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## APPLIED SCIENCE DIVISION

# Automatic Lighting Controls Demonstration

F. Rubinstein and R. Verderber

February 1990

APPLIED SCIENCE DIVISION

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*Research and Development*

# Automatic Lighting Controls Demonstration

**Customer Systems**
**Report 008.1-89.24**

**Project Manager: Matt Andersen**

**End Use**

**Final Report, March 1990**

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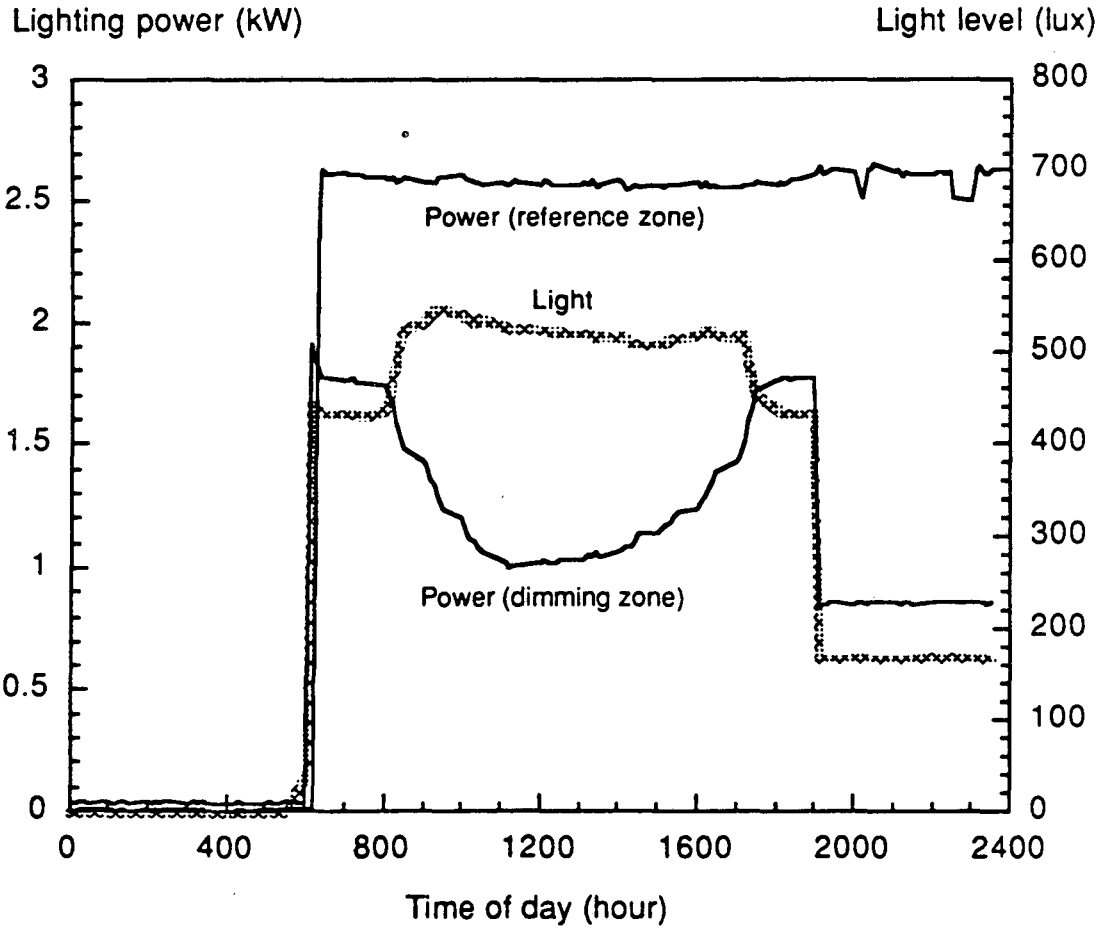
## EXECUTIVE SUMMARY

The purpose of this work was to demonstrate, in a real building situation, the energy and peak demand reduction capabilities of an electronically ballasted lighting control system that can utilize all types of control strategies to efficiently manage lighting.

The project has demonstrated that a state-of-the-art electronically ballasted dimmable lighting system can reduce energy and lighting demand by at least 50% using various combinations of control strategies. By reducing light levels over circulation areas (tuning) and reducing after hours light levels to accommodate the less stringent lighting demands of the cleaning crew (scheduling), lighting energy consumption on weekdays was reduced an average of 54% relative to the initial condition.




Typical day. Lighting power to dimmable lighting zone (north daylit) and non-dimming reference zone as a function of time of day for November 27, 1989. Light level maintained at eight feet in from the north window in north daylit zone shown with grey line. Right axis scale is light level in lux (500 lux ≈ 50 footcandles).

Using available daylight to displace electric lighting loads in daylit portions of the building (daylighting), and efficiently compensating for light losses due to lumen depreciation (lumen maintenance), we reduced lighting energy consumption by 55% (see figure on previous page) on winter weekdays and over 61% during the summer. Far larger savings were measured on weekends by significantly reducing the number of hours that the lights were left on when the space was unoccupied. The energy savings were significant and consistent. Equally important, the demand reduction during core operating hours (6 am to 6 pm) was measured up to 70% during the summer months.

The electronically-ballasted lighting system produced illumination at the workplane approximately 20% more efficaciously than the low-loss magnetically ballasted system it replaced.

A novel two-part control photocell was effective in allowing the daylighting and lumen maintenance strategies to be implemented simultaneously with the same hardware.

The projected cost of the electronic ballasts and associated controls resulted in a payback of less than two years under the operating conditions measured at this site. The cost of conserved energy for this system was about $0.02/kWh.

Project Manager Matt Andersen

Matt Andersen

Research Director David A Christensen

David A. Christensen

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Section 1

# INTRODUCTION

Lighting is one of the major consumers of electrical energy in commercial buildings. Because of this, lighting is often identified as a key area for reducing electrical energy use in the building sector. From the utility perspective, lighting in the commercial and industrial sectors is particularly significant because it is a major contributor to peak power demand. This report discusses an advanced lighting control system that provides appropriate light levels for the performance of visual tasks while reducing lighting energy consumption and peak demand.

The concept of using automatic lighting controls for energy management emerged after the 1973-1974 oil embargo. Prior to that time, controls were mainly used for their aesthetic functionality, i.e., dimming systems in conference rooms and theaters. After the embargo, however, several companies responded by developing lighting control systems and components and marketing them for managing and reducing lighting energy. These systems were designed to exploit one or more lighting control strategies, such as daylighting (dimming lights with available daylight) and scheduling (controlling light levels according to occupancy or time of day).

The initial lighting control systems required special magnetic dimming ballasts that could dim fluorescent lamps over a wide range. But these ballasts were (and still are) costly specialty items requiring non-standard wiring and high power switching equipment to dim. Subsequently, other lighting control products were introduced that could dim lamps with standard magnetic ballasts. However, the flexibility of these systems was limited because dimming was accomplished by conditioning the input power to the ballast, which requires switching high power. With the emergence of the electronic ballast in the late 1970s, dimmable electronic ballasts began to appear. These ballasts offered a major advantage over the previous technology in that the dimming control could be accomplished with low voltage control wiring and did not rely on expensive high power switching components. Various reports [Jewell 1980] had established that dimming fluorescent lamps with electronic ballasts was a cost-effective technique for curtailing lighting energy use. However, the reliability of the electronic ballast was not yet established at that time and therefore severely limited market penetration. By the mid 1980s, the reliability of dedicated (i.e., non-dimming) electronic ballasts had been generally accepted, in part because a major manufacturer of magnetic ballasts entered the electronic ballast market. Moreover, several successful major installations of electronic ballasts had been reported in the engineering literature [Abesamis 1989]. More recently, several companies have advanced the technology by developing dimmable electronic ballasts. With this development, it is

expected that the full potential of electronically-ballasted dimmable control systems will be realized.

Despite the increased use of controls in buildings, there is little information available concerning the magnitude of the savings achievable with these systems [Rubinstein 1984, Usibelli 1985]. Some early work has indicated that the savings attributable to the scheduling and daylighting strategies, at least, may be significant, but the few documented buildings do not provide potential end-users with much confidence that these new technologies are viable or can provide the consistent savings necessary to justify their additional cost.

The purpose of this work is to demonstrate in a real building situation the energy and peak demand reduction capabilities of an electronically ballasted lighting control system that can utilize all types of control strategies to efficiently manage lighting.

In the following section, we describe the demonstration site, the installed control equipment, monitoring instrumentation, and the methods used to implement the various control strategies at the site. The next section presents the results obtained by exploiting various combinations of control strategies. Results are presented both in terms of the energy saved per day and in terms of the lighting power reductions accomplished during core operating hours. The discussion section presents more detail on why the results were obtained and their significance. We then present recommendations both to PG&E for future work in this area and to the manufacturer to improve the control system.

Section 2

# METHODS

Demonstrations are an effective method for establishing the performance of an advanced commercial prototype under realistic operating conditions. In addition, demonstrations can uncover system design flaws that may not be evident in laboratory conditions; thus they are important to assess the commercial readiness of a product. From a market development standpoint, demonstrations can also help convince end-users that the technology under consideration is cost-effective, robust, and reliable. In the case of lighting controls, demonstrations are especially effective since lighting controls save energy not *because* they are used but rather because of *how* they are used. For example, if a newly installed lighting control system is foolishly programmed to leave the lights on excessively when no occupants are present, energy use will not be diminished but increased. Lighting controls demonstrations therefore inform end-users how to use controls effectively so that energy use will be curtailed without compromising building function or occupant productivity.

## EXPERIMENTAL DESIGN

An experimental protocol was designed for this project that would allow the savings potential of the lighting control strategies (scheduling, daylighting, tuning, and lumen maintenance) to be analyzed both separately and in appropriate combinations. Initially, we characterized the state of the lighting system before installing the electronic ballasts and controls by measuring the power input to the four lighting circuits serving the demonstration site and measuring the illumination levels provided. After installing the system (electronic ballasts, new lamps, and controls), we repeated the measurements to assess the change in lighting system performance with respect to light output, input power, and efficacy. The experimental design called for a sequence of tests ranging in duration from three weeks to several months during which we measured the performance of the new system and its capabilities to exploit the various control strategies.

The first task was to characterize the operation of the lighting system at the demonstration site before making any modifications to it. Photometric measurements were taken on 3/1/89 at various task locations throughout the space to assess the illuminance levels as delivered by the original system and repeated on 5/4/89. The input power levels to each of the four major control zones were measured with watt transducers installed in the electric room. The monitoring equipment was installed on 4/11/89 along with the data acquisition system.

