Title

LIGHTING SYSTEMS PERFORMANCE IN AN INNOVATIVE DAYLIGHTED STRUCTURE: AN INSTRUMENTED STUDY

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ABSTRACT

This paper presents conclusions from a one-year instrumented study of an innovative daylighted commercial building in the San Francisco Bay area. The building, a five-story structure housing 3,000 employees, has a series of architectural features specifically developed to admit daylight into interior office zones. These are complimented by a continuously dimmable fluorescent lighting system that supplements available daylight under the control of open-loop ceiling-mounted photosensors. Monitored data indicate that the architectural daylighting features of the building are performing admirably and contribute significant daylight to most areas of the building's open plan offices. Field tests have determined that, under manual control, the electric light dimming hardware is capable of dimming to 27% of full power consumption. Operational savings, however, are limited by inappropriate performance of the control system in many of the building's lighting circuits.

INTRODUCTION

In a previous study, the Windows and Lighting Program at Lawrence Berkeley Laboratory conducted an assessment of the potential of daylight as a commercial-sector energy-conserving strategy (Usibelli et al. 1985). The study concluded that "performance data for daylighted buildings is virtually nonexistent. A review of over 40 'daylighted' buildings described in the architectural and engineering press provided virtually no useful data on the magnitude of daylight savings. These data are necessary, not only to validate computer models that provide guidance to designers, but also to convince hardnosed decision makers that these approaches are viable and cost effective."

This paper presents conclusions from an instrumented field study of daylighting performance in a major office structure. The building is located in the San Francisco Bay Area and incorporates a coordinated set of lighting system features designed to displace electrical energy consumption for ambient lighting. Completed in 1983, the scheme has been widely published in the U.S. architectural press as an innovative example of daylighting (Gardner 1984; Shanus et al. 1984). It is an ambitious example in which natural light serves 3,000 employees in the building's 600,000-ft^2 (56,000-m^2) interior. To meet the owner's daylighting objectives, the building must provide daylight, without glare and in proper quantity, to all five open-plan floors of its 400 ft (122 m) by 240 ft (73 m) area. To meet this challenge, the architects have designed a system that combines architectural features for the admission and distribution of daylight, a dimmable electric lighting system, and a control system to operate the electric lights in response to available daylight.

The Windows and Lighting Program at Lawrence Berkeley Laboratory has recently completed a year-long study of the building's daylighting systems. The study, funded by the Energy Services Department of Pacific Gas & Electric Company and the U. S. Department of Energy, gathered detailed data describing interior light distribution, lighting control system performance, and electrical energy consumption for lighting. The paper draws conclusions about the effectiveness of the building's daylighting strategy, individual daylighting system features, and their interaction with an emphasis on the performance of the lighting control system.

The building design was strongly driven by daylighting criteria, a process that produced several unconventional features. The building plan, diagramed in Figure 1, is elongated on a nominal east-west axis resulting in major facade orientations facing 25 degrees east of north and 25 degrees west of south. During interior space planning, the core function spaces, those lacking a strong need for daylight (computer facilities, conference rooms, restrooms, etc.), were concentrated in the opaque east and west ends of the building. The remainder of the building contains open-plan offices with 5.6-ft (1.7-m) high partitions in an open space that runs clear from the north exterior wall to the south exterior wall. A central atrium, 60 ft (18.3 m) wide, is placed in the center of the building to provide light, visual relief, circulation and drama. This geometry produces two separate sides to the building, north and south, each of which is 90 ft (27.4 m) wide. In the vertical dimension a large floor-to-floor separation of 18 ft (5.5 m) increases the penetration of daylight from the exterior facade and the atrium. As shown in Figure 2, window head heights are maximized by sloping the ceiling from a low point at the center corridor of each side to full—height, floor-to-floor openings at the exterior wall and atrium.

At the north and south exterior walls, there are large interior light shelves located just inside the glazing. Shown in Figure 3, these horizontal elements, 7.5 ft (2.3 m) above the floor and 12.3 ft (3.7 m) wide, serve as light reflectors and glare control baffles. The south side of the building has an additional exterior light shelf, which compliments the functions of the interior device and also provides solar shading of the vision window below. Glare and solar control issues resulted in the installation of low-transmittance glazing below the light shelves (17% transmittance on the south and 41% on the north). The glazing above the light shelves is clear.

