Extended Abstract

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THE EFFECT OF CONTROL ALGORITHM AND PHOTOSENSOR RESPONSE ON THE PERFORMANCE OF DAYLIGHT-FOLLOWING LIGHTING SYSTEMS

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INTRODUCTION

Increased utilization of daylighting in commercial buildings is one method of reducing the requirement for daytime lighting energy and for moderating peak demand. For daylight to efficiently supply some portion of the design light level at the task, the electric lighting system should be photo-electrically controlled so that it responds (dims) in proportion to the amount of available daylight entering the building space. The location and spatial response of the photosensor that controls the electric lighting system must be chosen so that the photosensor's output is approximately proportional to the illumination at the task surface. Furthermore, the system's control algorithm, which relates the photosensor signal to the output of the electric lights, should be selected to properly account for the location of the control photosensor relative to the task and the sources of illumination within the controlled space. If the above considerations are not properly accounted for, then the illumination at the task will deviate significantly from the design level (Rubinstein 1984) and the occupants may respond negatively, especially if the control system supplies less than the design light level.

The paper describes experimental work done to analyze how the control algorithm and the photosensor's location and spatial response affect the ability of a daylight-following lighting system to maintain a constant light level at the task by responding to changes in daylight levels.

COMPONENTS OF A DAYLIGHT-FOLLOWING LIGHTING SYSTEM

A lighting control system that is designed to follow changes in daylight consists of three basic components:

1. A control photosensor that generates an electrical signal proportional to the amount of light impinging on its surface. The control photosensor typically consists of a silicon photodiode (or equivalent light-sensitive device) in a housing the geometry of which determines the photodiode's sensitivity to light from different directions.
2. A controller that incorporates an algorithm to process the signal from the photosensor and converts it to a control signal for the dimming unit.
3. A dimming unit that smoothly varies the light output of the electric lights by altering the amount of power flowing to the lamps.

Controller and Control Algorithms

The controller adjusts the output of the dimmer (i.e. the electric lighting level) using some chosen algorithm to process the photosensor signal. This paper discusses photoelectric control systems that dim linearly with respect to a change in measured photosensor signal. The three control algorithms that can be employed in a linearly-responding photoelectric control system are the 1) integral reset (I), 2) closed-loop proportional (P) control, and 3) open-loop proportional control (OL) algorithms. An integral reset system is one that continually adjusts the fractional light output, δ, so that the total photosensor signal measured, $S_T(t)$, does not deviate from a preset reference level (typically S_{E_m}, the photosensor signal produced when the electric lights

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are at full intensity at night). Open loop proportional control is defined as a system for which the fractional light output, δ, is a linear function of the photosensor signal:

$$\delta = M\, S_T(t) + 1 \qquad \text{open loop} \qquad (1)$$

A closed-loop proportional control system adjusts the electric light level so that $\delta(t)$ is a linear function of the difference between $S_T(t)$ and S_{Em}:

$$\delta = M\,(S_T(t) - S_{Em}) + 1 \qquad \text{closed loop} \qquad (2)$$

In the above equations, the value of M is negative and is determined empirically by calibrating the response of the system under appropriate daylighting conditions. If the photosensor is located in the ceiling of the controlled building space so that it is susceptible to the electric light that it controls, (closed-loop control), then the integral reset or closed-loop proportional control algorithms would be used. If, on the other hand, the photosensor is outside the controlled space (or inside but shielded from controlled electric light) so that it can detect only daylight and is negligibly sensitive to electric light, then the system would use the open-loop proportional control algorithm.

EXPERIMENTAL PROCEDURES

The primary objective of the experiments described here was to evaluate the performance of the three above control algorithms with respect to their ability to provide a constant total illumination level at the work surface. Daylight levels were measured, under real sky conditions, in a one-third scale model of a building section that simulated a small (15' x 15') office with a 9' ceiling height. The scale model had a removable window wall section with a fitted window to permit modeling of different fenestration strategies. For these studies, the window-to-wall ratio was one-third and, to prevent excessive amounts of daylight from penetrating the scale model space, a 43% transmittance window was used. The model could be rotated about a central pivot so that the window-wall section could be aimed towards any geographical orientation.

