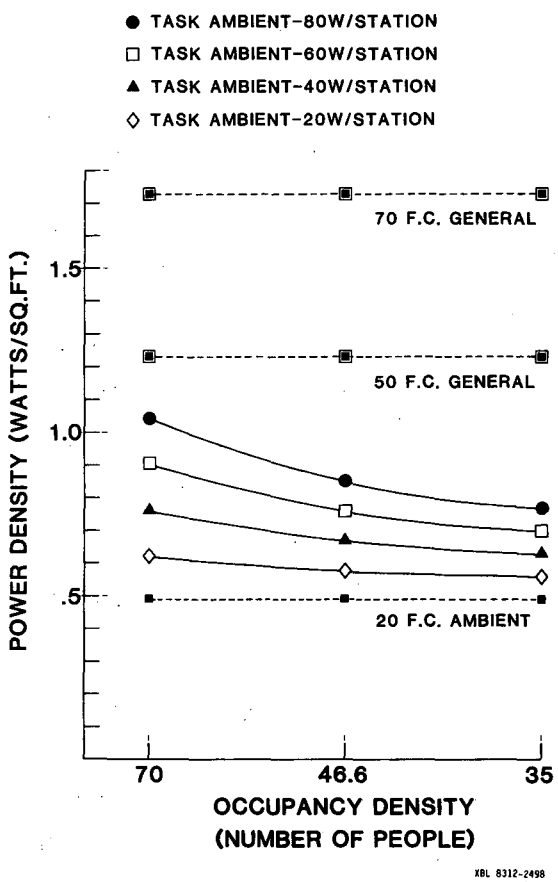

FIGURE 1: POWER DENSITY VERSUS OCCUPANCY DENSITY

Figure 1 shows that power density is highly sensitive to occupancy density for task/ambient lighting systems. In contrast, power density is independent of occupancy density for general lighting systems, for the assumptions made in this design procedure. However, the illumination capability of a general lighting system frequently decreases with increasing occupancy density because of the associated increase in the density of interior room cavity obstructions such as furniture and partitions. It is possible to compensate for this diminished illumination capability by increasing the power density of the general lighting system. If this effect were reflected in Figure 1, the power density curve for the general lighting system would also increase with increasing number of occupants, and the general lighting power density would be substantially higher than for task/ambient lighting at all the occupancy densities shown in Figure (1). In order to understand and quantify the effect of obstructions on general lighting performance, a series of scale model experiments were conducted, as described below.

EXPERIMENTAL PROCEDURE

The experimental work was designed to illustrate the level of reduction in illuminance associated with general lighting under realistic task and interior design conditions. The reductions in illumination capability are a direct function of the level of physical obstructions that exist in the room cavity. An "obstruction" is defined as any physical object that interferes with the transmission of light between the source (luminaire) and a visual task. This study examined experimentally three levels of room cavity obstruction: 1) hand shadow, 2) body shadow, and 3) furniture/workstation obstruction.

Hand and Body Shadow

The illumination for common visual tasks such as handwriting and reading will be subjected to shadowing effects from the body and hand. Lagiusa (6) indicated a 24% reduction in desktop illuminance resulting from a body shadow on a visual task being performed in a school study carrel. His principle observation was that study carrels, in conjunction with a body shadow, diminish general lighting capability substantially. We believe that modern task station geometries will tend to obstruct general lighting for offices in a similar manner.

The level of obstruction of hand and body shadow was determined in our study by conducting illuminance measurements in actual office environments. Hand shadows are particularly critical for handwriting. The eye must be able to see clearly the point of contact of the writing instrument on the work plane. Since this point of contact is very close to the hand, the shadow of the hand can be a significant factor. The following series of measurements was made for each task station:

1) Basecase with unobstructed work plane (no body or hand shadow).

2) Body shadow at a 25° viewing angle without a hand shadow.

3) Body shadow at a 25° viewing angle with a right-hand pencil task.

4) Body shadow at a 25° viewing angle with a left-hand pencil task.