The building has separate systems for task and ambient lighting systems. Task lighting is provided by fluorescent fixtures built into the office furniture. The designers did not intend for daylight to displace the use of these electrical task light fixtures. Ambient illumination for circulation and casual tasks is, however, provided whenever possible by daylighting and supplemented by an indirect fluorescent lighting system. In this indirect lighting system, each side of the building has six overhead rows of fluorescent fixtures running parallel to the exterior glazing and atrium. Interior daylight levels vary only in the direction perpendicular to these fixtures, allowing each row to be individually adjusted for the daylight penetrating to its depth. A photosensor located at either the exterior wall below the light shelf (see Figure 3) or atrium edge provides the signal to operate each row's control unit. Each unit dims 48 lamps operated by energy-efficient two-lamp core-coil ballasts. The lamps can be dimmed to 22% of full lamp output and 27% of full power with power reduction nearly proportional to reduction in light output. The installed cost of each control unit, including the photocell, was $850. With a target of 32.5 fc (350 lux) for ambient lighting, the architect projected substantial reduction in electric energy used for ambient lighting.

A separate computer-based light switching system is used to control the indirect fluorescent lighting system during periods of low occupancy. Between 8 PM and 6 AM the computer sweeps all overhead lights off at one hour intervals. If occupants desire a return of these lights they must walk to the center of the building and manually switch them on.

Monitoring Program

Detailed measurements of the daylighting illumination in this building have been made during each season (Warren et al. 1986; Benton et al. 1986). Preliminary site visits with hand-held instrumentation confirmed that significant variation in illuminance occurs only in a direction perpendicular to the windows and that similar zones on each floor have similar readings. The measurement strategy employed battery-operated dataloggers to poll illuminance sensors, temperature sensors, and watt transducers placed in representative daylighting zones on the building's third floor. Data were collected as fifteen-minute averages of measurements at 10 second intervals. Readings were made for four week periods in each of three seasons for three separate daylighting zones. Illuminance profiles across the north and south building sections were obtained from a series of ambient illuminance measurements taken in a horizontal plane at partition height. Additional photometric sensors were located in the space above the interior light shelves. Lighting power demand for individual lighting circuits was monitored using watt transducers installed in the local electrical closet. A fourth set of sensors measured representative air and surface temperatures at selected locations. Sensor deployment in a typical zone is shown in Figure 2.

Data from the battery operated dataloggers were stored on digital cassette tapes and downloaded to portable microcomputers at regular intervals. The measured data, in addition to energy end-use data from the building's energy-management system, were then analyzed off-site using microcomputer-based software. The data collected provide an interesting portrait of the building in operation. Our analysis examined the patterns of lighting system performance and their relationship to architectural features, electric lighting system hardware, and the building's lighting control system. Except where noted, the data presented in this paper represent summer conditions.

LIGHTING SYSTEM PERFORMANCE

Previous papers describing this monitoring project have reported our findings on instrumentation strategies for daylighting analysis (Warren et al. 1985), comparative light shelf performance (Benton et al. 1986), and building energy end-use (Warren et al. 1986). This section will briefly summarize our conclusions concerning the performance of the building's architectural daylighting features and fluorescent lighting hardware then describe the performance of the building's electric lighting control system in greater detail.

Architectural Features

The architectural features of the building are working well in providing interior daylight for ambient lighting. As shown in Figure 4, interior illuminance measurements exceed the 32.5 fc (350 lux) target level for major portions of the summer day in most areas of the building. The south side of the building has low illuminance levels during the morning, because the building is oriented slightly west of south, and that facade receives no beam radiation during this period. The south side exterior zone experiences a strong increase in illuminance once the sun reaches the south facade. During the summer, natural light in the south side peaks at 140 fc (1500 lux). The exterior light shelf is a key source of this light during summer months as beam radiation does not strike the interior light shelf during this period. The south side is even brighter during the winter when direct sun does strike the upper surface of the interior light shelf producing interior illuminance values of 240 fc (2600 lux). In contrast, the north side has a lower, more uniform light level year round with the exception of early morning brightness during the summer when the sun strikes the northern facade. On both sides of the building, the relatively high window head height allows natural light to penetrate into the deep interior.

As a rule, there is a clearly discernible illuminance gradient that runs from the bright exterior wall to the dimmer central corridor region and then to the bright edge of the central atrium. Ironically, the area directly below the south-side interior light shelf breaks this pattern by being much too dim. This location, with easy access to exterior light, requires continuous supplemental lighting during the summer due to low-transmittance glazing and the exterior shading device.

The central atrium provides a dramatic visual focus and offers pleasant visual relief but is inefficient in providing light deep into adjacent spaces. This is largely due to a strong downward component in light from the atrium. There is a particularly sharp illuminance gradient at the atrium's edge, which makes the interior office spaces seem dim in comparison to the extremely bright atrium. Qualitatively, the atrium seems more a location of light than a source of light.