Once the existing system had been assessed, the electronic ballasts, control wiring, and new lamps were installed in three control zones. The control photosensors were also

installed at this time, but closed-loop photocell controlled operation of the lighting system did not commence until August. The retrofit took place over two days (5/6/89 and 5/7/89). During the initial "breaking-in," the lighting levels were set to 67% of full light output by adjusting potentiometers on the six controller boards (see Section 2).

There are four basic strategies that can be used to reduce energy consumption for lighting with lighting controls: scheduling, daylighting, lumen maintenance, and tuning (see glossary in Appendix B). In addition, there is a fifth strategy, load shedding, that reduces lighting power at times of peak demand (its economic advantage is based upon reducing peak demand charges rather than saving energy). These strategies have been identified in previous research and the energy savings attributable to certain strategies, particularly daylighting and scheduling, have been measured in a limited number of building sites. Despite this body of research, well-documented studies of systems exploiting all these techniques are non-existent. Thus demonstrating the energy savings from the strategies in combination was a major objective of this project.

## BUILDING DESCRIPTION

### Physical

The demonstration site selected was one portion of the sixth floor of an office building located in the city of Emeryville in the San Francisco Bay Area. The entire sixth floor of this building, the Watergate Tower 1, is leased by the Insurnet Company. The site area is approximately 4,544 square feet, or roughly 22% of the sixth floor's gross area. The building has a relatively unobstructed view to the north and south. As with most portions of the Bay Area, the weather conditions are variable, with frequent periods of morning fog.

The building architecture is conventional, with windows running the length of all the exterior walls. The windows are 6.5' high measured from the top of the window sill (40" from the floor) to just below the level of the dropped ceiling. The windows are standard clear glass with an estimated transmittance of 88%. The two window-walls running along the north and south sides of the demonstration site are equipped with loosely woven heavy drapes that can be drawn to reduce thermal and visual discomfort when the sun is low in the sky. Based on our visual observations, the occupants on the north side never close the drapes, apparently because the only time direct sun penetrates is late in the afternoon when most of the occupants have left. On the other hand, we observed that during the winter months, the occupants on the south side of the building close the drapes on sunny days to block the direct sun.

### Functional

Almost all the people working on this floor of the building use computer terminals for a significant portion of their work. Because so many individuals use CRT screens, the overhead lighting system had been previously retrofitted with low angle brightness panels (see below).

Many of the individuals work standard shifts, i.e., 8 am to 5 pm. However, since the insurance company also does business overseas, a few individuals work at least a few hours during the graveyard shift. This is significant because prior to the demonstration project, the lights throughout most of the site were left on at night to accommodate the needs of just a few individuals.

The office area on the south portion of the site consists of partitioned cubicles branching off a linear circulation aisle. These partitions are 6' high and colored a medium light beige. Though the partitions are not dark, their height is sufficient to block much of the daylight that would otherwise penetrate deeper into the space.

In contrast, the north zone is much more open: effectively a bull pen with only a few low partitions between some desks. This zone is quite pleasing aesthetically with its panoramic view of the Bay. Moreover, since it faces north, there is little glare from the windows. As in the south zone, CRT screens are ubiquitous.

## EXISTING LIGHTING SYSTEM

The existing lighting system in-place at the demonstration site consists of four-lamp lay-in fluorescent troffers on 8-foot centers. The ceiling lighting system operates on 277 VAC. Thirty-five-watt lamps and a mixture of standard and energy-efficient core-coil ballasts of various ages were in use throughout the site. Most occupants use only the overhead lighting but we observed that a few individuals use portable desk lamps to supplement (or replace) the overhead lighting.

The original lenses had been previously replaced with 1-inch "paracube" type louvers to reduce the amount of high angle light produced by the luminaires. These louvers also make it difficult to see the lamps unless one is directly underneath one looking up. While relatively inefficient in terms of fixture efficiency, the paracube louvers greatly reduce the problem of ceiling fixtures reflecting in the computer screens by reducing high angle light.

Prior to installation of the controls, the lighting system was controlled by rotary-type switches installed at the entrance to the office space. If the lights were not already on, individuals entering the space would rotate one switch to indicate their lighting zone and

then depress an adjacent switch to activate their lights. The shape and size of these zones was dictated by the existing branch circuit wiring for the lighting system. Generally, the occupants did not use the entrance switches to any degree. This function was left to a security guard who turned the lights off fairly regularly at 3:30 am and turned them on at approximately 5:00 am.

## DEMONSTRATION SYSTEM

### Three-lamp electronic ballasts

The high-frequency electronic fluorescent lamp ballasts used in this demonstration were advanced commercial prototypes manufactured by the Braydon Corporation. The ballasts convert the supply 60 Hz alternating current to 65 kHz, thereby increasing lamp efficacy and virtually eliminating flicker. Each ballast operates three lamps rather than two, allowing higher system efficiency by distributing the ballast losses over a larger number of lamps.

The ballasts can be dimmed over a wide range: from 100% to approximately 20% of full power. Light output at maximum dim is approximately 15% of full light output. Dimming is achieved either by means of a low voltage control signal to the ballasts or by manually adjusting a potentiometer mounted directly in the ballast. In an installation, each ballast is connected to a pair of wires (the control wiring) which connect all the ballasts in a given control group. All the ballasts in a control group dim in unison in proportion to the amplitude of a 5 kHz square wave transmitted over the low voltage control wiring.

Prior to installation, all the ballasts were burned-in and tested for 100 hours at the PG&E test facility in San Ramon.

### Controller

The controller is an electronic circuit that provides a voltage signal to control the light levels for all the ballasts in a control group. One controller is required per control group. The controller board can be used to set the illumination level manually (from a potentiometer on the board) or automatically in response to a signal from ceiling-mounted photocells. In addition, the controller serves as the interface between a building energy management system (EMS) and the lighting system. Thus time-of-day control can be executed by using the EMS to provide appropriate command voltages as a function of time of day and year. When the controller is in automatic mode (i.e., photocell control is in operation), the set point light level that the controller will maintain can be changed as a function of time by the building energy management system. The controllers used in this demonstration project were also manufactured by the Braydon Corporation. We mounted the controller boards in

the electric room but for many installations it would be more convenient to mount the controller boards nearer the controlled lights in order to facilitate system calibration.

### Control wiring

The control wiring consists of pairs of teflon-coated wires (class II) running to each of the control groups. Within a given control group, each ballast is wired to the control string in parallel. The control wiring was run at the same time that the lighting control retrofit was performed. During installation, the control wiring into and out of each fixture was routed through knockouts at opposite ends of each fixture.

### Photocells

To take advantage of available daylight, the control system requires photocells to measure the illumination in the space (daylight plus electric light). Novel two-part photocells developed by Braydon Corporation were used to permit compensation for lumen depreciation effects as well as permitting daylight-linked control. These photocells were mounted in the ceiling immediately adjacent to selected fixtures in each control group (see Figure 2-1). Each photocell consisted of two silicon photo-diodes mounted in a hollow plastic stalk (Figure 2-2). One photocell was mounted at the end of the stalk aimed downwards into the space, while the other was mounted higher up the stalk and aimed upwards (at about 45° to the horizontal) at the lamps of the immediately adjacent fixture. The lower cell, fitted with an opaque shield to prevent it from seeing out the window, is used to provide a measure of the daylight component that is approximately proportional to the daylight arriving at the task surface (see Verderber [1989] for a more complete discussion of this topic). The upper cell is sensitive to the brightness of the nearby electric light as determined by the angle of acceptance of the photocell. By raising or lowering the stalk, the relative contribution of the upper cell to the total signal can be varied. When the stalk is lowered, the output of the upper cell will increase since it sees a larger area of the lamps while the output of the lower cell remains essentially constant. Calibrating the response of the photo-control system consists of adjusting the height of the stalk and trimming the set point level to the correct value for the specific lighting conditions. The calibration process is described in detail in section 3.

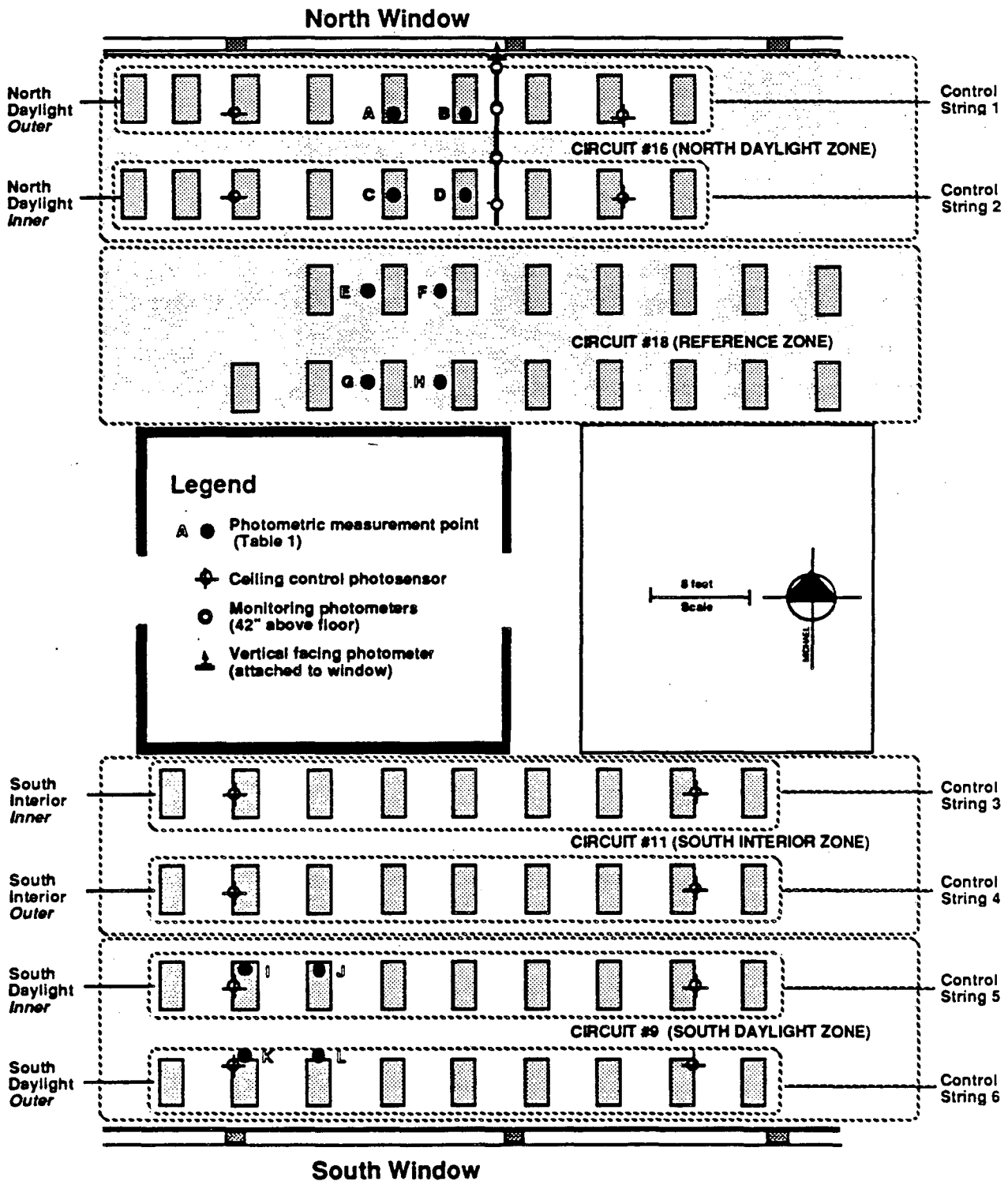


Figure 2-1. Plan view of demonstration site showing control zones and location of photometric instrumentation