As shown in Figure 1, electric lighting in the model was provided by mounting dimmable fluorescent lamps above a false ceiling that contained appropriately-scaled apertures. The apertures in the false ceiling were fitted with industry standard prismatic lenses to simulate the appearance and light distribution properties of standard ceiling systems.

The scale model was instrumented with 26 photometers to measure illuminance and luminance both inside and outside the model. To measure the illuminance distribution at the workplane in the model, sixteen photometers (cosine- and color-corrected) were installed in the model in a regular 4 x 4 array on 16" centers at a height of 10" above the floor (Figure 2). At 1/3 scale, the 16" spacing is equivalent to 4' and the 10" measurement height is equivalent to 30" (desktop height).

A cluster of specially-modified photometers were mounted in the ceiling of the model to act as control photosensors for the electric lighting system. Three of these sensors, designated P_{UNSH}, P_{PSH}, and P_{FSH}, were designed to be attached flat to the center of the ceiling (Figure 1) simulating three different types of commercially-available photosensors. The P_{UNSH} photosensor is an unmodified cosine-corrected photometer; it therefore measures the *illuminance on the ceiling.* The P_{FSH} photosensor was fitted with a Gerschun tube (Figure 1 inset) that restricted its field of view (FOV) to a cone of 30-degree semi-angle. The sensor's FOV was selected so that the output of the photosensor would be approximately proportional to the average luminance of the floor below. P_{PSH} was equipped with an opaque baffle to shield it from direct light from the window as shown in the Figure 1 inset.

The roof of the 3rd floor roof of Building 90 at the Lawrence Berkeley Laboratory was the test site for the scale model. The model is anchored to a wood deck of 20-40% reflectance. The model has a virtually unobstructed view of the sky when the window-wall was oriented toward the west or south. The north elevation is occluded by the 4th floor penthouse and the east elevation is partially obstructed by three evergreen trees.

RESULTS

By examining the relationship between the daylight illuminance(s) at the work plane and the daylight striking the photosensor, the performance of any control photosensor can be examined independent of the control algorithm employed by the controller. These relationships are shown in Figs. 3a-c for three of the scale model photosensors: P_{UNSH}, P_{PSH}, and P_{FSH}. Every data point on these scatter plots represents a simultaneous measurement of daylight on the photosensor (along the horizontal axis) and the daylight illuminance at the workplane (along the vertical axis). (The daylight illuminance at the workplane is defined here to be average of the individual daylight illuminances measured by the two workplane photometers at the assumed task location shown in Figure 2). The dotted horizontal line is the design illuminance level (720 lux) -- the light level supplied by the electric lights at full intensity at night.

The scatter plots for control photosensors P_{PSH} and P_{FSH} are roughly proportional at lower workplane illuminances but tend to diverge, exhibiting increased scatter, at higher illuminance levels. The extended linear range for these two shielded ceiling-mounted sensors is particularly marked for the west-facing model data as evidenced by the relatively small degree of data scatter for daylight task illuminances below 600 lux.

The total task illuminance (daylight plus electric light) is shown as a function of time of day for integral reset type control systems driven by the photosensors P_{UNSH}, P_{PSH}, and P_{FSH} in Figs. 4 through 6, respectively, for the model facing west. Corresponding plots are shown for closed-loop proportional control systems driven by the same photosensors P_{UNSH}, P_{PSH}, and P_{FSH} in Figs. 7 through 9, respectively.

The solid line in each graph is the median values for the total illuminance at the workplane as a function of time of day for the 39 measured test days. Thus 50% of the data points lie below this line and 50% above. The shaded area bordering the solid line encompasses 66% of the calculated values and therefore corresponds to a measure of the statistical spread of the illuminances about the median value. The horizontal dashed line on each figure is the design illuminance level in the scale model. The dashed curve in each graph is the corresponding median value for the electric lighting power.