Electric Lighting System

The separation of systems providing task and ambient illumination is a successful strategy. The low target illuminance of the ambient lighting system requires a relatively low density of overhead electric lighting at .93 w/ft^2 (10 w/m^2) connected. One control unit covers a large area of approximately 2,000 ft^2 (186 m^2) and, therefore, the ambient lighting control system was relatively inexpensive.

Although the daylighting system was designed explicitly for providing ambient light, there is some evidence that it is displacing the use of task lighting as well. During typical summer work periods, spot surveys found approximately 50% of the task illumination fixtures were turned off because of either high ambient light levels or employee absence. On the negative side, the high levels of daylight on the building's south side are a source of unwanted heat gain and glare.

Based on field measurements, the electric light dimming system, when manually controlled, can effectively manipulate the electric lighting power. During an unoccupied period at night, each controlled circuit in our test zone was manually adjusted through its entire dimming range. The resulting curve of illuminance vs. power matched the data published by the manufacturer with the exception that maximum dimming occurred at 22% of full output rather than the 15% claimed for the unit.

Lighting Control System

From the first inspection of the building it was apparent that something was amiss in the operation of the electric lighting system. During these early visits, the indirect fluorescent system appeared to be operating near full power in areas where ambient daylight far exceeded target illuminance levels. As our study progressed, the collection of simultaneous data profiling interior illuminance and electric lighting power demand allowed a more detailed analysis of electric lighting dimming patterns.

A comparison of electrical power demand for ambient lighting with concurrent interior illuminance readings reveals widespread variation in the performance of the electric light control systems. Illustrated with representative cases in Figure 5, a majority of the third-floor control circuits examined had control patterns that result in excess use of electric lighting. In several cases, circuits are dimming less than 10% from full power during periods when interior illuminance exceeds target levels by 400%. Even though the architectural features and dimming hardware are working well, system performance is substantially degraded by problems with the dimming control system.

Lighting power demand measurements from the summer season were analyzed to determine the extent of electrical light dimming on the building's north and south sides. A data set for each side of the building was assembled using data from only those days that had normal weekday occupancy. The data file was then filtered to include only those data that occurred during the normal daytime occupancy period of 8 AM to 6 PM. An analysis of these 15-minute average measurements during a nine-day occupied period in May indicates that on the third-floor south side the average electrical energy consumption for ambient lighting was 75% of full power. A similar study, covering eight occupied days in July, establishes the average electrical energy consumption for the north side as 50% (Benton 1986). Figure 6 illustrates actual ambient light energy consumption for each side (from the periods noted) as a function of distance from the exterior wall.

These profiles of actual dimming indicate ambient lighting energy consumption that far exceeds that projected for the building.

In a separate analysis, illuminance data from unoccupied days during the summer was used to calculate potential dimming of the electrical lighting system. During these unoccupied days (typically Sundays) a check of the lighting power demand data confirmed that there was no electric lighting contribution to interior illumination. The measurements, therefore, represent daylighting contributions to ambient lighting at each of the 24 measurement locations. For each of these locations, the data set of illuminance on unoccupied days was filtered to include only measurements from the 8 AM to 6 PM daytime occupancy period and then sorted into bins with 70 lux increments. To establish potential dimming, the total number of observations for each bin at each illuminance sensor location was then multiplied by the lighting energy required to raise that bin to the target illuminance level. A summation across bins provides a lighting energy consumption profile for sections across the north and south sides of the building. The illuminance sensors are not spaced evenly across the building section, therefore, the results for each sensor location were weighted in proportion to the floor area represented by that sensor.

A potential dimming analysis of illuminance data for four unoccupied days in May indicates that, under proper control, the south side of the third floor should require only 44% of full power to achieve target illuminance. A similar analysis, based on eight unoccupied days in July, establishes that the north side should require only 30% of full power for ambient lighting. These trends, illustrated as the background shading in Figure 6, identify significant potential for dimming that is not being realized. The north side of the building, with lower and more uniform patterns of natural light, has greater dimming potential than the more dramatic south side. Although the north side's daylight levels are lower, they consistently exceed the target of 350 lux.

The Lighting Control System Reconsidered

A primary design objective for the ambient lighting system was the reduction of charges for electric energy consumption and its accompanying power demand. Our measurements indicate that substantial dimming potential is not being realized, even though the architectural features of the building admit plentiful daylight and the indirect fluorescent lighting system can dim to a small fraction of its full power load. It is apparent that the electric lighting control system is failing in its mission of accurately adjusting the fluorescent system in response to available daylight. This failure deserves closer scrutiny.