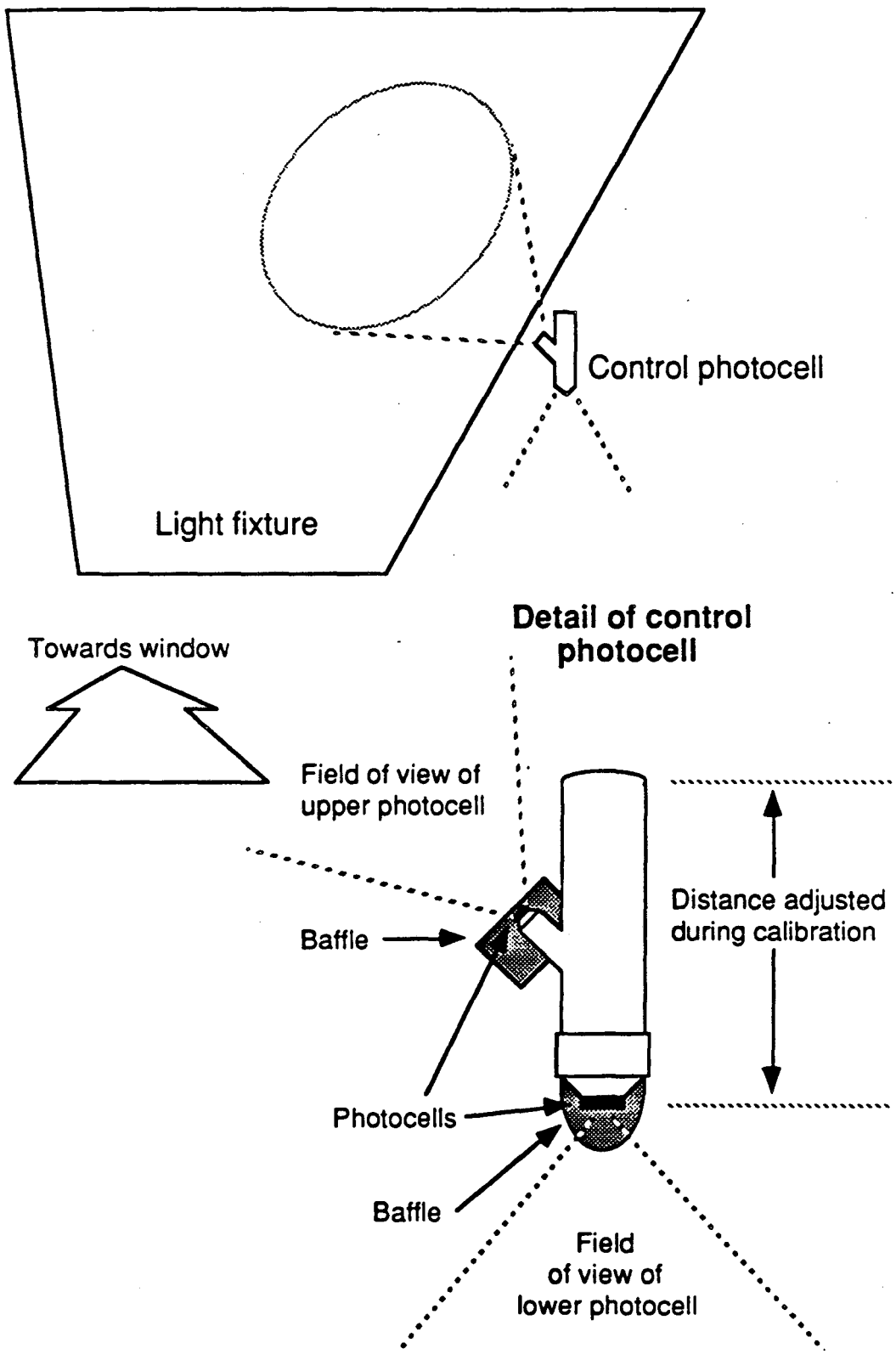


Figure 2-2. Location of control photocell relative to fixture. The distance of the photocell from the ceiling was adjusted as described in text.

### Input control from digital-to-analog converter

The controllers are designed to accept analog inputs (4-20 mA current loop) from an energy management system (EMS) for changing the supplied illumination level at different times of the day or in response to a demand monitor. For the purpose of this demonstration, the controllers were modified to extinguish the lamps when supplied with a 5-volt signal from an EMS input. When the input voltage supplied by the EMS was 0 volts, the controller would command the ballasts to full power. By supplying voltages between 0 and 4 volts, any intermediate light level can be achieved. (Input voltages between 4 and 5 volts cause unpredictable results and, following the manufacturer's advice, we avoided this region). Supplying a 5-volt input caused the lamp current (and light output) to go to zero, but the ballasts still consume a small amount of power (approximately 2 watts/ballast).

The Watergate Tower is not equipped with an EMS capable of providing the variable command voltages to the controller as described above. Consequently, for purposes of this demonstration, we used a Campbell Scientific CR-10 Data Acquisition and Control Unit with two 4-channel multiplexed digital-to-analog (D/A) converters to provide the necessary voltage supply functions. We programmed the CR-10 to schedule the lighting operating hours to provide reduced light levels for the cleaning crew. In addition, as described below, the CR-10 was used to process switch inputs that were activated either from a preprogrammed schedule or from an override system that the occupants could use to switch their lighting zones on and off as necessary.

Configuring the controller as described above causes the system to run in a reverse "dead-man switch" mode. Should the D/A malfunction and fail to supply any input voltage to the controller, the lights will go to full light output providing the necessary illumination for safety and security reasons.

### CR-10 used for scheduling control

During the scheduling tests, we programmed the CR-10 to schedule the operation of the lighting system in the following manner. First, we programmed the CR-10 to implement a control scheme for weekday operation. This schedule drives the lights to a reduced light level (~35% of full power) at 5 am and switches them off at 2 am the following morning. (This schedule was derived based on conversations with management to accommodate the anticipated schedule of the cleaning crew.) Thus, in the absence of any overrides, the CR-10 would switch the lights on to reduced level for 21 hours a day on weekdays. (No schedule was imposed on weekends). Then, we programmed the CR-10 to process switch inputs as described below.

## Switch input processing

In this site, an existing relay-based switching system (General Electric Programmable Control system) was already in operation to control the lighting and HVAC systems in other portions of the Watergate Office complex. The GE system can switch latching relays on and off based on any desired switching schedule or on inputs from a telephone interface system. We elected to use this system in conjunction with the CR-10 described above to automatically switch the lights on at the beginning of the work day and to process switch inputs that can be activated by the occupants using their touchtone telephones.

We assigned three relays to the system, each relay corresponding to a control zone as described below. Low voltage wires were run between these relays and the CR-10 in the sixth floor electric room. The CR-10 was programmed to check the state of the relays at 5-second intervals and to switch on the appropriate control strings to nominal full light output upon detecting a closed relay. The GE system, in turn, closes or opens the relays either by means of a preprogrammed schedule or in response to the telephone interface. Building personnel programmed the switching system to close all three relays at 5 am on weekdays and open them at 6 pm. When the CR-10 detected a closed relay, it commanded the controllers to drive the lamps at nominal full power. Once an opened relay was detected, control of the light level "dropped through" to the CR-10's underlying reduced lighting schedule discussed previously.

In addition to the preprogrammed schedule, the GE system can also switch a particular relay when so instructed by the telephone interface. This provided the link by which the occupants could restore their light levels to full, should they need to work after 6 pm. Furthermore, the system was instructed to override any telephone-input overrides at 3-hour intervals. (This last measure was done to prevent occupant overrides from keeping the lights on unnecessarily if the occupants neglected to switch off the lights themselves.)

A schematic of the entire system including the associated control hardware is shown in Figure 2-3.