From Fig. 4-6, it is seen that all three tested photosensors, when used with an integral reset control systems, provided less illumination than was required to meet the target light level. The electric lighting demand curves show that these systems tend to operate at minimum power (and thus at minimum light) for a majority of daylight hours. The P_{UNSH} photosensor is an extreme example because it is so sensitive to direct window light that it calls for minimum light and power even when total task light levels fall far short of the design level. Integral reset systems driven by the P_{PSH} and P_{FSH} photosensors also failed to provide sufficient illumination to meet the target level but provided more light than equivalent systems driven by the P_{UNSH} photosensor.

When driving closed-loop proportional control systems, the same three photosensors, P_{UNSH}, P_{PSH} and P_{FSH}, provide total light levels at the task much closer to the target level than equivalent integral reset systems. Systems using the proportional control algorithm show very similar electric lighting demand profiles, indicating that, unlike the integral reset system results in Figures 4-6, these systems are operating within their dynamic range for most hours of the day. Furthermore, the proportional control systems tend to be at minimum dim only when daylight levels are sufficiently saturating.

SUMMARY

The study shows that the performance of daylight-following lighting systems driven by ceiling-mounted photosensors was significantly improved by using a closed-loop proportional control algorithm that allowed the system gain to be adjusted according to local daylight and room conditions. The results also indicated that controls employing an integral reset algorithm provided insufficient illumination at the task although performance was improved somewhat by shielding the ceiling-mounted photosensor from direct light from the window. Since proportional control systems provided satisfactory results regardless of the spatial response characteristics of the photosensor, the results suggest that the proper choice of control algorithm is more important to satisfactory system performance than either the placement of the photosensor or its spatial responsivity.

REFERENCES

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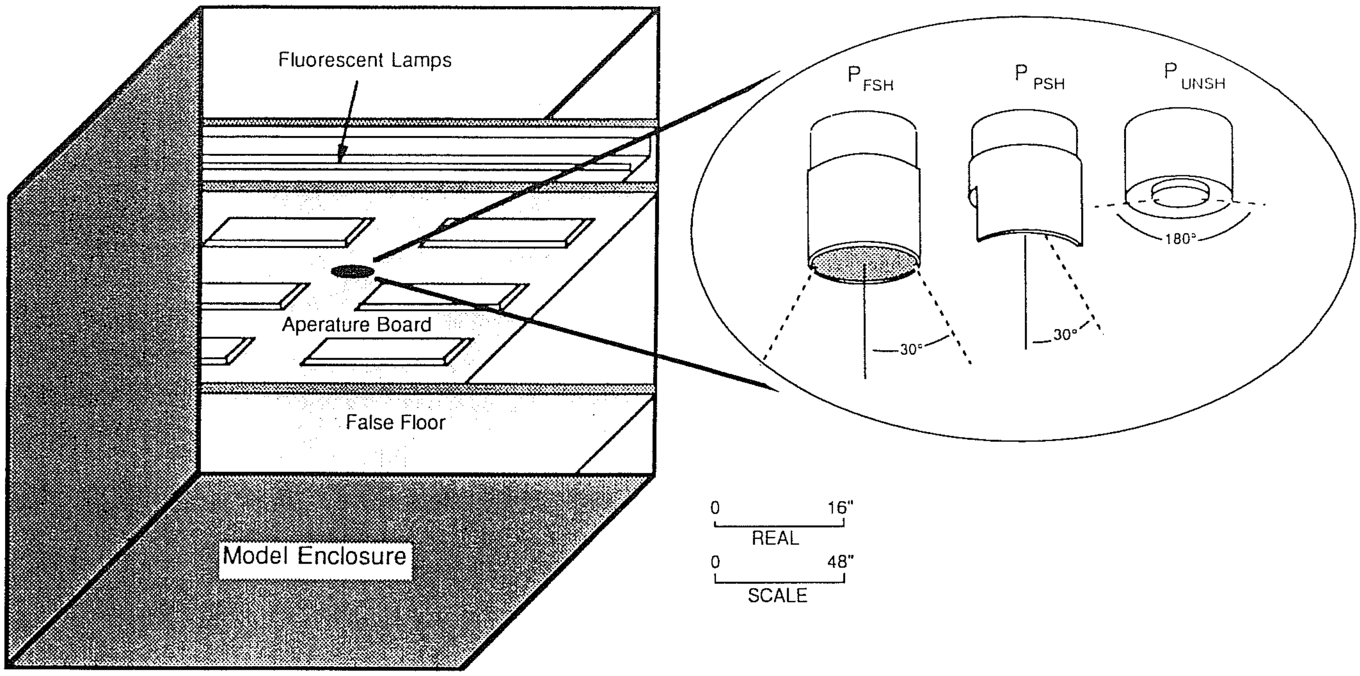