To empirically establish the operating patterns of the photosensor-based control system, we conducted a set of performance checks. To determine if the photosensor control system was capable of producing full dimming, a 150-watt incandescent lamp was used to cycle the sensors during a late evening period. When exposed to this strong light source, the dimming system properly lowered electrical power demand to the maximum reduction of 27% of full power. This established that there was at least some connection between each photosensor and the circuit it controlled. A second spot check was made to determine if the monitored third floor data wererepresentative of the entire building. This test, made during a sunny weekday afternoon, involved spot current measurements of all ambient lighting circuits on the south-side third and fourth floors. During this spot check, average ambient lighting system power demand was 73% of full power. This figure is in close agreement with the 75% of full power calculated from monitored watt transducer data in the previous section. On the fourth floor, a small percentage of the lighting control circuits were found disconnected at the electrical closet. This factor contributed to an even lower level of dimming on the fourth floor which was measured at 84% of full power.

The electric lighting control system is an open loop design. For each fixture row in the building interior, there is a control circuit with a photosensor located near the source of daylight for the region of that fixture. A specific adjustment is needed for each photosensor and dimming controller to relate illuminance at the photocell to the level of daylight at that controlled light fixture's location. Lighting fixtures in the exterior zones have control photosensors located in the underside of the interior light shelves just inside the building's vision glazing. The photosensors for all exterior zone fixtures are grouped in this single location requiring each individual photosensor to be accurately calibrated for the fixture it serves. The lighting fixtures located in the atrium zone of the building are controlled by a group of photosensors in the ceiling near the atrium edge. There are three potential sources of error in the lighting control system of this building:

Control System Design. The design, specifically the location of the photosensors, can cause improper dimming patterns. In an open loop dimming system the control sensors must be carefully located in a position where daylight levels are linearly related to the daylight contribution to illumination at the location of the fixture under control. Establishing the correct relationship between photosensor and light fixture location becomes particularly challenging in schemes that involve beam sunlight or complex fenestration geometries.

Control System Commissioning. The correct adjustment of each individual control sensor / lighting circuit should be made under conditions of normal occupancy including properly installed furnishings and partitions. However, commissioning normally takes place during the most hectic stage of building construction, the final days before the building is officially delivered to its owner.

Control System Recalibration. Following occupancy the control sensor / lighting circuit calibration should be checked periodically and adjusted if necessary. Changes in occupancy, partition layout, interior finishes, and maintenance procedures can affect the relationship between daylight available at the control sensor location and daylight delivered to the lighting fixture location.

Each of these categories has affected control system performance in this case study. The design decision locating exterior zone photosensors below the south-side interior light shelf is probably the major cause of poor system performance in this zone. This portion of the building receives its interior daylight through the glazing above, and reflection from, the upper light shelf elements. Locating the control sensors below the light shelf and behind low transmittance glazing has disassociated the sensors from the patterns of daylight above the light shelf. The control sensors are denied sunlight during the summer by the same exterior device that reflects substantial sunlight into the building's interior. Annual solar geometry effects produce an interesting dilemma in commissioning the south-side control system. It is unlikely that the adjustment specific to the date of commissioning would be appropriate for all times of the year due to major seasonal variation in the amount of beam radiation that strikes the upper interior light shelf surface. Periodic re-calibration of the control sensors, which has not occurred, is important for two reasons. First, a set of dark interior venetian blinds has been added to the vision glazing below the interior light shelf. This addition, an ineffective effort to combat winter heat gain, probably affects light reaching the control sensor even when the blinds are withdrawn. Second, the upward-facing indirect lighting system has accumulated an appreciable amount of dust on its bulbs and reflectors. This soiling increases the fixture's maintenance factor and reduces its ability to deliver light to the offices below and, therefore, changes the relationship between lighting fixture and control sensor. Although these effects should, to a certain extent, cancel each other out, recalibration would be appropriate.

At a minimum, improvement in the performance of the building's south-side, and other, zones will require re-calibration of the control system's circuits. More likely, major improvements will require the relocation of the photosensors to an area more directly representative of light levels in the building's interior. Photosensor relocation is a relatively minor task involving revision to low voltage wiring and a small amount of interior finish work. To gauge the suitability of alternate photosensor locations we monitored several potential sites.

The brightness of the upper surface of the interior light shelf has a good correlation with daylight in the building's interior. A downward looking illuminance sensor placed above the interior light shelf facing downward (see figure 2) demonstrates a nicely linear relationship with interior illuminance readings at several locations on the building's south-side exterior zone. Figure 7 shows this correlation for three interior locations using data from unoccupied daylight hours during a nine day period in May. The figure shows, for instance, that in a location just beyond the light shelf interior illuminance exceeds the target value of 32.5 fc (350 lux) if illuminance above the light shelf reaches approximately 160 fc (1700 lux). Happily this relationship remains linear and stable through the entire year. Figure 7 also includes October data from the north-side exterior zone. Under this diffuse sky regime correlation is not quite as strong but it is not bad either.