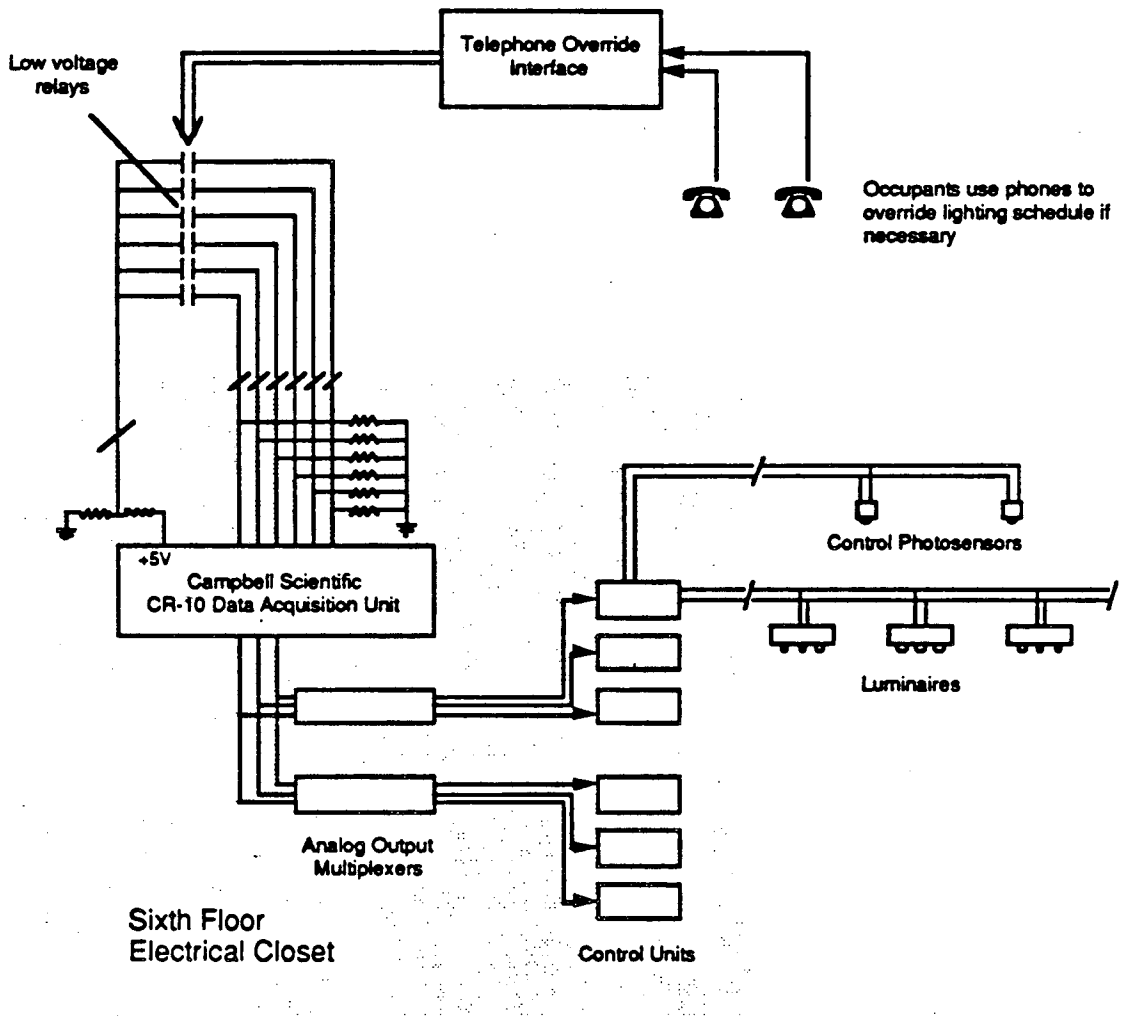


Figure 2-3. Schematic showing lighting control system with related equipment

## LAYOUT OF CONTROL GROUPS

Installing lighting controls and implementing the control strategies requires subdividing the building space into appropriate control groups. A control group is defined to be a group of lights which are controlled together to supply the same illumination level. Generally, these control groups are organized to accommodate the functional requirements of a desired combination of strategies. For example, to use available daylight, one should organize control groups according to the building's physical geometry and the placement of windows. In a retrofit situation, there may be the additional requirement of preserving existing lighting wiring to minimize installation costs.

Often, a control group will correspond to a portion of a branch circuit or the entire circuit. At the Watergate Tower 1, we needed to accommodate the daylight distribution from the vertical glazing as well as the scheduling requirements. Since the daylight workplane light levels drop rapidly as one moves away from the window (especially in the partitioned south zone), we elected to control each string of lights running parallel to the window walls. The existing branch circuit wiring dictated that pairs of these control strings be operated off a single branch circuit. As shown in Figure 2-1, this grouping resulted in the formation of six independently controllable strings of lights energized by three branch circuits. The control strings were numbered from 1 to 6 as shown in Figure 2-1 and will be referred to as such throughout this report. Circuit zone 9 served the area immediately next to the south window wall and encompassed control string 6 (nearest the window) and string 5. Circuit zone 11 is the interior area on the south side and includes control string 3 and control string 4, which is directly over an aisleway. Circuit zone 16 served the area next to the north windows and included control strings 1 (nearest the window) and 2.

Each control string requires at least one photocell input for daylight and/or lumen maintenance control. We used two photocells per string with photocells mounted near the ends of each string. The exact photocell position is dictated by practical considerations such as avoiding locations that may be susceptible to spurious light reflections (such as sunlight reflecting off plastic printer covers).

In addition to the six control strings, we established another area, circuit zone 18, to serve as a reference zone against which to compare the performance of the controllable zones. Although such a group would ordinarily be termed a control group, we use the term reference zone throughout this report to avoid confusion.

## MEASUREMENT INSTRUMENTATION

### Electrical measurements

The lighting power and current to the four branch circuits servicing the demonstration site (including the reference zone) were monitored with power and current transducers installed in the electric room. These transducers accurately measure true RMS power and current regardless of any current wave shape distortion. All the transducers were mounted in an electrical enclosure mounted adjacent to the lighting circuit breaker panel. The watt and current transducers were recently checked for linearity and calibrated at the LBL Meter Shop.

Measuring the power at the branch circuit level was the easiest and most convenient method for determining lighting energy use. One disadvantage, however, is the fact that each branch circuit encompasses two control strings. This meant that we could only determine the total power to pairs of control strings rather than the power to each string individually.

### Photometric measurements

Light levels at various locations in the site were monitored with an array of photometers. These color- and cosine-corrected photometers, Li-Cor Model 210S, are purely for monitoring purposes and should not be confused with the ceiling-mounted photocells used by the dimmable lighting system to control the electric light levels. To get a representative measure of the daylight levels at varying distances from the side windows, we mounted the photometers in a linear array perpendicular to the north window wall. Four of the five photometers were affixed on 4-foot centers to a low partition separating rows of desks. As shown in Figure 2-1, the photometer nearest the window was approximately 8" from the inside window surface while the outermost photometer was 12' further in. In addition to these four photometers, we mounted one photometer directly to the window pointing outwards. This photometer provided a measure of the vertical daylight illuminance on the window.

### Data Acquisition

The transducer outputs were recorded using a Campbell Scientific 21X Data Acquisition and Control Unit. This unit can read up to 16 analog inputs at 12 bits precision. We programmed the CR-21X to scan and record the outputs from all the watt and current transducers every 10 minutes. This scan interval has proven to be a useful compromise of temporal precision and storage limitations. The CR-21X was programmed to automatically dump its stored values periodically onto a audio style tape cassette unit (also marketed by Campbell Scientific).

For the photometers in the North zone, we used another CR-10 Data Acquisition Unit to record the photometer outputs. The CR-10 was programmed to scan all the photometers every minute and to store averages and standard deviations every ten minutes. Data was stored on storage modules (also marketed by Campbell Scientific).

Using two data acquisition systems, one for electrical transducers in the electric room and one for the photometers out on the office floor, eliminates the need for running long signal leads back to the CR-21X in the electric room.

In addition to the automatically acquired data, we measured light levels at periodic intervals using a hand-held Tektronix J-16 photometer.

The data stored on the audio tapes and storage modules were periodically downloaded to a PC and then transferred to the Lighting Group Sun 3/60 workstation for processing and analysis. The data reduction and analysis software was developed by Greg Ward of the Lighting Group under an earlier contract to EPRI [Verderber 1989].

## LABORATORY BENCH MEASUREMENTS

Before the ballasts were installed at the demonstration site at the Watergate Building, we performed a series of tests at LBL on two representative Braydon ballasts to measure the efficacy, ballast factor, filament voltages, dimming range, and current harmonic content. These measurements were performed under standard ANSI test conditions with the lamps operated in a 25°C ambient temperature (minimum lamp wall temperature 40-42°C). On standard 40-watt F40 T-12 cool white lamps we measured the lamp/ballast system efficacy to be 80 - 81 lumens/watt with 119 watts input to the ballasts. Using the potentiometer on the ballast, we could dim the lamps to 8 - 10% of full light output with power input of 15 - 18% of full power. The ballast factor was found to be between 1.06 and 1.08. The cathode voltages averaged 2.15 volts with little change at different dimming levels. Finally, we found that the third harmonic current content was 13-15%. These tests indicated that the ballast specifications were appropriate for installation at the demonstration site.

## INSTALLATION

Installation consisted of replacing the existing 2-lamp ballasts with the 3-lamp electronic ballasts in all the fixtures in the six control strings. Note that we replaced all the ballasts in the demonstration area even in those fixtures with non-functional ballasts. Control wiring was run to each fixture in a string and wired back to the controller boards in the electric room. Also, two control photocells were installed for each control string and the photocell wiring run back to the electrical room. Maintenance consisted of simply wiping out any dirt in the fixtures and relamping with new 40-watt standard cool white fluorescent lamps. (Although this system can operate 35-watt lamps at full light output, dimming performance with these krypton-filled lamps is limited and they should be avoided [Verderber 1989].)

Since the fixtures in place used four lamps (one 2-lamp ballast running the inboard tubes with the second operating the outboard lamps), it was necessary to remove one lamp to accommodate the 3-lamp electronic ballast. Although this would seem to imply a compromise in light level, an electronic ballast can provide more light for the same input power than a conventional energy-efficient core-coil ballast. Moreover, these particular ballasts have a relatively high ballast factor (between 1.07 and 1.08 as measured in lab bench tests) and we were replacing 35-watt lamps with 40-watt lamps that produce proportionately more light. Also, since the ballast factor for the original 35-watt lamp/ballast system is only 0.87, we anticipated little change in fixture light output.

Although we were initially concerned that the removal of one lamp would cause undesirable brightness patterns on nearby walls, our fears proved unfounded. The paracube louvers cut off the high angle light in such a manner that it is very difficult to tell which of the outboard tubes was removed merely by looking at the lighting patterns on the walls.

To simplify the installation, existing lampholders were replaced with prewired lampholder assemblies. The entire changeout and installation of the ballasts in the six control strings was carried out by the Goldsmith and Lathrop maintenance crew on a weekend and took approximately 20 man-hours for 54 fixtures. At $50/hour, this translates to an installation labor cost of $18.50/fixture. This includes the cost of running the control wire and would undoubtedly be less expensive in a new construction job or major renovation.

In addition to the measures undertaken in the six control strings, the maintenance crew also wiped out any dirt in the fixtures in the reference zone and relamped with new 35-watt cool white lamps.

## Occupant notification

The occupants were alerted to the lighting modifications by way of a memorandum which is reproduced in Appendix A. The occupants were also given instructions for activating the lighting system in their zones using the telephone override system.

Although the opinions of the occupants were not formally solicited, informal conversations with the office personnel indicated that they had little difficulty adapting to the new lighting system or switching arrangement.

## Photocell calibration procedure

Calibrating the response of the photocells is a critical step in establishing a properly-responding photoelectrically-controlled lighting system. Experience at the Lockheed building in Sunnyvale, CA [Benton 1989] has shown that without proper calibration and maintenance, the savings potential of a daylight-responding lighting system can be severely compromised. In the present demonstration, proper calibration was especially critical since, unlike the Lockheed building, we were using a unique photocell system that could compensate for lumen depreciation changes as well as responding to available daylight.

To calibrate the response of the system, we first selected the specific locations (i.e., the control points) where we would provide the design light level. (Because the daylight levels drop rapidly as one moves away from the window, it is a physical impossibility to provide the design light level everywhere.) For simplicity, the control points were chosen to be 2.5 feet above the floor (desktop height) immediately underneath each ceiling-mounted control photosensor. Since there were two ceiling-mounted photocells per control string, there were also two control points per control string.