For simplicity, an unobstructed luminous ceiling was used for the hand and body obstruction studies presented in this paper. For a luminous ceiling.

the hand and body shadow effects will be independent of orientation or position within the space. A longer version of this paper currently in preparation will describe experiments on general lighting systems with discrete luminaires. The potential variety of spatial relationships between task and ceiling sources is obviously greater for the case of general lighting systems with discrete sources than for luminous ceilings. Typically, general lighting systems with discrete sources involve a range of both favorable and unfavorable spatial relationships between sources and tasks.

Figure 2 illustrates the level of reduction in basecase illuminance (unobstructed) resulting from hand and body shadow for the luminous ceiling system. It is apparent that the hand and body substantially obstruct the transfer of light from the luminous ceiling to the work plane. The body shadow alone caused a 21% reduction in illuminance on the work plane, and the combination of body and hand caused a 30% reduction in illuminance on the work plane. In situations where partitions and furniture are obstructing the passage of light from the ceiling to the work plane, the percent reduction in illuminance on the work plane resulting from body and hand shadows would be even higher than the percent reductions shown in Figure 2. This amplified effect of hand and body shadows results from the directional nature of the light which the partitions and furniture allow to reach the work plane.

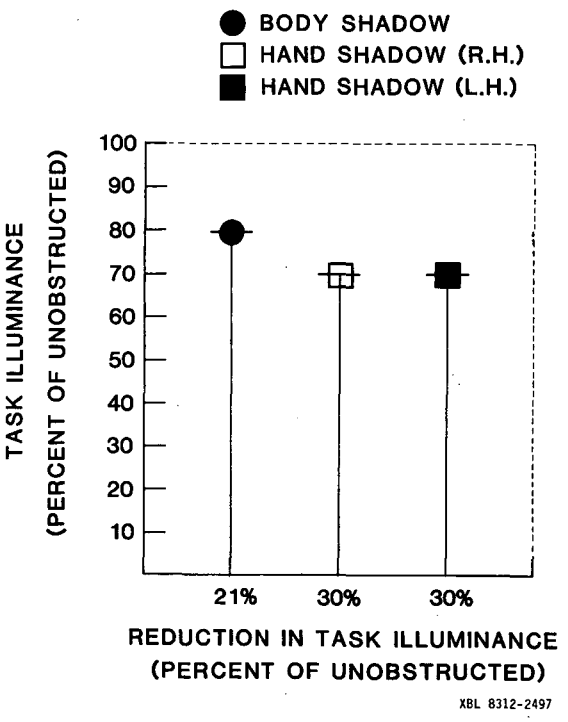

FIGURE 2: REDUCTIONS IN ILLUMINANCE FROM HAND AND BODY SHADOWS

For comparison, a series of measurements was made with and without a body shadow in task station configurations that employed task lamps mounted under a storage cabinet in front and above the visual task. The illuminance levels were not substantially affected by the presence of the body. Although this task light configuration may not be ideal in terms of light quality (e.g., veiling reflections would diminish visual acuity), this example illustrates the point that task lighting systems can be designed which are unaffected by body shadow. The same argument can be applied to hand shadow effects.

Furniture and Partition Obstructions

For simplicity and economy, the effects of furniture and partitions in obstructing the transfer of light from the luminous ceiling to the task surface was investigated using scale models. The objective was to illustrate the level of obstruction associated with a range of representative task furniture in office spaces illuminated by general lighting.

A office space with a floor area of 900 square feet and a floor-to-ceiling height of 10 feet was built at 1/12 of full size. Two general lighting systems were constructed, the first a luminous ceiling and the second made with diffusing, recessed luminaires of dimension 2 feet x 4 feet, positioned on a square grid with a spacing of 8 feet. This layout was chosen as being highly representative of office lighting practice.(10) A range of representative task station geometries was developed and tested under the two types of ceiling-lighting system.

