CONF-9010395--1

LBL-30611

Lawrence Berkeley Laboratory

UNIVERSITY OF CALIFORNIA

APPLIED SCIENCE DIVISION

Presented at the VIIIth International Scientific and Technical Conference on Illumination, Lighting 90, Varna, Bulgaria, October 3–6, 1990, and to be published in the Proceedings

Control System Performance in a Modern Daylighted Office Building

C. Benton, M. Fountain, S. Selkowitz, and J. Jewell

October 1990

APPLIED SCIENCE DIVISION

Prepared for the U.S. Department of Energy under Contract Number DE-AC03-76SF00098

LBL-30611
DA-281

Presented at the VIIIth International Scientific and Technical Conference on Illumination, Lighting 90, October 3-6, 1990, Varna, Bulgaria

LBL--30611

DE91 016419

Control System Performance in a Modern Daylighted Office Building

C. Benton, M. Fountain, S. Selkowitz, and J. Jewell

Applied Science Division
Lawrence Berkeley Laboratory
University of California
1 Cyclotron Road
Berkeley, California 94720

October 1990

MASTER

The study was supported by the Energy Services Department of the Pacific Gas and Electric Company and by the Assistant Secretary for Conservation and Renewable Energy, Office of Building Technologies, Building Systems and Materials Division of the U.S. Department of Energy, under Contract No. DE-AC03-76SF00098.

ep

CONTROL SYSTEM PERFORMANCE in a MODERN DAYLIGHTED OFFICE BUILDING

C. Benton, M. Fountain, S. Selkowitz, and J. Jewell

ABSTRACT

Lockheed Building 157 is one of the United States' largest experiments in contemporary daylighting. Built in 1983, the five story structure houses 3,000 employees and uses daylight for ambient illumination throughout its 56,000-m^2 office interior. A continuously dimmable fluorescent lighting system supplements interior daylight under the control of open-loop ceiling-mounted photosensors. In 1985 Lawrence Berkeley Laboratory (LBL) began a year-long program to measure lighting system performance in the building. Data from this study indicated that architectural features of the building performed admirably, admitting significant daylight to large areas of the open plan interior. Operational savings, however, were limited by inappropriate performance of the control system in many of the building's lighting circuits. LBL recently completed a follow-up investigation of the lighting systems in Building 157 addressing the interaction between daylight and the lighting control system with the goal of improving control system performance. We modified a 1,700-m^2 test zone by relocating the photosensors, attenuating the photosensor control signal, changing the response pattern of the photosensors, and implementing a LBL-developed calibration procedure. Following these modifications, we installed four data-acquisition systems and collected detailed data describing illuminance and lighting power demand during two week periods in the summer, equinox, and winter seasons. This paper presents a comparison of lighting system performance before and after the LBL modifications. Analysis of the data indicates our modifications were successful in maintaining interior illuminance at the target of 350 lux with minimal electric energy consumption.

BUILDING DESCRIPTION

Lockheed Building 157, located in Sunnyvale, California, incorporates a set of lighting system features designed to displace electrical energy consumption for ambient lighting. The scheme has been widely published in the U.S. architectural press as an innovative example of daylighting (*Shanus et al., 1984; Gardner, 1984*). It was presented as an ambitious example in which natural light serves a large staff of high-salaried technical employees in the building's 56,000-m^2 interior. The owner's lighting objectives called for a significant daylighting contribution to the ambient lighting of all five open-plan floors of the building's 128-m by 73-m plan area. In meeting this challenge, the architects designed a system that separates task and ambient lighting systems. The ambient lighting system combines architectural features for the admission and distribution of daylight, dimmable electric lighting circuits, and a control system to operate the electric lights in response to available daylight.

The building design was strongly driven by daylighting criteria, a circumstance that produced several unconventional architectural features. The building plan, diagramed

---

C. Benton, Faculty Research Associate and M. Fountain, Research Associate, S. Selkowitz, Staff Scientist, Lawrence Berkeley Laboratory; and J. Jewell, Lighting Consultant.

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, bathrooms, etc.), were concentrated in the opaque east and west ends of the building. The remainder of the building contains open-plan offices with 1.7-m partitions in an open space extending from the north exterior wall to the south exterior wall. An atrium, 18.3 m wide and five stories tall, in the center of the building provides light, visual relief, circulation, and drama. This geometry produces two separate sides to the building, north and south, each of which is 27.4 m wide. In the vertical dimension, a large floor-to-floor separation of 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 openings at the exterior wall and atrium.

The north and south exterior walls feature large interior lightshelves located just inside the glazing. Shown in Figure 2, these horizontal elements, 2.3 m above the floor and 3.7 m wide, serve as light reflectors and glare control baffles. The south side of the building has an additional exterior lightshelf that complements the functions of the interior device and also provides solar shading for the vision window below. The vision glazing has a solar control tint while the glazing above the lightshelves is clear.

FINDINGS FROM THE 1985 STUDY

Our 1985 study addressed general lighting system performance in Lockheed Building 157. Preliminary site visits with hand-held instrumentation confirmed that significant variation in illuminance occurs only in a direction perpendicular to the windows and that corresponding zones on each floor have similar readings. Our measurement program employed battery-operated dataloggers to poll illuminance sensors, temperature sensors and watt transducers placed in representative daylighting zones on the building's third floor. Figure 3 illustrates the sensor placement for a typical building zone. Measurements 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 the 1.7 m partition height. Additional photometric sensors were located in the space above the interior lightshelves. Lighting power demand for individual lighting circuits was monitored using watt transducers installed in the local electrical closet. Figure 4 compares interior illuminance and lighting power demand for a location 10 meters inside the building's south-facing facade. On the illuminance graph, a dashed line indicates the target illuminance of 350 lux. Power demand for the electric lighting fixtures is graphed on a scale of 0% to 100% of full power. Under manual control the lighting system is capable of dimming to 28% of full power.