With proper control the system economics are quite attractive. The electrical lighting control system has a low installation cost of \$0.44/ft^2 (\$4.77/m^2) made possible by a combination of simple daylighting distribution patterns, a large number of lamps per controller, and the relatively low electric lighting density. During a substantial portion of the day, including the period of peak demand, electric lighting system demand can be reduced from 0.93 W/ft^2 (9.95 W/m^2) to about 0.25 W/ft^2 (2.7 W/m^2). A reduction of energy consumption to an average of 40% of full power (a realistic target considering measured interior illuminance) could provide an annual energy savings, assuming 3750 hours of daytime occupancy during a year, of 2.08 kWh/ft^2 (22.4 kWh/m^2). With electricity charges of \$0.08/kWh the annual cost savings, excluding benefits from reduced peak demand, would be \$0.166/ft^2 (\$1.79/m^2). The simple payback for a properly operating control system would be 2.6 years.

Areas of the building near the exterior walls and atrium have daylight levels that consistently exceed the 32.5 fc (350 lux) target illuminance. It should be noted that an on/off control system in these zones would have the advantage of lowering the minimum lighting energy consumption from the 27% of the current continuously dimming system to 0%. In addition the hardware would have a lower initial cost.

CONCLUSIONS

The building monitoring program produced data that, in combination with field observations, support a series of conclusions. The architectural features of the building are quite capable of delivering natural light, without major glare and in appropriate quantity, to the building's interior. The fluorescent system used for ambient lighting can, under manual control, dim adequately. The lighting control system, however, fails to capitalize on the significant potential for displacing electrical lighting energy consumption. The control system is fortunately the easiest of these three components to revise, and a relatively straightforward redeployment of the control system sensors combined with periodic maintenance should produce significant benefits.

The monitoring techniques used in this study have provided an insightful portrait of daylighting performance in an innovative building. The ease of data collection using portable battery operated dataloggers recommends these techniques to the study of additional daylighted buildings.

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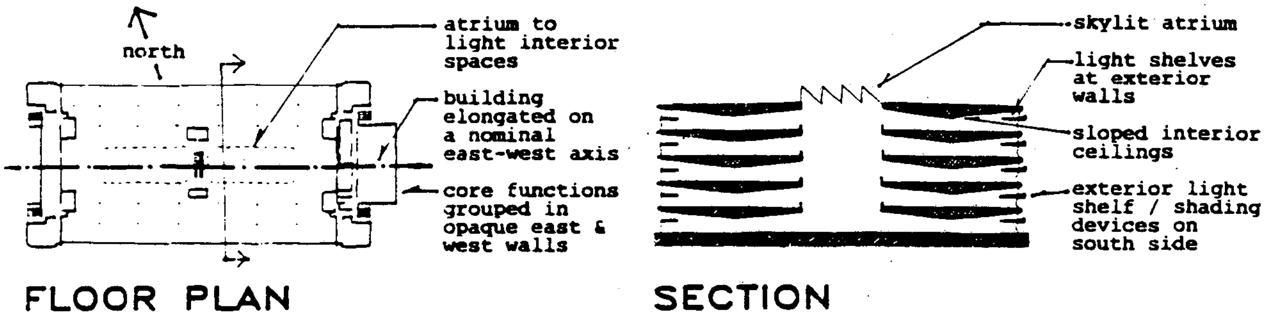


Figure 1. Diagram of building plan and section, showing architectural features of the daylighting system.