We performed the calibration during the day at a time when the daylight contribution to the total illuminance at each control point was less than the design level of 50 fc. This assured that some electric lighting would be necessary to supply 50 fc of total illumination at the control point.[1] With the electric lights off, we recorded the daylight illuminance at the control point using a hand-held photometer, and the voltage output from the control

[1] A design light level of 50 footcandles (538 lux) was selected to be consistent with lighting levels provided in the reference zone.

photocell. From this measurement, the control photocell set point level is determined[2]. For example, if the control point illuminance was 30 fc and the photocell output was 1.4 volts, then the control photocell set point level was 2.33 V (50 fc ÷ 30 fc x 1.4 V). A trim pot in the controller was adjusted to make this voltage the set point voltage. Once the set point level was calculated and set, it was necessary to adjust the photocell's sensitivity to electric light relative to daylight by adjusting the distance that the control photocell projected below the ceiling plane (see Figure 2-2). This was accomplished by turning on the electric lights in the zone, setting the controller to automatic closed-loop control and measuring the resultant total illuminance at the control point. If the light level at the control point was below 50 fc, we raised the photocell up a small amount. (The photocell was lowered a little if the light level was too high.) We measured the light level again and readjusted the photocell depth until the design level was achieved. As a final check, we then closed the drapes to greatly reduce the daylight level and checked to make sure that the design light level was still provided.

## TROUBLESHOOTING

As would be expected in any demonstration project, unforeseen circumstances arise that must be addressed. Since this is a new system, we encountered several operational problems that were diagnosed and resolved as discussed below.

### Shorting of control wiring to fixture housing

After running the scheduling tests for a few weeks, it was discovered that the lights were not turning off during the early morning hours as intended. The problem was eventually traced to the control wiring. When the control wiring was run between neighboring fixtures, the wire had to penetrate the fixture housing through knockouts. Unfortunately, these knockouts were not deburred which resulted in abrasion of the teflon wire. This caused a subsequent short of the control signal to the fixture case. Because all the control wiring is low voltage, there was never any shock hazard. In addition, the fact that the controls and ballasts worked at all when supplied with a distorted control signal testifies to the robustness of the electronic controls. The problem was eventually solved by wrapping the control wires with electrical tape near the knockouts.

In future installations of this type, we recommend that grommets be used for all knockouts to prevent such problems.

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[2]When properly calibrated, the set point level is the specific control photocell output voltage that the system will attempt to maintain under all daylighting conditions by raising or lowering the electric light level.

## Premature lamp failure in deep dimmed mode

After the installed lighting control system had been operational for about three months, we observed excessive end-blackening in a number of lamps. Furthermore, in some lamps, sputtering of the lamp cathodes became sufficiently severe that the lamps failed. The problem was found to be most acute for the lamps in string 4, presumably because that string had been operated in heavily dimmed mode for a longer time than the other control strings. Initially, we were puzzled because lab measurements had shown that the ballasts were supplying an average of 2.15 volts to the lamp filaments, a value only slightly lower than the ANSI required minimum cathode heater voltage of 2.5 V. We were fairly certain that the solution lay with increasing the cathode heating voltage but did not know the best method to achieve it. Two other factors served to confuse matters further. First, when the lighting system was initially relamped, an off-brand type of lamp was mistakenly substituted for the originally specified name brand lamp. It was thought that these lamps might be sub-standard and have lower quality filament construction (and therefore higher impedance) than name brand lamps. If this was the case, then the cathode voltages might drop to a point where lamp life was compromised. Second, the prewired lampholder assemblies used to expedite the ballast changeout employed standard brass contact lampholders rather than the silver-plated contact lampholders recommended for some dimming applications. It was thought that the increased contact resistances might also reduce the cathode voltage.

Since we had to re-lamp anyway to start the experiments with a "clean slate," we decided to first try to solve the problem by re-lamping the demonstration site with standard name brand lamps from a regular supplier. This did not solve the problem, however, and lamps continued to show signs of excessive lamp-end blackening and premature failures. At this point, the ballast manufacturer modified each ballast in order to insure that 3.5 - 4 volts was supplied to the cathodes at all dimming levels. This was a fairly simple (if tedious) modification requiring changing the values of four capacitors in each ballast. The ballast modifications were first performed on just two of the six control strings. Subsequent on-site measurements showed that the cathode voltages in the newly-modified ballasts remained at or above 3.5 V even when substantially dimmed while the unmodified ballasts had cathode voltages as low as 1.9 volts. There were no signs of lamp-end blackening in any of the luminaires with the modified ballasts. The manufacturer then modified the rest of the ballasts in the remaining four strings and, during the last week of September, we re-lamped the demonstration site again.

Since increasing the lamp filament voltage by the modification described above, the problem with lamp-blackening and premature lamp failure has apparently been entirely eliminated. During the 6-1/2 months since the second re-lamping, there has been no sign of blackening in any lamp, and no lamps have failed. Since the lamp blackening encountered previously occurred after only a few weeks of operation, we are confident that

the problem with premature lamp failures has been solved. However, our experience in this matter argues strongly for maintaining at least 3.5 V to the cathode heaters to assure good lamp life.

Section 3

# RESULTS

## DAILY LIGHTING ENERGY USE: THE BIG PICTURE

Between the date when we installed the electrical monitoring equipment (approximately three weeks before the retrofit) and the end of 1989 (the end of this contract), we recorded approximately nine months' data on the power input and light output performance of this lighting system under varying conditions. To provide the reader with a "broad brush" look at the long-term results, we split the data into two groups: 145 weekdays and 60 weekend days. We then calculated the daily energy use for each circuit zone in two ways: over the entire day, and between the hours of 6:00 am and 6:00 pm only (core operating hours). Dividing the data up in this manner allowed us to distinguish between the savings accrued over the entire day from that captured only during the building's core operating hours. These results are graphed in Figures 3-1 through 3-4. Several patterns immediately emerge from these graphs. First, it is apparent that both the weekday and weekend lighting energy use dropped dramatically after installation of the controls and remained that way regardless of the particular combination of strategies under test at a given time. *During the eight months after installation, the energy use in the control circuits was generally 45-60% of the energy used in the unmodified reference zone.* The data also show that the energy use during core hours was less variable than the energy use over all hours. This was expected since the non-core hour usage is determined by the occupant overrides and was quite variable from day to day.

Another trend emerges from the core hour data: the energy use from the reference zone dropped slowly but significantly until September and October, when it rose sharply in two steps to roughly its initial value. The explanation is a simple one. Seven standard ballasts (out of 34 total) failed one by one in the reference zone and were not reported by occupants.[3] The failed ballasts were eventually replaced but the reference zone data were as a result not as "clean" as they should have been. This introduces a complexity in the interpretation of the subsequent data. Should the lighting energy use actually measured prior to the installation be considered the "baseline" energy usage or should the measured usage be corrected to account for what the usage would have been if all ballasts had operated? In this section, we present the results as measured without correcting for the effect of rehabilitating the lighting system during the retrofit. At the end of the results section, we then calculate what the baseline energy use would have been assuming all the

[3]After the 7 ballasts were replaced, another ballast in the reference zone was found to be cycling on and off due to a defective thermal protection switch. This caused a negligible effect on the energy use data.

ballasts were operating. The implications of this calculation with respect to measured energy savings is then treated in the discussion section.

Having shown the daily energy use patterns for all the collected data, we now discuss selected data subsets that illustrate the energy savings from the various combinations of strategies tested.

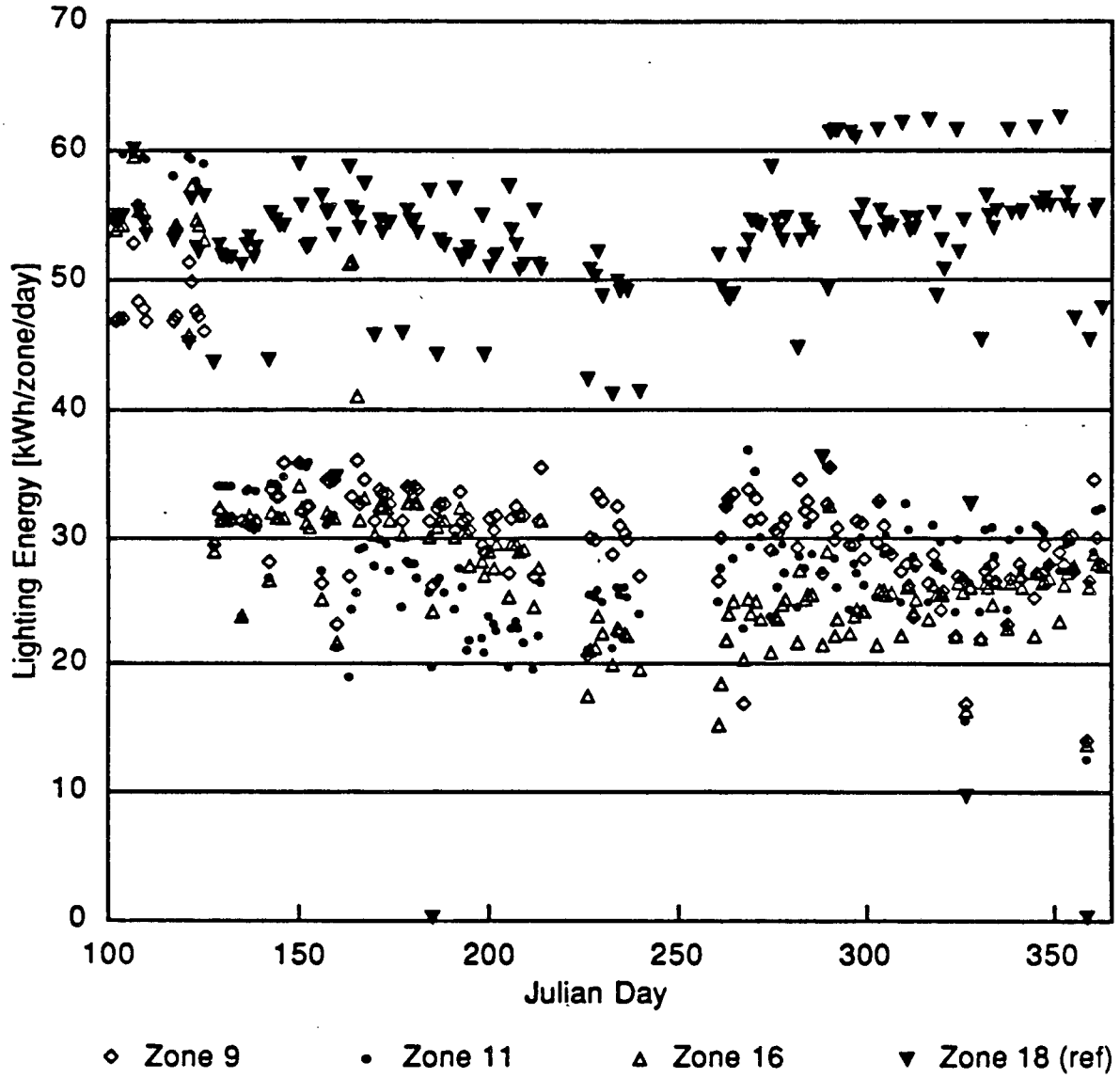


Figure 3-1. Plot of daily energy use on weekdays. Julian day is number of day of year beginning with January 1, 1989. The dimmable electronic ballasts were installed in zones 9, 11, and 16 on julian day 127.