Figure 5 summarizes the summer performance of a typical test zone in the 1985 study. While illuminance exceeded target levels through the workday, there was little concurrent dimming of the electric light system. Our original study presented several conclusions:

- The architectural features of the building worked well in admitting comfortable interior daylight.
- The central atrium provided a dramatic visual focus and offered pleasant relief but was inefficient in providing daylight deep into adjacent spaces

- The electric dimming system, when manually controlled, effectively manipulated lighting output and electricity demand.
- There was widespread variation between circuits in the relationship between interior illuminance and lighting power demand with most circuits operating poorly.
- Areas of the building near the exterior walls and atrium had daylight levels consistently exceeding the 350 lux target illuminance.

In summary, monitored data from the 1985 study indicated that although the architectural daylighting features of the building perform admirably, operational savings were limited by inappropriate performance of the control system in most of the building's lighting circuits. This circumstance sets the context for our Phase II study: an attempt to capture unrealized savings inherent in the building's design.

THE CONTROL SYSTEM REVISITED (1988 STUDY)

The 1985 study led to the hypothesis that relatively minor revisions to the control system design could substantially improve lighting system performance. In 1988 we tested this hypothesis by returning to Lockheed Building 157, modifying the building's electric lighting control system, and monitoring the effectiveness of these revisions. Our tests were conducted in the 2,500-m^2 southeast quadrant of the third floor, a zone monitored during the earlier study. We began with revisions to the lighting control system including a relocation of the photosensors and changes in their response pattern (see Figure 6.) The revisions for our test zone required a single morning of labor and $650 in supplies. Following these physical modifications to the control system we conducted a brief period of experimentation concerning calibration of the control system. From these experiments we derived a calibration procedure ('LBL' calibration) that appeared to offer better performance than the control system manufacturer's standard procedure ('manufacturer's' calibration.)

The monitoring phase of our study began with the calibration experiments and continued through the summer, equinox, and winter periods. During the calibration phase, conducted in July 1988, monitored data supported the fine tuning of control system performance. At the beginning of August 1988 we adjusted the system for the final time using the 'LBL' calibration technique. From this point forward the die was cast and our monitoring systems were used only to document the control system's subsequent performance. Measurements for this portion of the study followed the protocol established in 1985 (Figure 3), allowing us to make direct comparisons of performance before and after the modifications. The challenge at this point was clear: the control system, without additional adjustment, should adjust the electric lighting system to the minimum output required to provide the target interior illuminance of 350 lux. The system should automatically and consistently account for variations in daylight due to weather, time-of-day, season, and location in the building's interior.

RESULTS

This section presents data characterizing seasonal effects in the building's performance and the influence of weather on interior illuminance and electric power demand. Figures 7 through 9 describe diurnal patterns of illuminance and electric power demand at a location 10 meters inside the south exterior wall. This location, the same position used to illustrate the 1985 data (Figure 4), represents performance trends common to all daylighting zones in the test space. Data were collected at one second intervals and averaged for 15-minute periods. The building had normal weekday occupancy for the periods presented.

The first test of control system performance was the system's behavior under the condition of its calibration: the clear summer sky. Figure 7 presents system performance from before (1985) and after (1988) our control system modifications. The 1988 data include system performance after implementing the manufacturer's calibration procedure and data following the LBL-developed procedure. The revised control system meets the 350 lux interior illuminance target throughout the day without exceeding 550 lux. This is an improvement over the situation in 1985 when interior illuminance at this location peaked at over 725 lux. The reason for the improvement is evident in the graph of electric light dimming. Whereas the dimming pattern in 1985 was ineffectual with a minimum of 90% of full power, the dimming in 1988 was much improved. Under the calibration midday dimming fell to under 40% of full power. Following the 'LBL' calibration, the system reached maximum dimming at 28% of full power from 11 a.m. to 6 p.m. A comparison of the 1985 data to the manufacturer's calibration shows a clear performance gain due to our physical modifications to the control system. A significant performance improvement is also evident in comparing the two 1988 calibration methods. The 'LBL' calibration method produced additional dimming while maintaining target illuminance.

The next test of the control system was the stability of system performance during seasonal variation in solar geometry. During the summer, direct sun does not penetrate the building's south-facing glazing but does strike the upper surface of the exterior lightshelf. During winter, however, the entire interior lightshelf surface is flooded by beam radiation Figure 8 provides a comparison of system performance during clear, sunny days in each of the three seasons. As the seasons progress toward winter, the days shorten and the sun takes a lower path through the southern sky. As a consequence, interior illuminance at our representative location reaches 900 lux during the winter compared to approximately 500 lux in the summer. While the illuminance data clearly show the shorter winter day length, the electric light dimming data indicate a substantial 7-hour period of maximum dimming in December. In fact, all three seasons have continuous periods of maximum dimming coincident with the availability of beam sunlight at the building's south-facing facade. The electric lighting control system passed the test of seasonal stability, performing in a consistent fashion despite an impressive variation in the direction and quantity of available daylight.

An examination of cloudy day performance provides a final illustration of control system performance following our revisions. Figure 9 provides the comparison of system performance on a clear winter day with the results from a winter day with a broken stratus cloudcover. On occasion, the direct sun would emerge from behind low, scudding clouds providing a test of the system's capacity to adapt to rapid change. For the cloudy day, the interior illuminance graph features a distinct control plateau between 350 and 400 lux. The concurrent electric light dimming data indicate a timely and precise adjustment of the electric light system in response to available daylight.