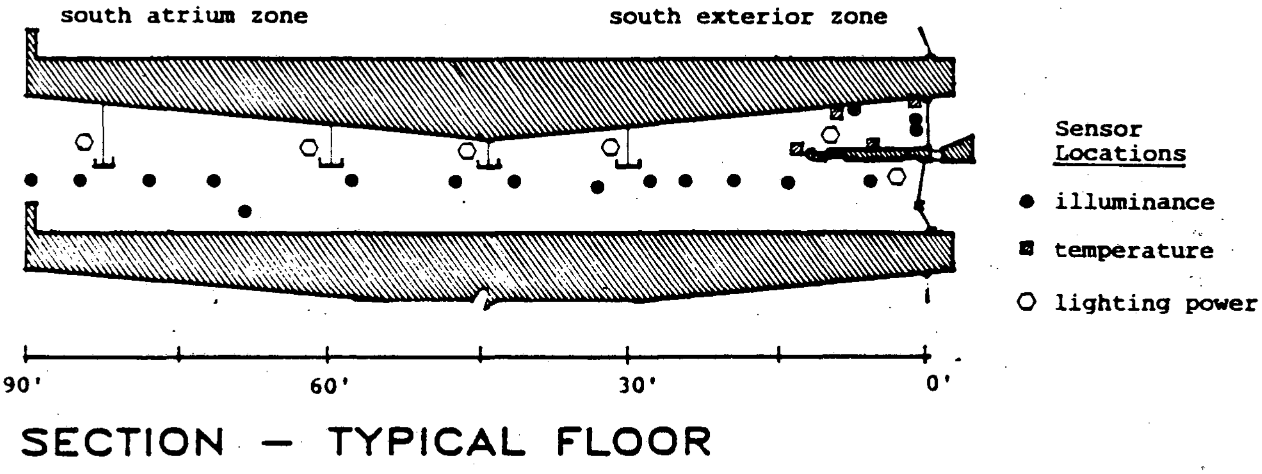
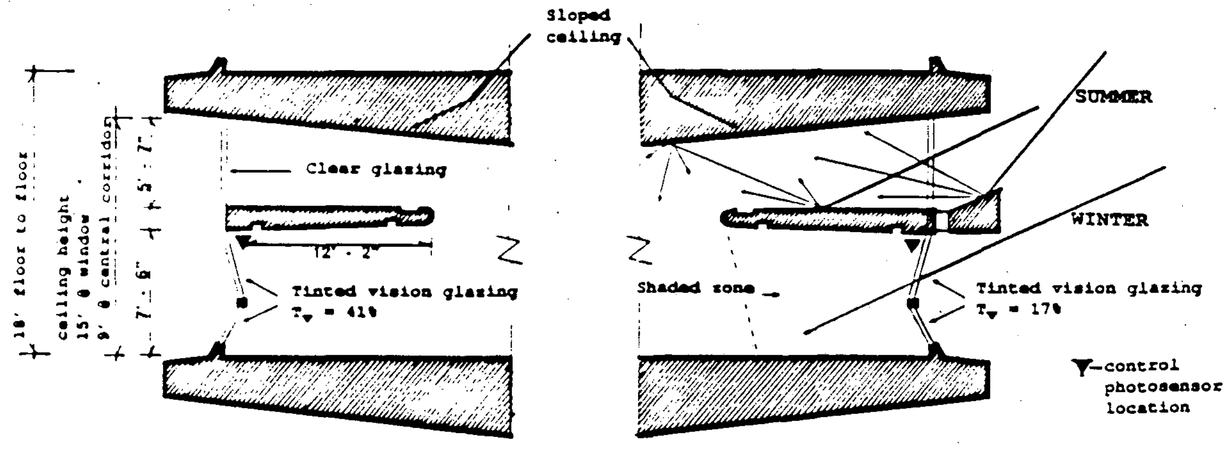


Figure 2. Section through the third floor on the south side of the building, showing sensor locations for data collected in this zone.



NORTH SECTION

SOUTH SECTION

Figure 3. Schematic section through south-side and north-side light shelves. Note location of photosensor for control of the direct fluorescent lighting system.