Figure 1. Scale model with window-wall section removed to show internal structure and components. The inset provides a detailed view of the three ceiling-mounted control photosensors discussed in the text

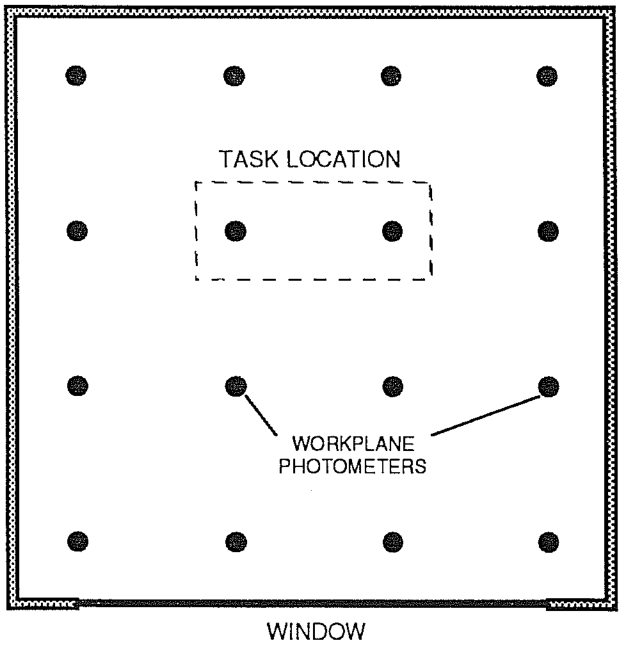

Figure 2. Plan view of workplane in scale model. The workplane photometers were mounted at desktop height. The dashed area shows the assumed location of the task