CONCLUSIONS

Lockheed Building 157 was a successful experiment in lighting strategies that included an architectural envelope designed explicitly for daylighting, a task/ambient split of electric lighting systems, a large array of continuously dimmable fluorescent circuits for indirect lighting, and an automatic lighting control system to coordinate electric lights with available daylight. Our 1985 study of lighting system performance in Building 157 concluded that the design and implementation of this building had been a qualified success. The major components of the lighting systems worked well when considered independently. The building admitted an impressive amount of daylight with proper distribution and a minimal amount of glare. The vast array of dimming ballasts worked well under manual control. A relatively minor component, the dimming control system, deprived the project of the majority of its savings in electrical energy and demand. We found fault with both the design and the calibration of Lockheed's existing dimming control system.

Our 1988 project was directed toward correcting the deficiencies in the control system and documenting improved lighting performance. We conducted the study in the same third floor quadrant of the building used during 1985. We revised the control system by specifying a new photometric response for the control sensors, placing a set of these manufacturer-supplied photosensors in a new location, and optimizing the control system calibration procedure. Our revisions have been successful in establishing proper lighting system operation for summer, equinox and winter conditions; and in clear and cloudy weather. In the comparison with the 1985 measurements, it is clear that the test zone system is now performing properly and using the appropriate amount of lighting energy to maintain an accurate target illuminance. Since many of the circuits spent a major portion of daytime hours at full dimming, a simple on-off system would provide substantial increases in energy savings by eliminating the unnecessary parasitic load of the dimmable system. We can provide an anecdotal report that occupants of the test zone are largely unaware of the increased dimming as it occurs during the brighter portions of the day. We have estimated annual saving from reductions in lighting energy and peak power demand to exceed $30,000 with additional savings accrued from reduced cooling loads.

REFERENCES

Benton, C., Warren, M., Selkowitz, S., and Jewell, J. 1986. "*Lighting system performance in an innovative daylighted structure: an instrumented study*." Proceedings of 2nd International Daylighting Conference, Long Beach, California.

Benton, C., Erwine, B., Warren, M., and Selkowitz, S. 1986. "*Field measurements of lightshelf performance in a major office installation*." Proceedings of 11th National Passive Solar Conference, ASES, Boulder, CO, June.

Benton, C., Warren, M., Selkowitz, S., Verderber, R.R., McBride, J., Morse, O., and Jewell, J. 1986. "*A field evaluation of daylighting system performance*." Proceedings of 10th CIB Congress, International Council for Building Research, Washington, D.C., September.

Gardner, James B. 1984. *"Daylighting cuts energy use to 19,600 BTU per sq ft per year."* Architectural Record, January 1984, pp. 139-143.

Shanus, M., Windheim, L., Riegel, R., and Davy, K. 1984. "*Going beyond the perimeter with daylight*." Lighting Design & Application, March 1984, pp. 30-40.

Usibelli, A., Greenberg S., Meal M., Mitchell A., Johnson R., Sweitzer G., Rubinstein F., and Arasteh D. 1985. "Commercial-sector conservation technologies." Lawrence Berkeley Laboratory Report LBL-18543.

Verderber, R.R., and Rubinstein, F.M. 1984. "*Mutual impacts of lighting controls and daylighting applications*." Energy and Buildings, Vol.6, pp.133-140.

Warren, M., Benton, C., Verderber, R., Morse, O.; and Selkowitz S. 1985. "*Instrumentation for evaluating integrated lighting system performance in a large daylighted office building*." Proceedings of Field Data Acquisition for Building and Equipment Energy-Use Monitoring Conference, U.S. Department of Energy, Dallas, Texas, September.

Warren, M., Benton, C., Selkowitz S., Verderber, R., Morse, O., and Thornton, J. 1986. "Phase I final report: field monitoring of office building energy consumption." Lawrence Berkeley Laboratory Report LBL-21257.

Warren, M., Benton, C., Verderber, R. R., Morse, O., and Selkowitz S. 1986. "*Evaluation of integrated lighting system performance in a large daylighted office building*." Proceedings of Energy Efficient Buildings Conference, American Council for an Energy-Efficient Economy, Santa Cruz, California, August.

ACKNOWLEDGMENTS

This study was supported by the Energy Services Department of the Pacific Gas and Electric Company and by the Assistant Secretary for Conservation and Renewable Energy, Office of Building Technologies, U.S. Department of Energy under contract No. DE-AC03-76SF00098.

Figure 1. Building Plan and Section

Daylighting decisions affected the basic architectural layout of Building 157.

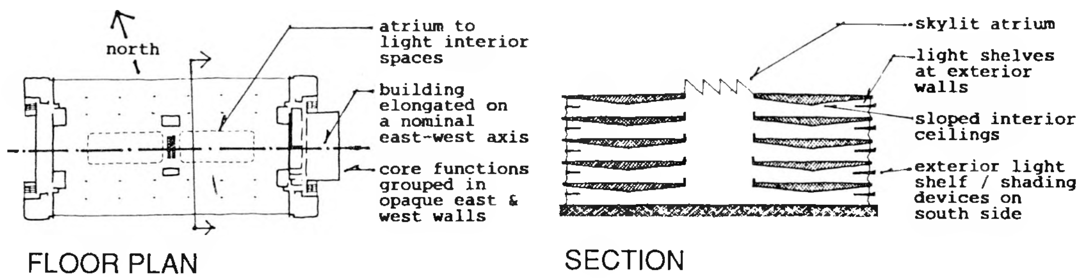


Figure 2. Lightshelf Section.