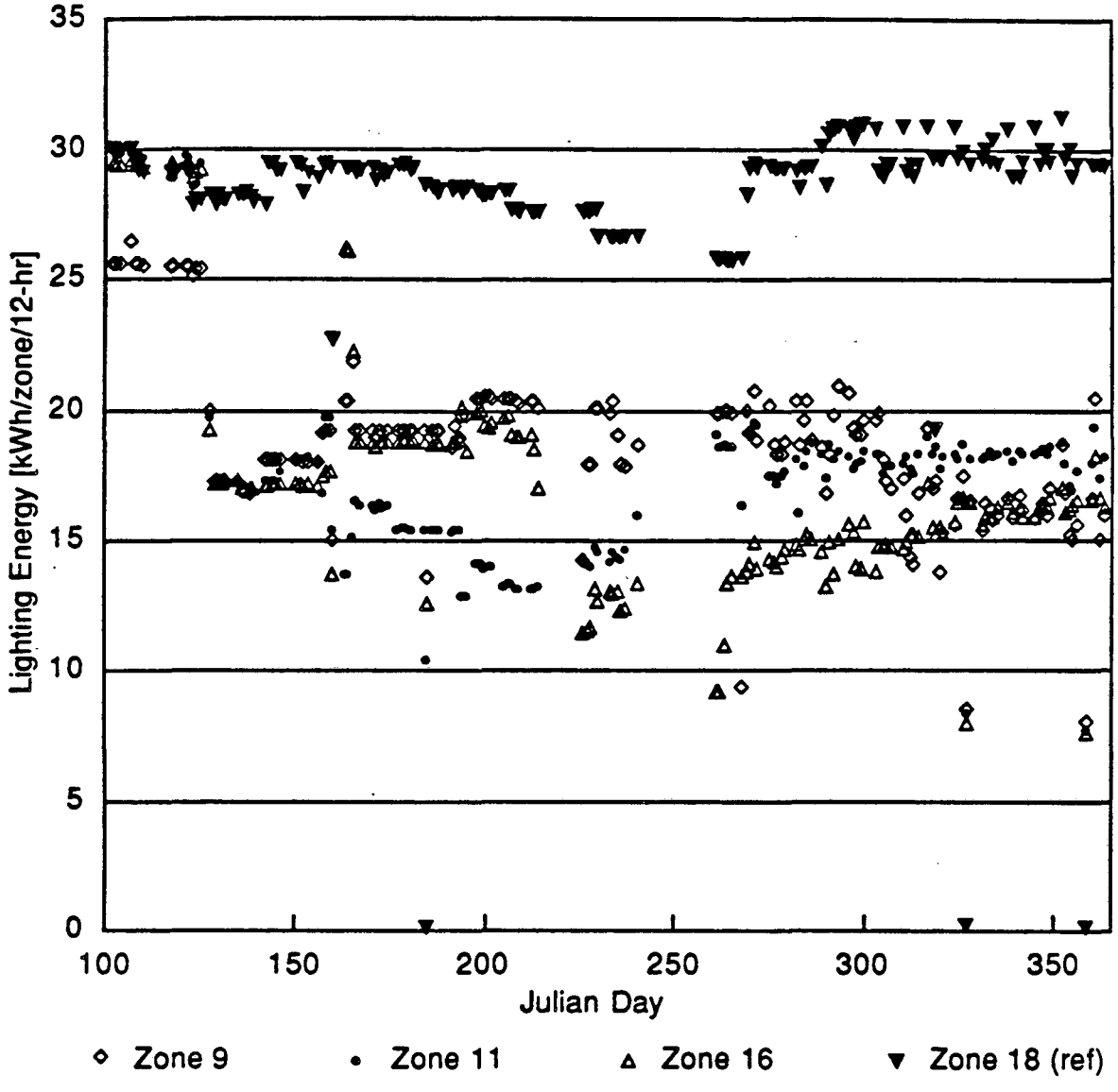


Figure 3-2. Plot of energy use during core hours only (6 am to 6 pm) on weekdays. Julian day is number of day of year beginning with January 1, 1989. The dimmable electronic ballasts were installed in zones 9, 11, and 16 on julian day 127.

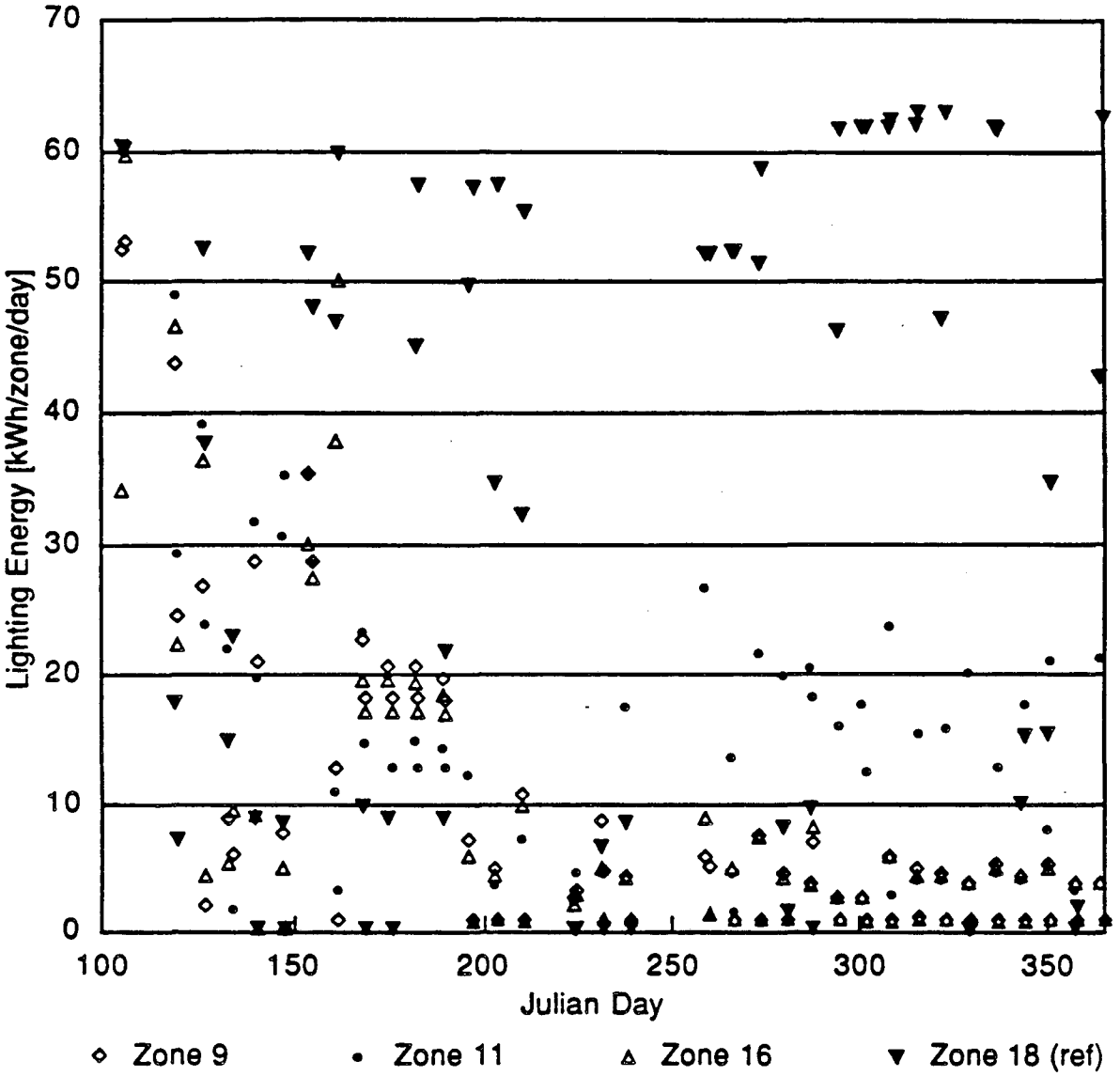


Figure 3-3. Plot of daily energy use on weekends. Julian day is number of day of year beginning with January 1, 1989. The dimmable electronic ballasts were installed in zones 9, 11, and 16 on julian day 127.