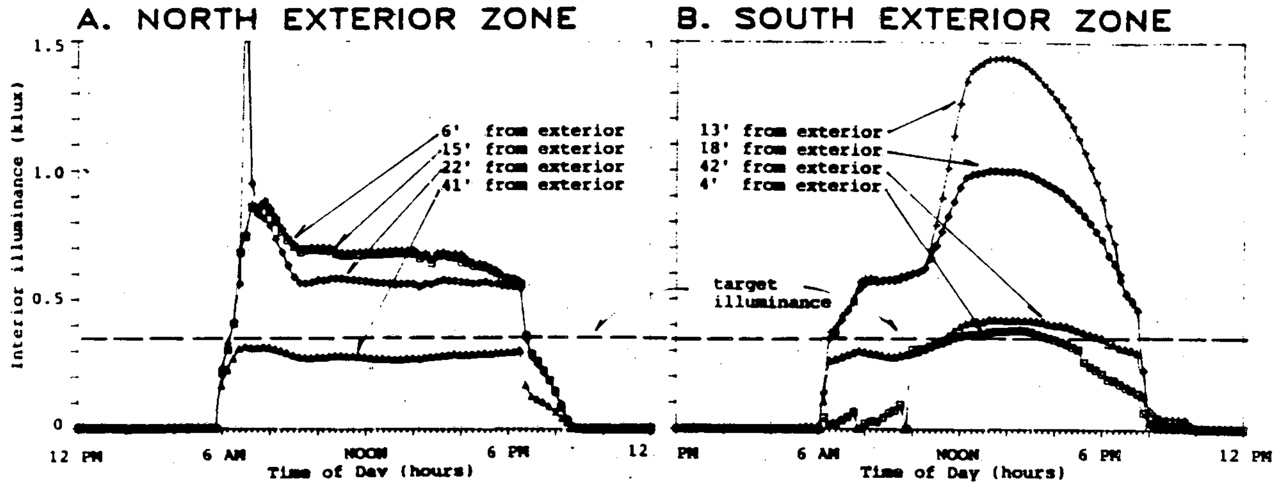


Figure 4. Interior illuminance data (averages for 15-minute periods) from a typical clear summer day in the building's north-side (A) and south-side (B) exterior zones. These readings include an electric light component that can be seen as a plateau of approximately 28 fc (300 lux) at the base of each curve.

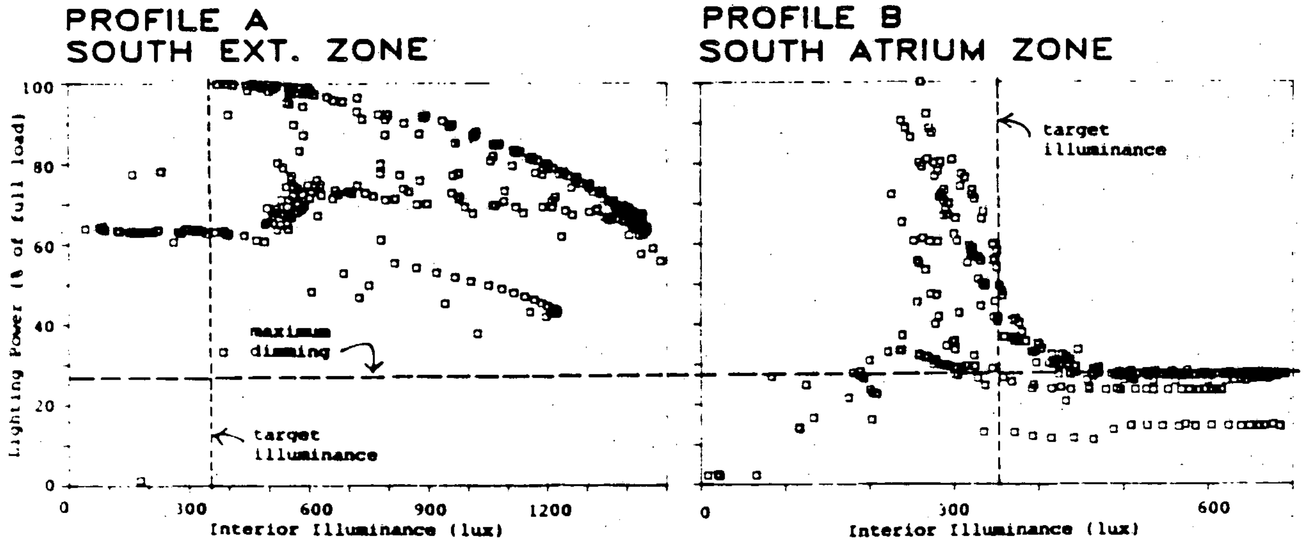


Figure 5. Scatter plots of measured lighting power vs. concurrent interior illuminance for two representative circuits. Profile A, with relatively little dimming at high interior light levels, proved to be a pattern common to a majority of the 14 measured circuits. Profile B, demonstrating reasonably strong correlation between dimming and illuminance, was found, paradoxically, in one of the darkest areas of the building interior.