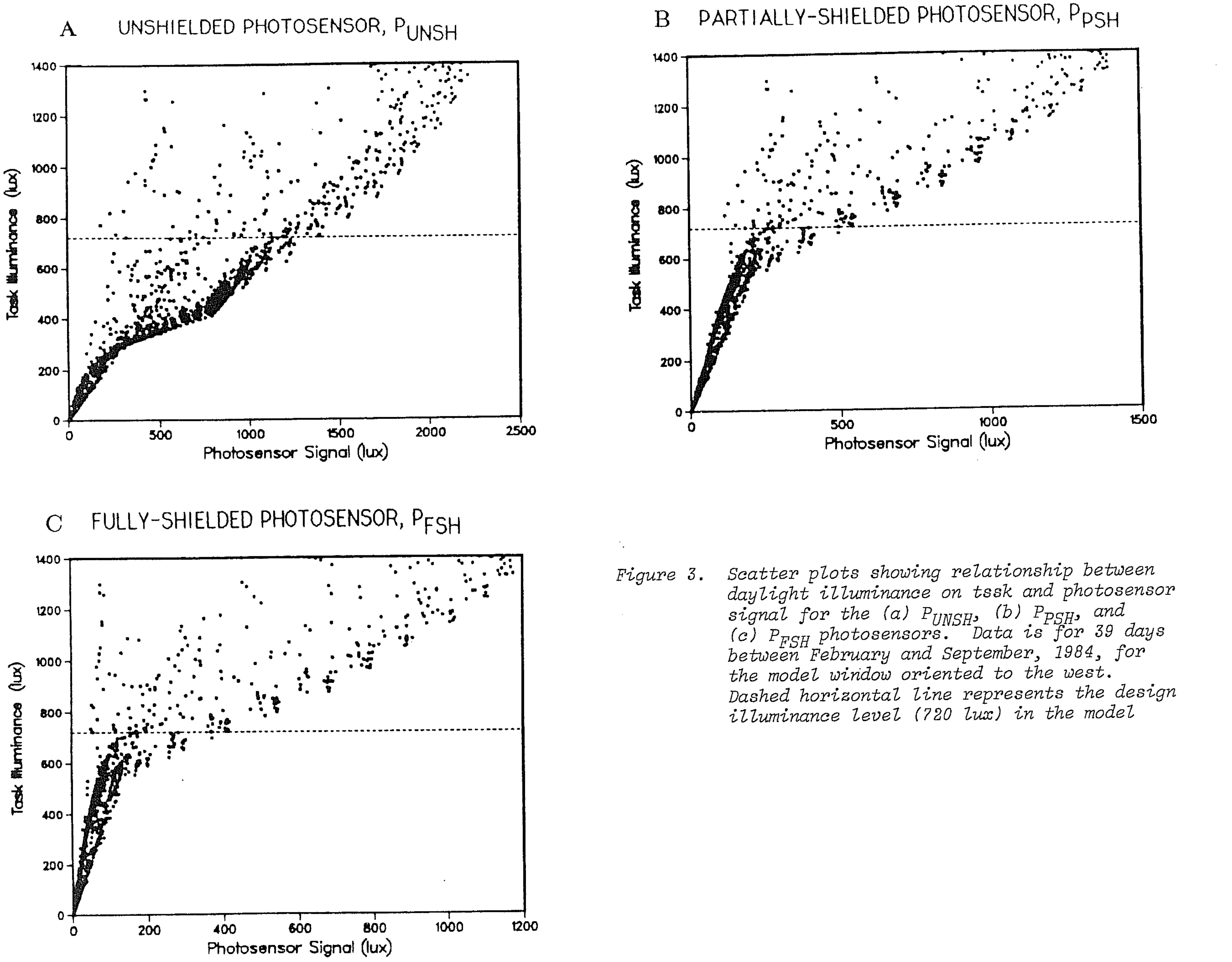

Figure 3. *Scatter plots showing relationship between daylight illuminance on tssk and photosensor signal for the (a) P_{UNSH}, (b) P_{PSH}, and (c) P_{FSH} photosensors. Data is for 39 days between February and September, 1984, for the model window oriented to the west. Dashed horizontal line represents the design illuminance level (720 lux) in the model*

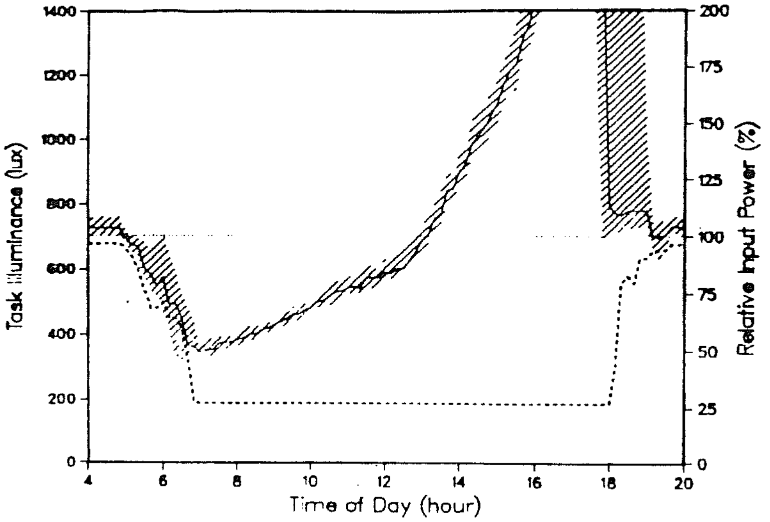

Figure 4. Unshielded photocell, P_{UNSH}. Total workplane illuminance--daylight and electric light (hatched area) and electric lighting power (dashed line) for integral reset system