Task station description. A standard 30" high by 30" deep horizontal work task plane was used as the base condition for which the unobstructed room cavity illuminance measurement was made. This base condition was then selectively modified to represent a range of station geometries. Task station variables included vertical height and reflectance of a backwall divider and the presence of a storage cabinet mounted on the rear wall. The base task station was tested in three different locations within the space in order to account for variation in the spatial relationship between ceiling sources and the task. The remaining interior of the room cavity was unfurnished so that primary obstruction effects could be observed.

Task station geometries. Seven types of task stations were observed:

Type 1 - Desk with 4' vertical backwall divider, 80% reflectance
Type 2 - Desk with 4' vertical backwall divider, 20% reflectance
Type 3 - Desk with 5' vertical backwall divider, 80% reflectance
Type 4 - Desk with 5' vertical backwall divider, 20% reflectance
Type 5 - Desk with 6' vertical backwall divider, 80% reflectance
Type 6 - Desk with 6' vertical backwall divider, 20% reflectance
Type 7 - Desk with 6' vertical backwall divider, 20% reflectance and an open, two-shelf storage cabinet, with a height of 2 feet and a depth of 1 foot.

FIGURE 3: REDUCTIONS IN ILLUMINANCE FROM TASK STATION GEOMETRY

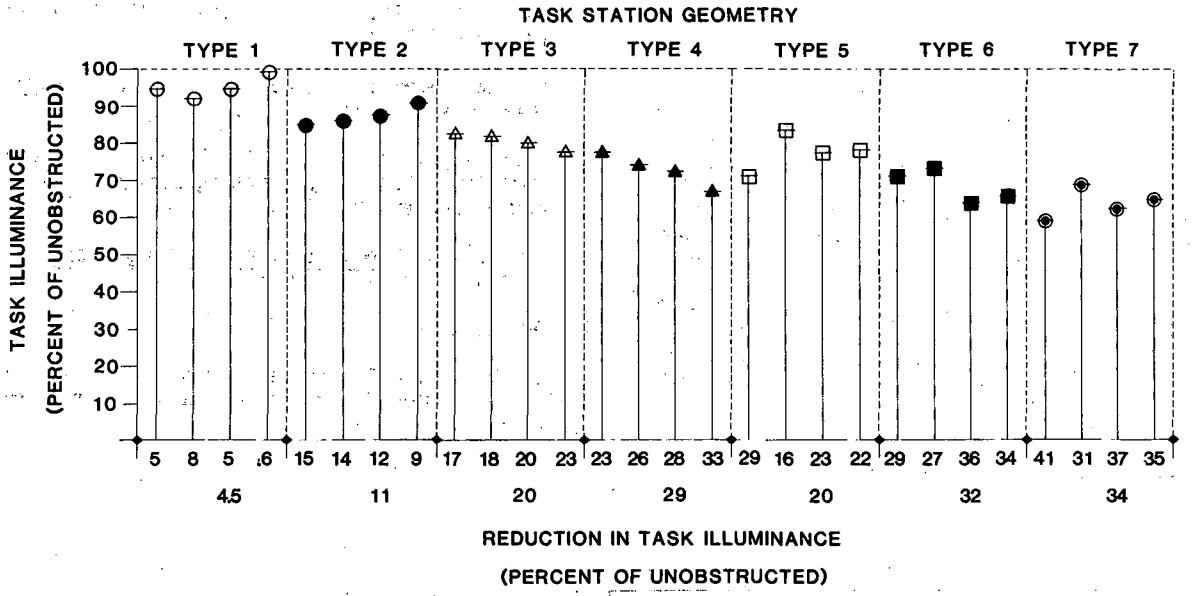

Figure 3 graphs the measured task illuminance for twenty-eight cases: for each of the seven station geometry types the illuminance is given first for the luminous ceiling and then for the three different positions of the ceiling with discrete luminaires. Underneath each vertical bar is a number indicating the reduction in illuminance, as a percent of the unobstructed illuminance. For the three different positions of the ceiling with discrete luminaires, the average reduction in illuminance is also given. The largest reduction was 41%, corresponding to the case of a luminous ceiling with a backwall divider and shelves overhanging the work surface. This office arrangement is not unusual, and, in fact, more severe examples occur commonly (e.g., with additional obstructions to the left and right of the task surface). If we multiply the reduction factor of 0.59 associated with the this office arrangement time the reduction factor of 0.70 associated with the combined effect of hand and body shadows, the net reduction factor is 0.41. The inverse of 0.41 is 2.4, which is the factor by which the general lighting power densities in Table 1 and in Figure (1) would have to be increased in order to maintain the design illuminance for a person handwriting under a luminous ceiling with a backwall divider and overhanging shelves. For a design illuminance of 50 footcandles, the power density of the general lighting system would be 2.4 times 1.23 watts per square foot, or 3.0 watts per square foot! This is larger by a factor of 3.9 than the task/ambient power density of 0.77 watts per square foot, corresponding to the highest occupancy density and a task power allocation of 40 watts per station.

CONCLUSIONS

These analytic and experimental studies support the following conclusions, which in turn support the development of the prototypical office building model:

1. Task/ambient lighting systems can provide adequate illumination at substantially lower power density than for general lighting systems, even in situations where the number of task stations is relatively high.