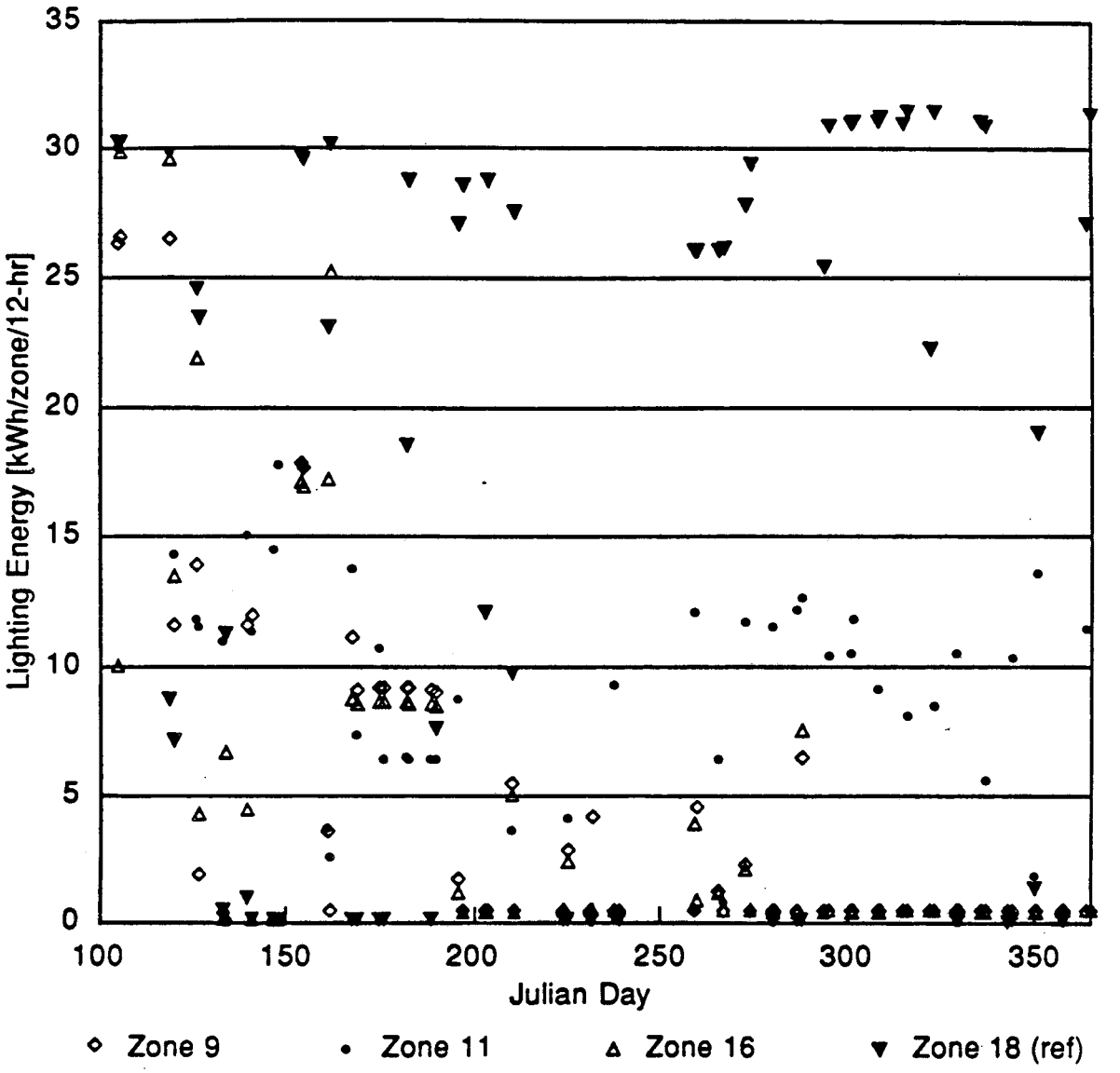


Figure 3-4. Plot of energy use during core hours only (6 am to 6 pm) on weekends. Julian day is number of day of year beginning with January 1, 1989. The dimmable electronic ballasts were installed in zones 9, 11, and 16 on julian day 127.

## PREINSTALLATION CHARACTERIZATION

Our first task was to characterize the state and energy performance of the lighting system before implementing any retrofit measures. We began collecting power and current data from the four lighting zones on April 11, 1989. Since the electronic ballasts and other controls were not installed until May 7, we had several weeks of baseline data with which to characterize the hours of lighting operation and installed lighting load.

A typical day's data (4/27/89) from the site prior to the retrofit are shown in Figure 3-5. The lights in all four zones were on steadily except for 90 minutes between 3:30 am and 5:00 am. This pattern was relatively typical of weekday usage and we predicted considerable potential for reducing lighting usage by more effectively scheduling the operation of the lighting.

We found that lighting use patterns were more variable on weekends, with lighting either on 24 hours a day or off until midday and then on for most of the rest of the day.

Power measurements made on May 4 (three days before the retrofit) showed that, averaged over the day, the lighting loads were 2.11, 2.39, 2.44 and 2.36 kW for circuits 9, 11, 16 and 18, respectively. Over the day, the power measurements showed a standard deviation of slightly under 1% although the maximum and minimum measured values deviated as much as 4% from the average. These deviations are thought to be a result of small fluctuations in supply voltage to the lighting system and changes in lamp ambient temperature.

Zones 9, 11, and 16 are 1,152 square feet in area. This area was calculated by multiplying the area per fixture (64 square feet per fixture) by the number of fixtures in the zone. From the measured lighting loads, we calculated the preinstallation lighting power densities to be 1.83, 2.07, and 2.12 W/ft$^2$, for zones 9, 11, and 16, respectively. The reference zone circuit (circuit #18) contains only seventeen fixtures and is therefore only 1,088 ft$^2$. Thus the preinstallation lighting power density in the reference zone was 2.17 W/ft$^2$.

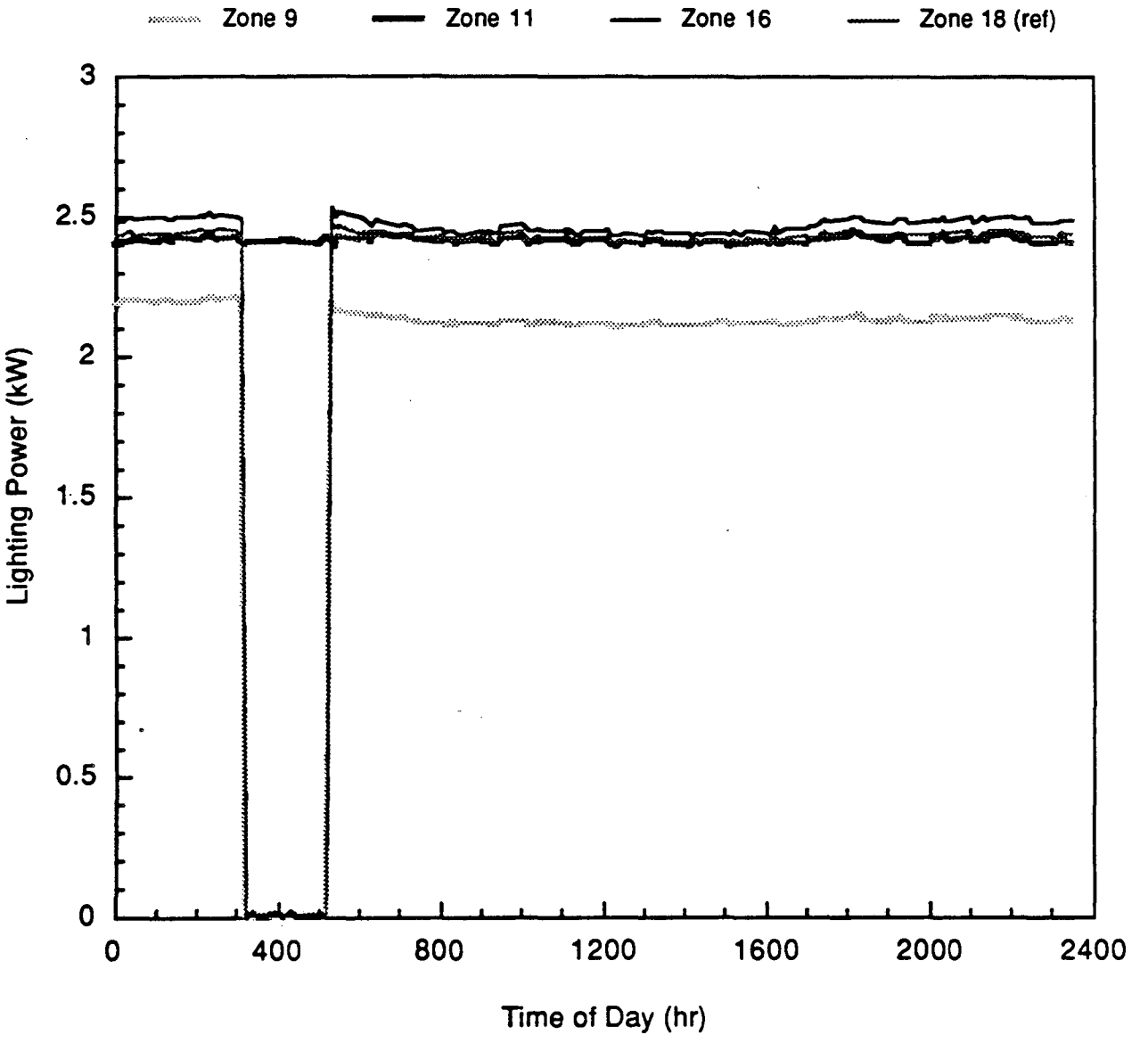


Figure 3-5. Lighting power as function of time of day for weekday (April 27) prior to installation of electronic ballasts and control system.

We noted that all of the zones had three or four nonfunctioning ballasts resulting in lower power densities than we would have expected based on a simple fixture count. Circuit 9 had the highest number of nonfunctioning ballasts and therefore exhibited the lowest load during these preinstallation measurements. In only one case was this clearly deliberate; one occupant had removed all the lamps from his fixture (and brought in his own incandescent desk lamp). In other cases, the ballast (or lamps) had failed in fixtures typically near the windows and the occupants had not bothered to alert maintenance.

## Light levels

We took photometric readings at the locations shown in Figure 2-2 to assess the light levels produced by the existing lighting system. Measurements were performed at desk height (30") using a calibrated Tektronix J-16 photometer. Because of the presence of nearby objects (i.e., books, terminals, and partitions), there was a considerable amount of variability in the readings. In addition, there was the problem of measuring light levels near a fixture with only two lamps burning. In the north zone we measured light levels of 450-575 lux (42-53 fc) with the points nearer the dark window being at the lower range. Slightly lower readings still (~40 fc) were found in the south zone due to the absorbance of the partition walls. (In fact in a few areas there was only about 10 fc because overhead storage cabinets obstructed the light from the ceiling fixtures.) Nonetheless, in most areas, the system provided an illuminance level reasonably close to that recommended by the IES for this type of task. From conversations with the maintenance staff we gathered that many lamps had been changed 18 months earlier, implying that most lamps were roughly at 12,000 hours. This in turn suggests that the lamps were producing 80-90% of initial lumens. Furthermore, the accumulation of dirt in the fixtures during this time would be expected to decrease light output an additional 10%.

This reasoning led us to the conclusion that the light levels currently being provided were correct for the tasks being performed and that they were liable to increase significantly upon relamping. We also realized that after the retrofit, we could "tune" all the lights down to approximately this level and still satisfy occupant lighting requirements since they were apparently satisfied previously.

## POSTINSTALLATION CHARACTERIZATION

### Load with lighting at full power

After the ballasts in the six control groups were replaced, the controllers were all set to about 67% of full power while the new lamps "burned-in."[4] After the new lamps had burned over 100 hours, we set the power to 100% and repeated the photometric measurements to calculate the change in the efficacy with which the overhead lighting system provided workplane lumens. On May 14, with the ballasts set at full output, we measured lighting loads of 2.11, 2.1, 2.13, and 2.34 kW in circuit zones 9, 11, 16, and 18, respectively. Thus, with the electronic ballasts at full output, we achieved load reductions of 0%, 12%, 12.7% for circuit zones 9, 11, and 16. As mentioned previously, we would have measured larger load reductions (approximately 23%) if all the ballasts in the three zones had been operating prior to the changeout.

From the above power measurements, we calculated that each ballast consumed 117.4 watts (at 100% power) which compares well to the laboratory bench measurements of 119 watts (Section 2).

### Light levels

Table 3-1 lists the light level measurements in the north zone at the measurement points shown in Figure 2-1 for three different days. Table 3-2 gives analogous results for the south zone. Conditions I and II were preinstallation measurements taken at night. The measurements taken during Condition III represents the state of the lighting system approximately three weeks after the ballasts and lamps were installed in north circuit zone 16 and 100 hours after relamping the reference zone.