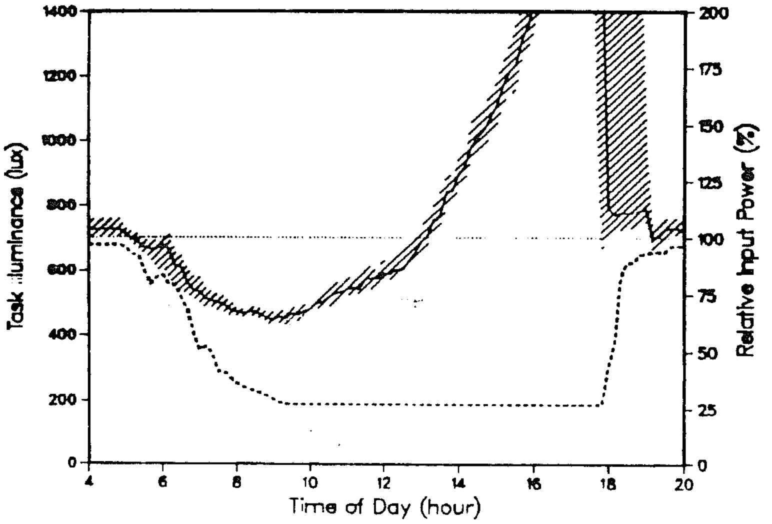

Figure 5. Partially-shielded photocell, P_{PSH}. Total workplane illuminance--daylight and electric light (hatched area) and electric lighting power (dashed line) for integral reset system

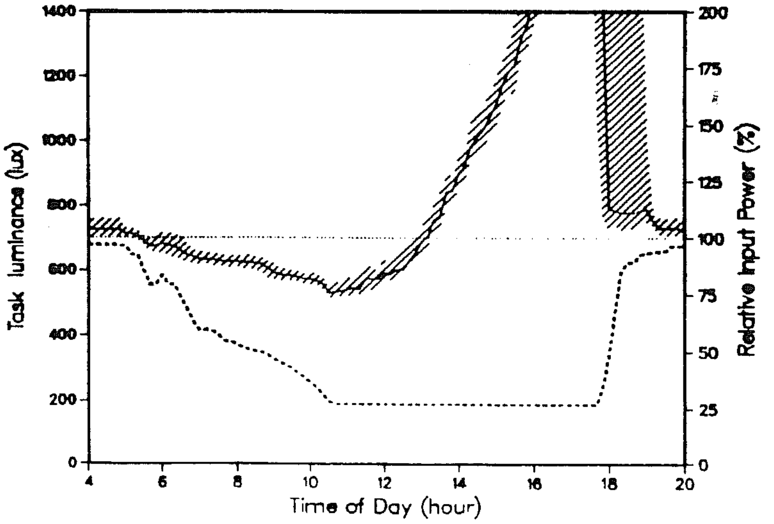

Figure 6. Fully-shielded photocell, P_{FSH}. Total workplane illuminance--daylight and electric light (hatched area) and electric lighting power (dashed line) for integral reset system