2. For common tasks, such as handwriting, the hand and body can substantially obstruct the transfer of light from distributed ceiling lamps to the work plane.

3. Commonly used furniture and partitions can substantially obstruct the transfer of light from distributed ceiling lamps to the work plane.

4. In comparison to general lighting, task/ambient lighting offers superior potential for maintaining design illuminance on the work plane, because the task lamps are relatively unaffected by hand shadow, body shadow, and the obstruction that would occur with modern task station furniture.

In summary, task/ambient lighting appears to have substantial advantages for office building applications in terms of energy efficiency and quality of illumination on the task surface. This conclusion follows from the relative inability of general lighting to provide design illuminance for a range of common interior spatial configurations and from the inherent advantages of task/ambient lighting in terms of reduced power density. However, there still exist interior arrangements where the lack of interior obstructions in conjunction with the need to utilize a large fraction of the work plane would make general lighting the preferred system. Also, in some instances, aesthetic considerations might make general lighting the preferred design approach.

DEFINITION OF BASE CONDITIONS FOR THE PROTOTYPICAL OFFICE BUILDING MODEL

The central objective in this study was to define base conditions for a prototypical building model, to be used in the parametric energy analysis of daylighting systems. The base conditions which were established from the preceding analysis are outlined below. In some instances, ranges are assigned to important variables; the effect of these variables will be investigated in the

parametric studies in order to fully understand the relative sensitivities of building energy performance to each of these factors.

From the space utilization study, it was determined that for the prototype building with 10,000 square feet of floor area that the likely range of occupancy levels could be effectively covered by the following numbers of occupants: 70 people, 46.6 people, and 35 people. Task/ambient lighting was selected because of the relatively high power density required to maintain design illuminance with general lighting systems. Ambient lighting levels of 20 foot-candles (requiring with a power density of $0.49 W/ft^2$) will be maintained for the total building area. A task power allocation of 40 watts per task station will be assumed, resulting in total task/ambient power densities of: 1) 0.77 watts per square foot (for 70 occupants), 2) 0.67 watts per square foot (for 46.6 occupants), and 3) 0.63 watts per square foot (for 35 occupants).

FUTURE RESEARCH (Daylighting Studies)

A major focus of this effort has been and will continue to be on determining the appropriate tilt and orientation for roof aperture glazing, accounting for both illumination and thermal benefits. The evaluation of roof aperture design parameters is made using a series of detailed parametric computer simulations of a prototypical building model in conjunction with meteorological data representing a variety of climatic conditions. Future work will first examine the prototype office building with the base conditions outlined above. The emphasis of the work will then shift to educational and industrial buildings, both of which represent significant potential for daylighting, since they require higher electric lighting power densities than office buildings with task/ambient lighting systems.

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