Schematic section through south-side and north-side lightshelves. Note original location of photocell for control of overhead fluorescent lighting system.

∇ *photocell*

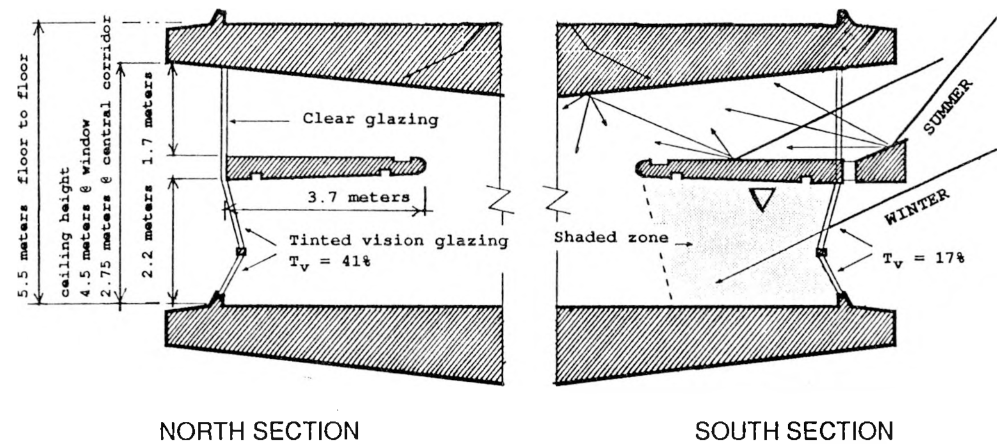


Figure 3. Placement of Sensors.

Illuminance is measured at the top of interior partitions (1.75 m above finished floor). Lighting power consumption is measured using watt transducers located in a local electrical closet. Subsequent graphs in this report provide example data from a location 10 meters inside the south-facing exterior wall (dashed line.)

● illuminance

▨ temperature

○ lighting power

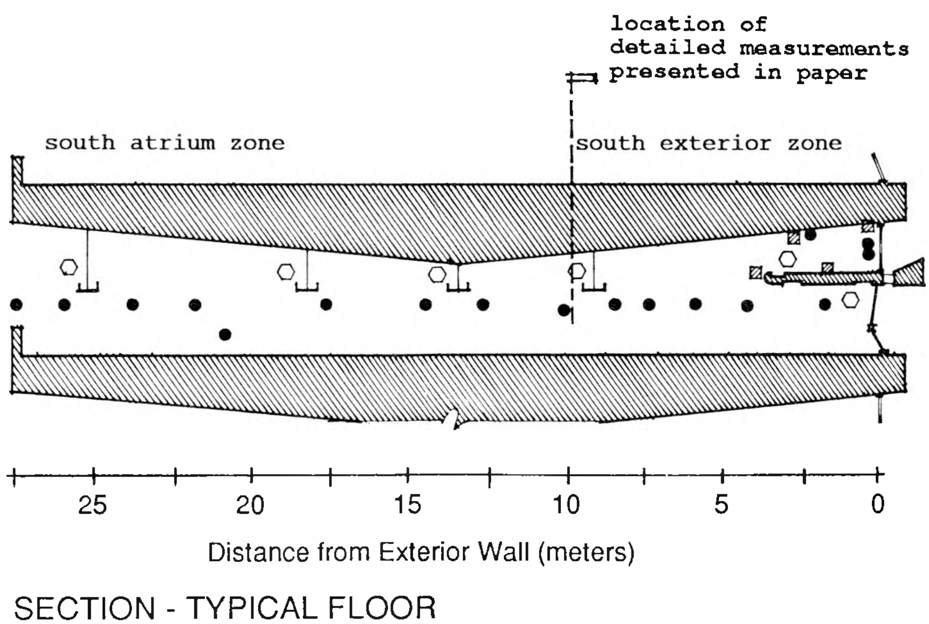


Figure 4. Illuminance vs. Lighting Energy, Interior Zone, Existing Conditions

For clear sky summer conditions, the interior zone shows a reasonable daylighting component during mid-day, offering the promise of substantial dimming.

1) The morning shoulder of diffuse-sky driven daylight is clearly visible.

2) Interior illuminance at 10 meters from the exterior wall remains above the target of 350 lux throughout the day and, in the afternoon, exceeds this target by a factor of two.

3) Unfortunately, the electric lighting circuit fails to show appreciable dimming.

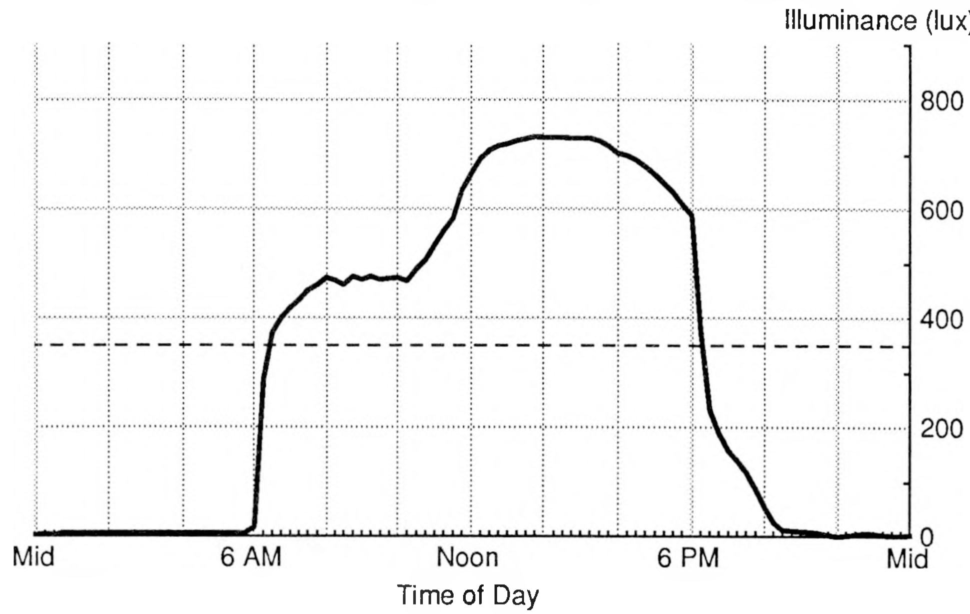
4) Sharp drops in electric power consumption occur in the evening and night hours due to sub-circuit switching.