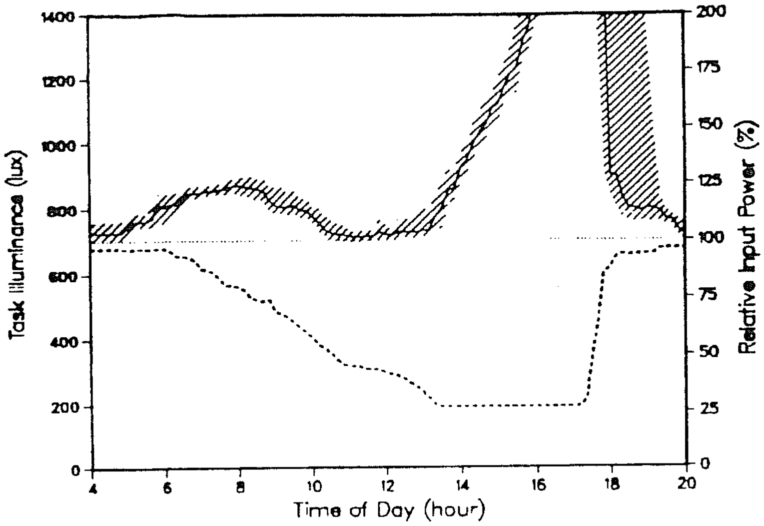

Figure 7. Unshielded photocell, P_{UNSH}. Total workplane illuminance--daylight and electric light (hatched area) and electric lighting power (dashed line) for closed-loop proportional system

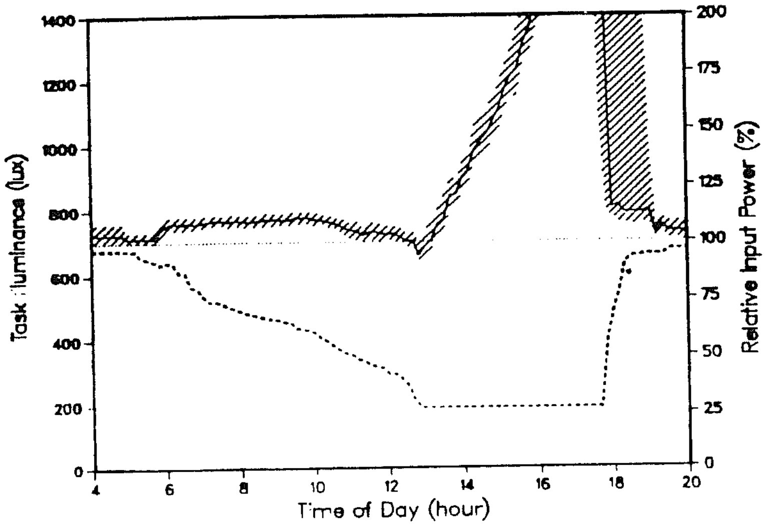

Figure 8. Partially-shielded photocell, P_{PSH}. Total workplane illuminance--daylight and electric light (hatched area) and electric lighting power (dashed line) for closed-loop proportional system

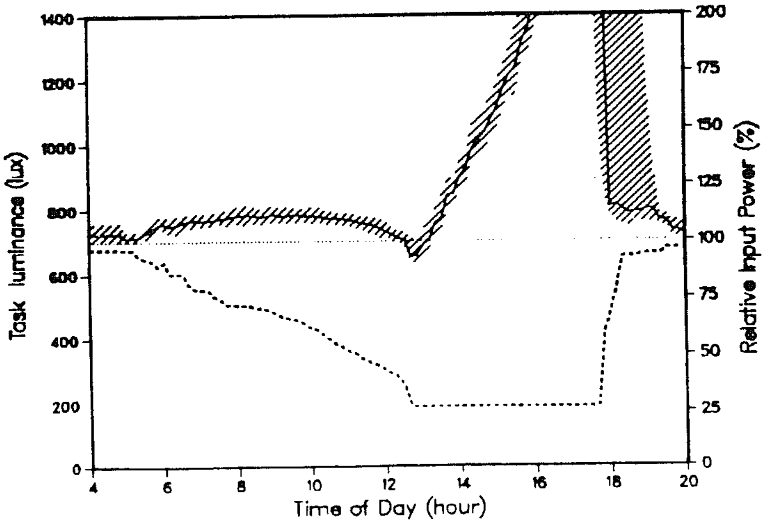

Figure 9. Fully-shielded photocell, P_{FSH}. Total workplane illuminance--daylight and electric light (hatched area) and electric lighting power (dashed line) for closed-loop proportional system

For Figures 4 through 9, the solid line through the hatched area represents a statistical mean for 39 days (between February and September, 1984) for the model oriented to the west. The hatched area encompasses 66% of the computed illuminances. The dashed horizontal line is the target design level in the model