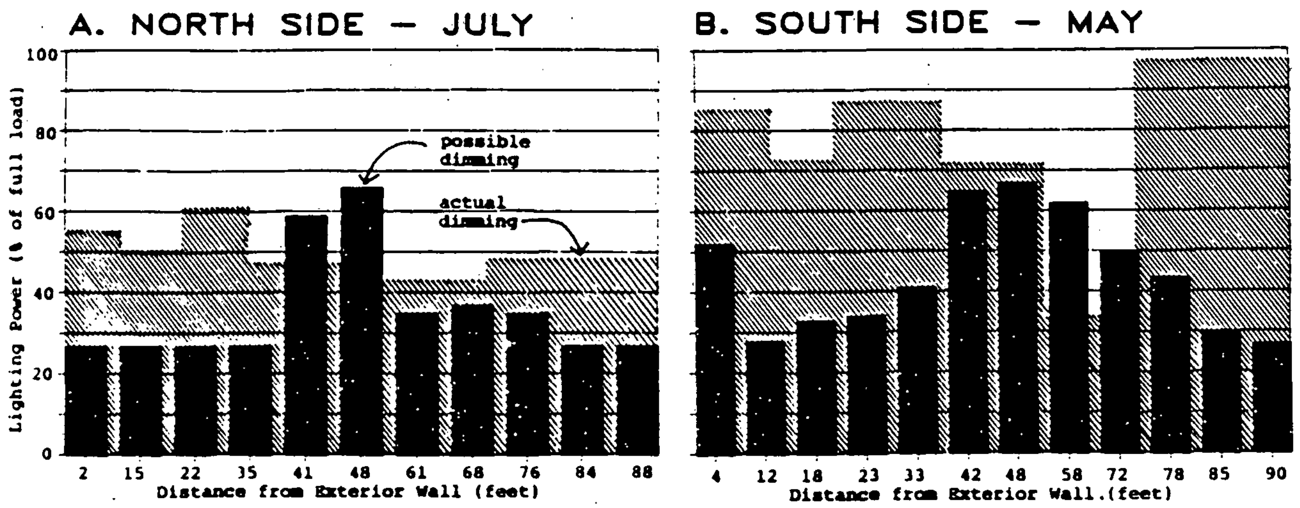


Figure 6. A comparison of measured average dimming for ambient electrical lighting to potential dimming for typical summer conditions. The estimate of potential dimming is based on day-long illuminance readings across the building section during a series of unoccupied days without electric lighting. The potential dimming was calculated as a function of available daylight and electrical lighting system efficacy.

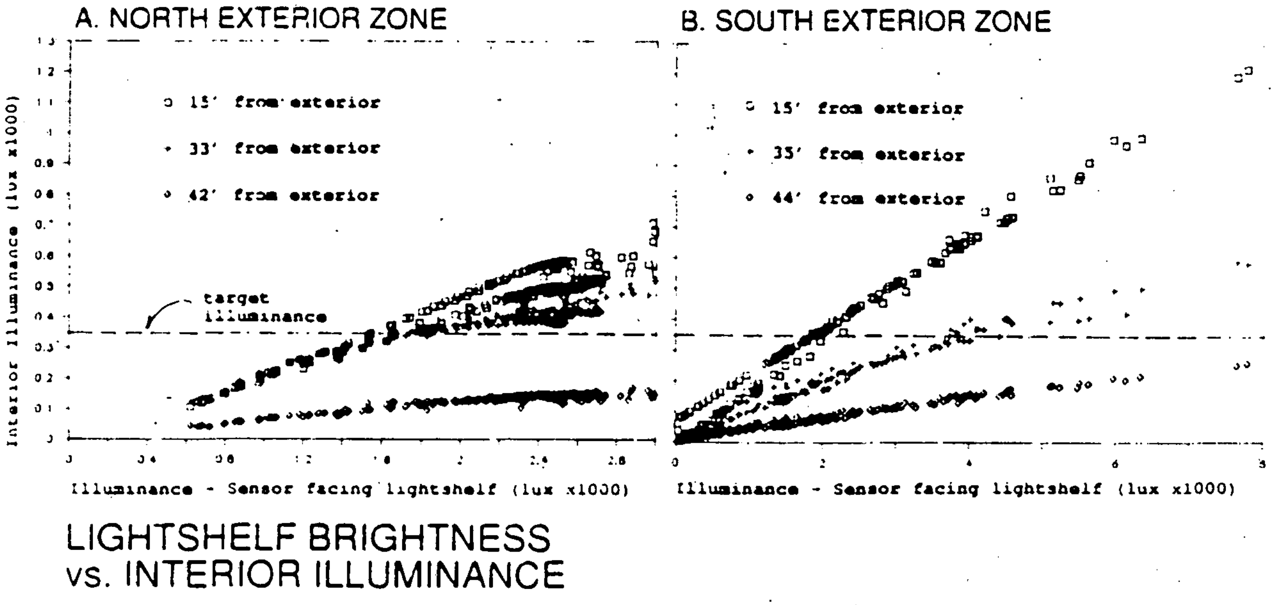


Figure 7. Scatter plots of illuminance above the interior light shelf surface (measured at upper ceiling looking downward) vs. interior illuminance in a horizontal plane at partition height. Data were collected during unoccupied summer days with no electric light component. The south-side exterior zone (B) has excellent linear correlation between natural illuminance at this potential control sensor position and the illuminance from daylight at interior locations. The north-side exterior zone (A), a scheme driven by diffuse light, demonstrates strong positive correlation as well.

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