KEY:

Summer
24 May 1985

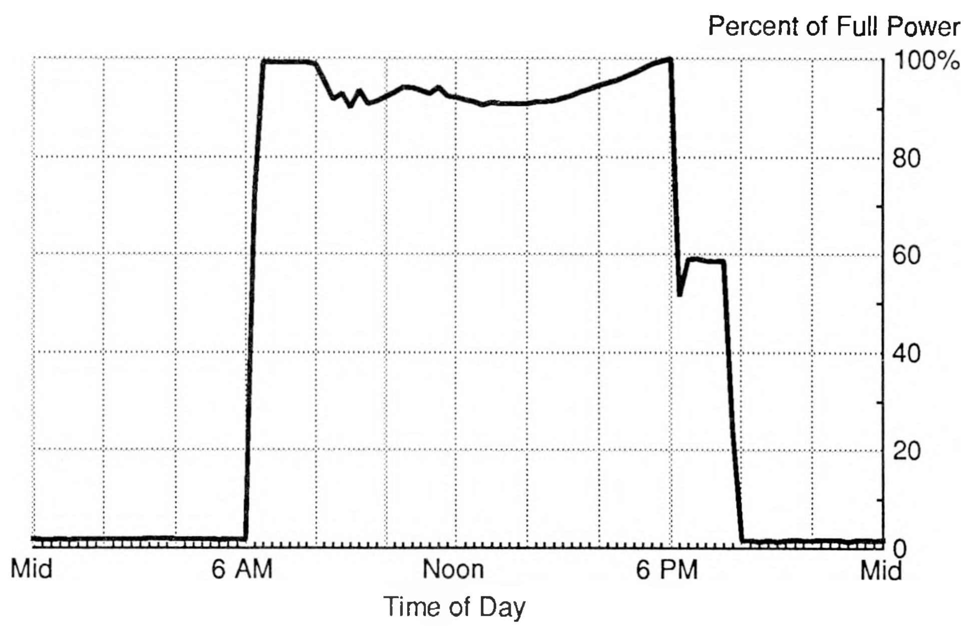
EXISTING CONDITIONS INTERIOR ILLUMINANCE

No. 88 (10 meters from the exterior wall)



ELECTRIC LIGHT DIMMING

Circuit 9 (10 meters from the exterior wall)



Data are for clear sky conditions on occupied weekdays.

Figure 5. Actual vs. Potential Dimming.

From the 1985 study at Lockheed: a comparison of measured average dimming for ambient electrical lighting (actual dimming) to the dimming that would occur with ideal control system response (potential dimming) for typical summer conditions.

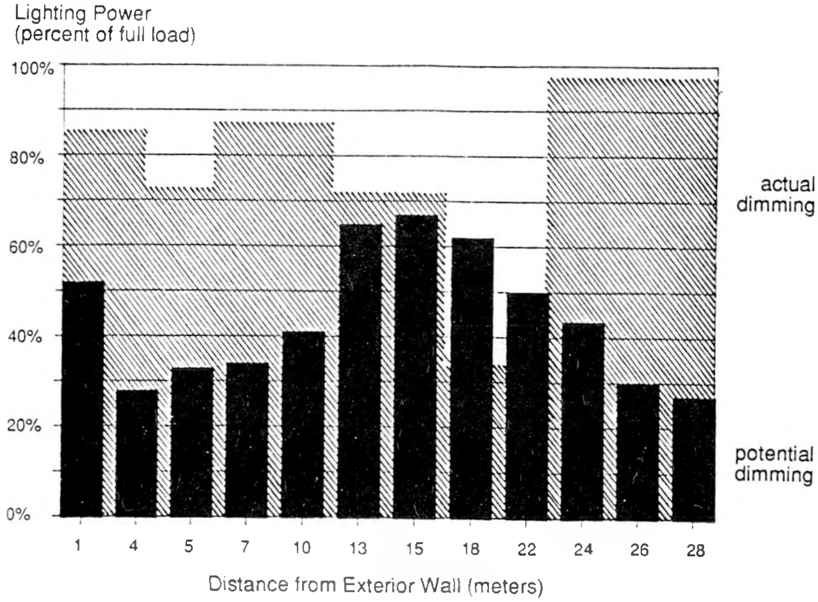
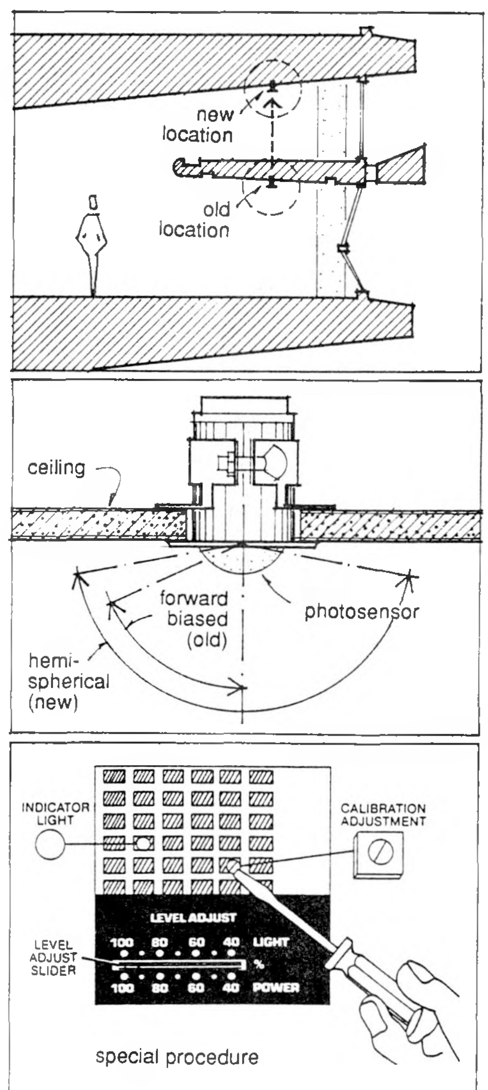


Figure 6. Modifications to the Lighting Control System

These measures have a relatively low cost. Installation and calibration time for one quarter of a floor was approximately one-half day. We used five new photosensors, eight signal attenuators, and about 100 feet of low-voltage wire to retrofit the test zone. Materials cost for the test zone was approximately $650 including new photosensors at $100 apiece.



1.

We relocated exterior-zone control photosensors to the ceiling above the interior lightshelf.

2.

We changed the photometric sensitivity of the photosensors from a forward-biased pattern to a hemispherical pattern and added signal attenuators to the circuit.

3.

We calibrated the control circuits using a procedure developed by LBL.

Figure 7. Illuminance vs. Lighting Energy, Interior Zone, Calibration Comparison

This figure reveals several interesting interrelationships between available daylight and electric lighting in the building's interior:

1) 10 meters into the building, the 1985 data indicate excessive midday illuminance due to unnecessary electric lighting.

2) Compared to the inconsequential dimming of the base case, the 'manufacturer's' calibration provides impressive reductions in lighting energy expenditure while maintaining the target illuminance.

3) The 'LBL' calibration, when compared to the 'manufacturer's' calibration, provides even greater dimming of the lighting circuit with almost no change in interior illuminance.

4) The circuit shows slightly over 30% of full power consumed 24 hours a day during 1988 as a portion of the circuit has been converted to emergency lighting.

KEY:

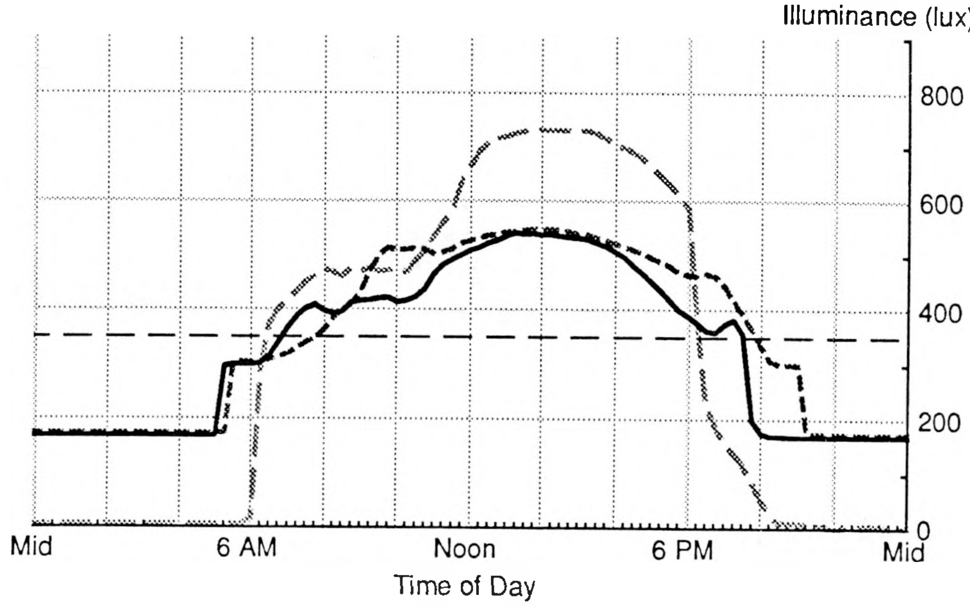
Summer
24 May 1985

Manufact. Calibration
1 August 1988

'LBL' Calibration
16 Aug 1988

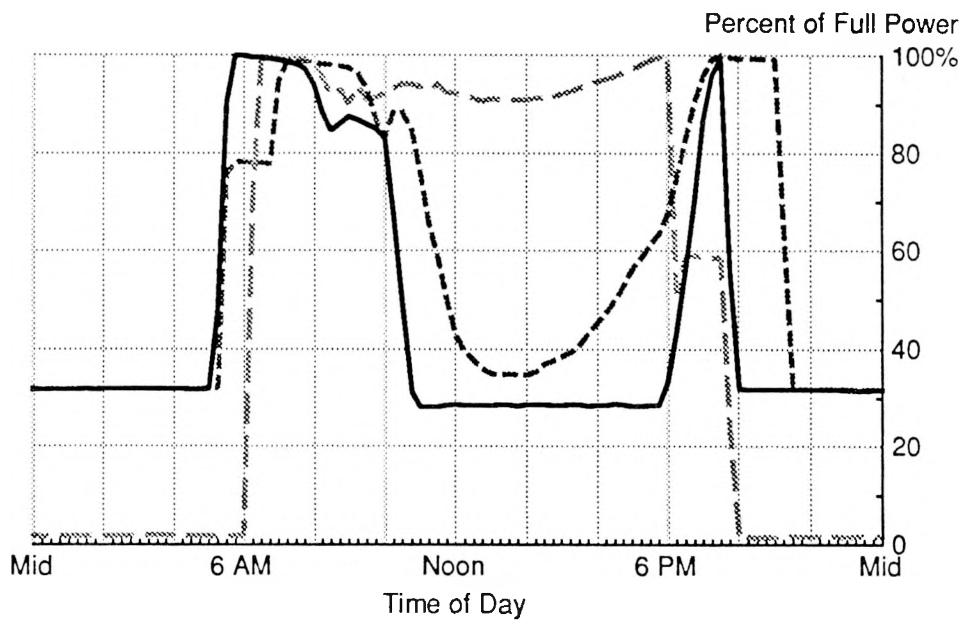
CALIBRATION COMPARISON INTERIOR ILLUMINANCE

No. 88 (10 meters from the exterior wall)



ELECTRIC LIGHT DIMMING

Circuit 9 (10 meters from the exterior wall)



Data are for clear sky conditions on occupied weekdays.

Figure 8.
Illuminance vs. Lighting Energy, Interior Zone, Seasonal Variation

The interior zone of the south side becomes brighter with the onset of winter:

1) At 10 meters into the interior, the increasing penetration of daylight allows maximum dimming for over 6 hours per day throughout the year.

2) There is a 30 minute spike of high interior illuminance (~ 10,000 lux) caused by beam sunlight penetrating past the interior lightshelf.

3) The shoulder of diffuse-sky-driven illuminance in the morning is reduced as the seasons progress toward winter.

KEY:

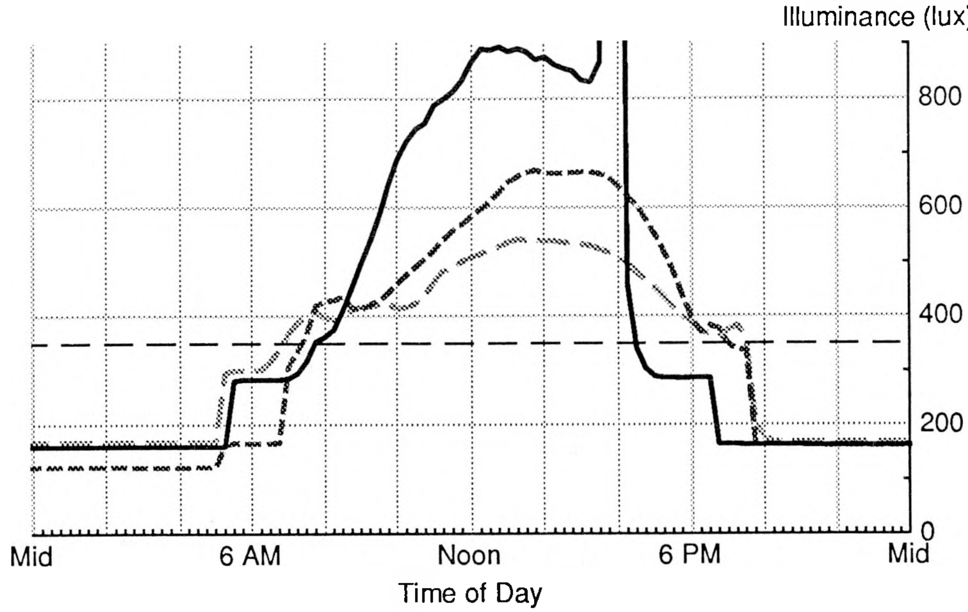
Summer
16 August 1988

Equinox
21 September 1988

Winter
13 December 1988

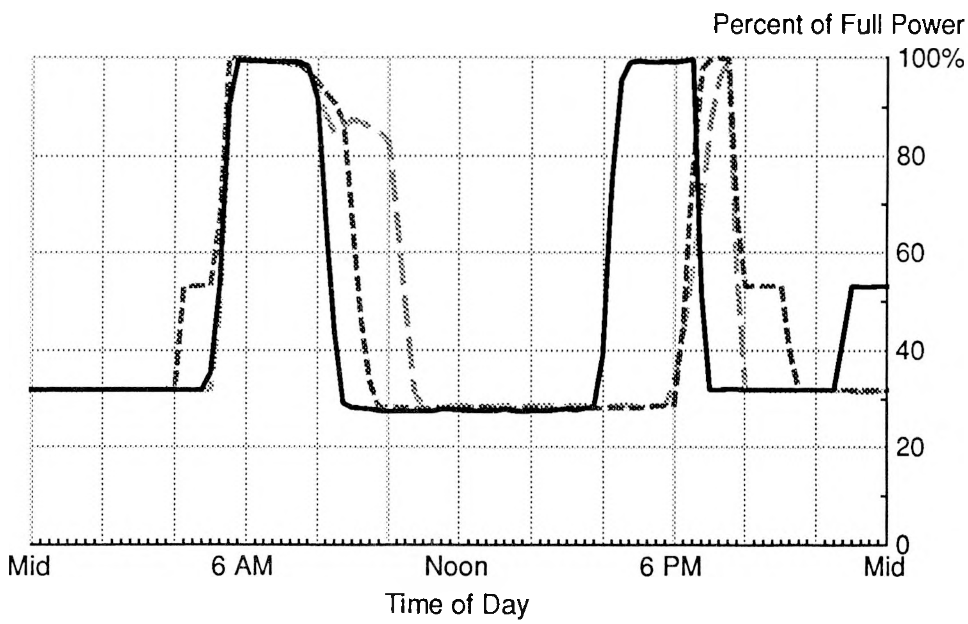
SEASONAL VARIATION INTERIOR ILLUMINANCE

No. 88 (10 meters from the exterior wall)



ELECTRIC LIGHT DIMMING

Circuit 9 (10 meters from the exterior wall)



Data are for clear sky conditions on occupied weekdays.

Figure 9. Illuminance vs. Lighting Energy, Interior Zone, Clear vs. Cloudy Conditions

The interior zone performs well under cloudy sky conditions:

1) During the midday period, the system is capable of maintaining interior illuminance at the target level. Rapid fluctuations in interior illuminance are limited to variations of approximately 200 lux.

2) The interior zone requires more electrical energy on cloudy days than on clear. Fluctuations in power demand are more pronounced as the cloudy day conditions allow less dimming in this zone. Nevertheless, the system was still able to produce dimming between 8 a.m. and 6 p.m. that averaged 75% of full power.

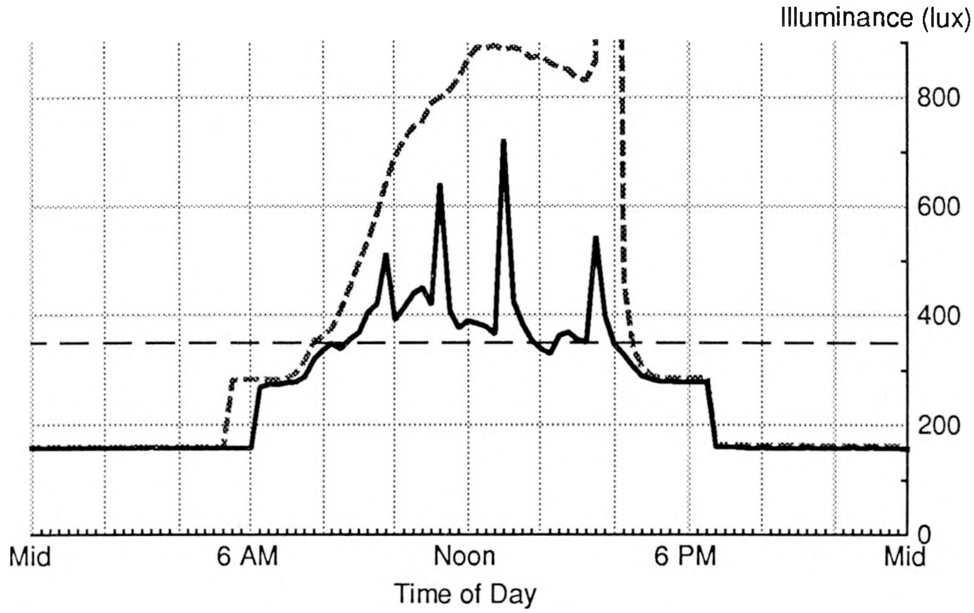
KEY:

Clear
13 December 1988

Mostly cloudy
17 December 1988

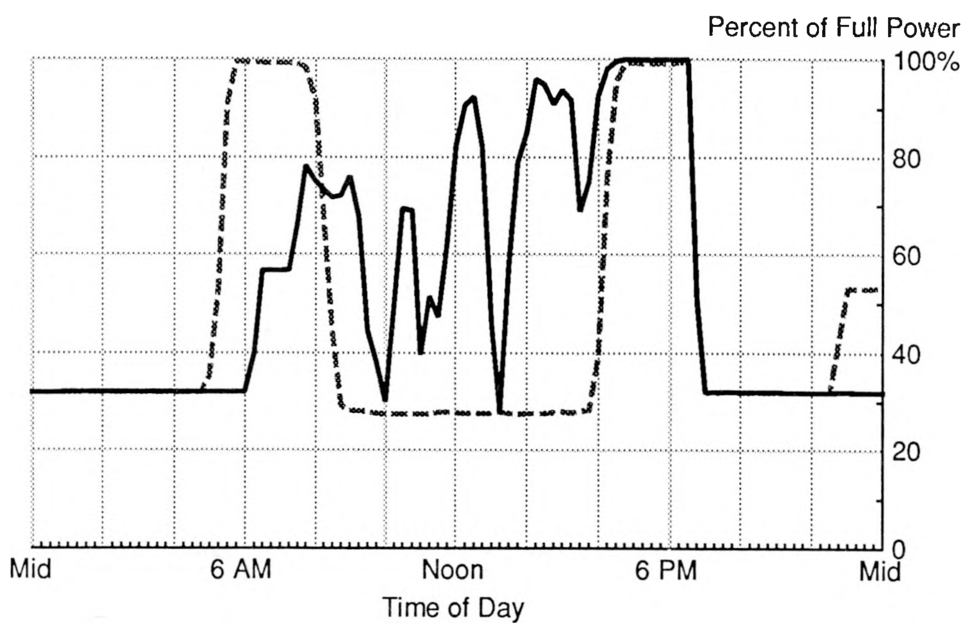
CLEAR vs CLOUDY INTERIOR ILLUMINANCE

No. 88 (10 meters from the exterior wall)



ELECTRIC LIGHT DIMMING

Circuit 9 (10 meters from the exterior wall)



Data are for winter conditions