[4]This is recommended operating procedure for dimming fluorescent lamps. Running the lamps at full (or near full) power without substantial dimming for the first 100 hours of operation "sets" the hot-spot on the cathode filaments.

Table 3-1

Illumination Measurements in North Zone
Before and After Installation of Electronic Ballasts

| | | | Illuminance at measurement points [lux (lumens/meter$^2$)] | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Date | Condition | | A | B | C | D | E | F | G | H |
| 3/1/89 | I. | Preinstallation | 473 | 455 | 518 | 316 ‡ | 554 | 563 | 575 | 539 |
| 5/4/89 | II. | Preinstallation | 442 | 431 | 482 | 303 ‡ | 488 | 342 ‡ | 530 | 487 |
| 5/26/89 | III. | Postinstallation with ballasts at 100% power | 639 | 635 | 659 | 676 | 608 | 685 | 698 | 709 |
| Change in condition III relative to condition I | | | 35% | 39% | 27% | [34%] | 10% | 22% | 21% | 32% |

‡ indicates reading near fixture with 2 lamps out

[ ] indicates estimate (reading / .625)

Table 3-2

Illumination Measurements in South Zone
Before and After Installation of Electronic Ballasts

| | | | Illuminance at measurement points [lux (lumens/meter$^2$)] | | | |
|---|---|---|---|---|---|---|
| Date | Condition | | I | J | K | L |
| 3/1/89 | I. | Pre-installation | 415 | 425 | 250 ‡ | 269 ‡ |
| 5/4/89 | II. | Pre-installation | 395 | 399 | 238 | 249 ‡ |
| 5/26/89 | III. | Post-installation with ballasts at 100% power | 515 | 495 | NA | 492 |
| Change in condition III relative to condition I | | | 24% | 16% | NA | [14%] |

‡ indicates reading near fixture with 2 lamps out
[ ] indicates estimate (reading / .625)

The light measurements taken under condition II were consistently lower than those under condition I. Since the ambient temperature in the building was noticeably higher under II, we believe that the differences were due to the fact that the lamp ambient temperature was higher during condition II. It is well-known that higher lamp wall temperatures result in both decreased light output as well as reduced power input. Furthermore, the two month time interval between when the I and II measurements were made is far too short to allow lamp lumen depreciation to be the significant cause of the discrepancy particularly with well-aged lamps. Ignoring the condition II data, then, we found that the average light level in zone 16 increased by 26% after the retrofit (with the electronic ballasts running at 100%). In the south zone, light levels increased about 20%. However, as alluded to above, only a portion of this light increase is attributable to the electronic ballast. Since Table 3-1 also shows light measurements in the reference zone (points E, F, G, and H) before and after re-lamping, we can use these measurements to estimate the increase in light output *due to re-lamping and cleaning alone*. This analysis indicates an average increase in light output of 21%.

### Change in workplane lumen efficacy

From the results above, one can estimate the change in the efficiency of the lighting system with respect to providing workplane lumens as a result of the retrofit. Light levels in circuit zone 16 increased by 26% while the lighting load dropped by slightly under 13%. This indicates that the efficacy of the lighting system was improved by 44% as a result of both the ballast changeout and relamping and cleaning. However, as described above, approximately 21% of the light output increase is attributable to the installation of the new lamps and fixture cleaning alone. After correcting for this, we find that the improvement in efficacy due to the electronic ballasts alone is approximately 20%. Given the many uncertainties in our estimate, this improvement corresponds quite closely to the improvement in efficacy that we had expected based on our laboratory measurements (see Section 2).

## TUNING

For this first test, we tuned the lights to operate at reduced light level (67% of full power) which reduced the power to all three dimmable zones from the preinstallation value of 2.11-2.44 kW to about 1.4 kW. During this period, however, we did not change the way in which the lights were switched on and off. The lights in all four circuit zones (including the reference zone) continued to be switched by the security guard. The data show that the hours of operation during this period (May 8 - June 5) did not change appreciably from what they were prior to the retrofit. Nonetheless this aggressively implemented tuning strategy reduced daily energy use by 34-43% relative to the energy usage measured immediately before the retrofit. It should be noted, though, that because the electronic ballasts were tuned heavily, the light levels provided during this month were also 10-15% lower than the light levels measured immediately before the retrofit. We received no complaints about this light level. In fact, a few individuals expressed a preference for it. However, during all the following tests, we settled on a more modest reduction (75% of full power) for the core hours lighting level.

## SCHEDULING AND TUNING

Automatically scheduled lighting operation commenced June 5, 1989. In addition, at this time, we implemented a second type of tuning technique (tuning II) in which we reduced the light level from string 4 (over the aisleway) during all hours to the level used for the cleaning crew. However, we left the adjacent string 3, as well as the other lights, at 75% power during core hours. Figure 3-6 shows the lighting power profile for a typical weekday, 7/18, during the test period (7/13 to 8/13).

Note that the lighting load during the day in circuits 9 and 16 was about 1.6 kW; this is higher than the 1.4 kW obtained in the previous test using tuning. This difference is a

direct result of raising the core hours lighting level from 67 to 75%. Note that the lighting load for circuit 11 (which includes the heavily tuned string 4 over the aisleway) was just 1.2 kW; less than half that of the reference circuit.

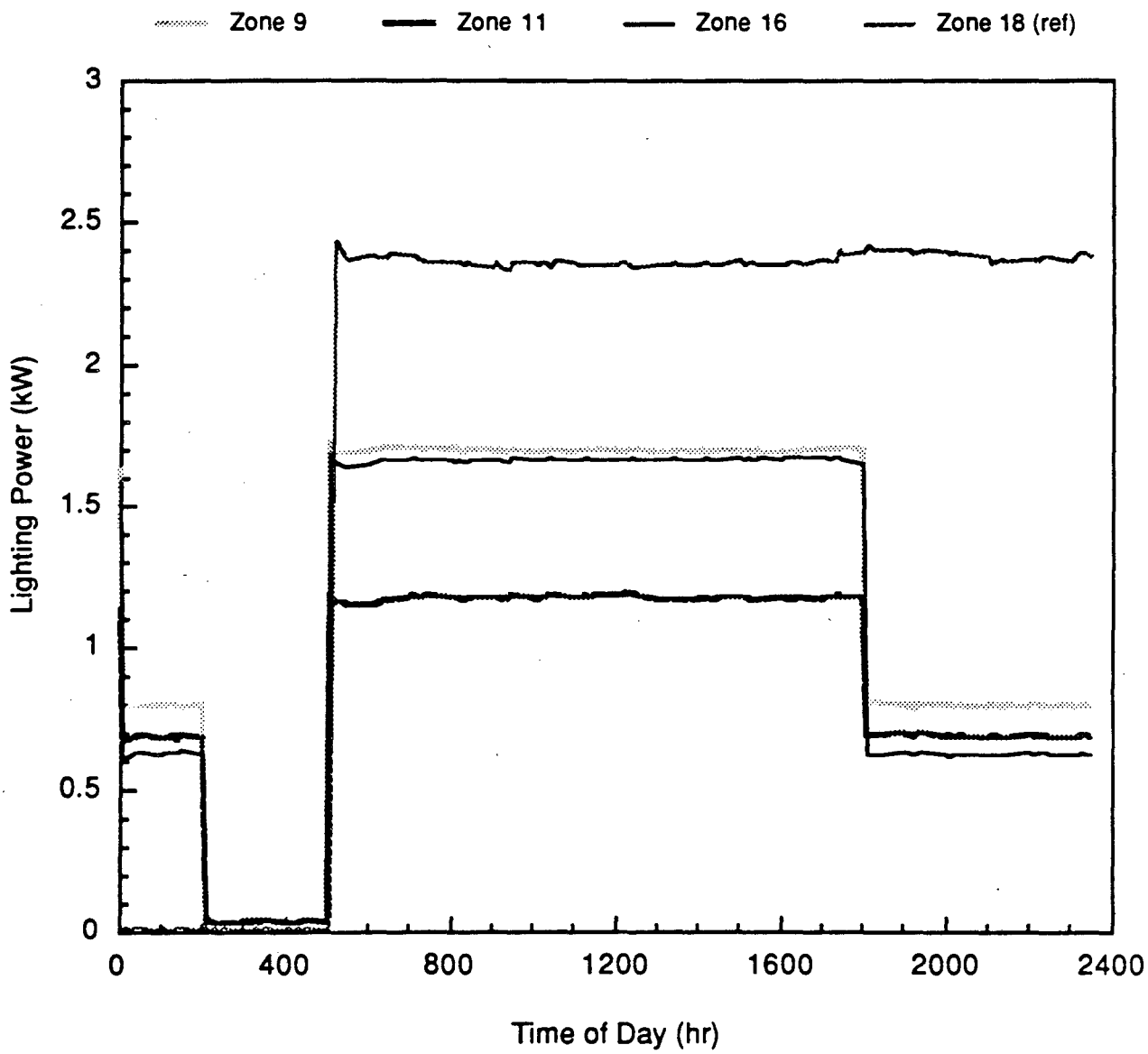


Figure 3-6. Lighting power as function of time of day for weekday (July 18) during test demonstrating scheduling and selective tuning. Aisleway lights in zone 11 are tuned down to provide low light level throughout day.

The careful reader will notice that, in Figure 3-6, the lighting load in the test circuits (i.e., circuit zones 9, 11, and 16) did not drop to exactly zero between 2 am and 5 am. This small, but non-zero, load is attributable to the fact that when the lights are commanded to zero, some residual power is still consumed by the ballasts even though lamp power is zero. This is clearly a very small effect and is dwarfed by the energy savings.

## DAYLIGHTING, LUMEN MAINTENANCE, AND SCHEDULING

Implementing daylighting and lumen maintenance required calibrating the ceiling-mounted photocells and putting the control system on automatic, thus "closing the loop" on the photocell control. We calibrated the photocells at locations immediately below the control photocells (as described in Section 2). Since there are two photocells serving each zone, this was necessarily an average. We closed the loop on August 14, and except for a 3-week period, this mode has been in effect since that time. We continued to schedule reduced light levels in the evenings for the cleaning crew as before.

### Daylighting (summer)

The lighting load data for a representative day during the summer (August 15) is given in Figure 3-7. The north daylight zone shows significant reduction in load throughout the day. During on-peak hours (12:00 pm - 6:00 pm), this circuit was using only about 0.75 kW, less than 45% of the power it used at night (i.e., without daylight).

The load profile in circuit 9 (south daylight) deserves further comment since it was anomalous. Unknown to us at the time, a switch in the controller board for string 5 was defective, causing an incorrect response to the daylight stimulus. The load for this zone should drop substantially below the apparent plateau seen in the figure because this is a south zone with significantly more daylight penetration than the north zone.

Note that some savings can be attributed to daylighting even in the interior zone on the south side.

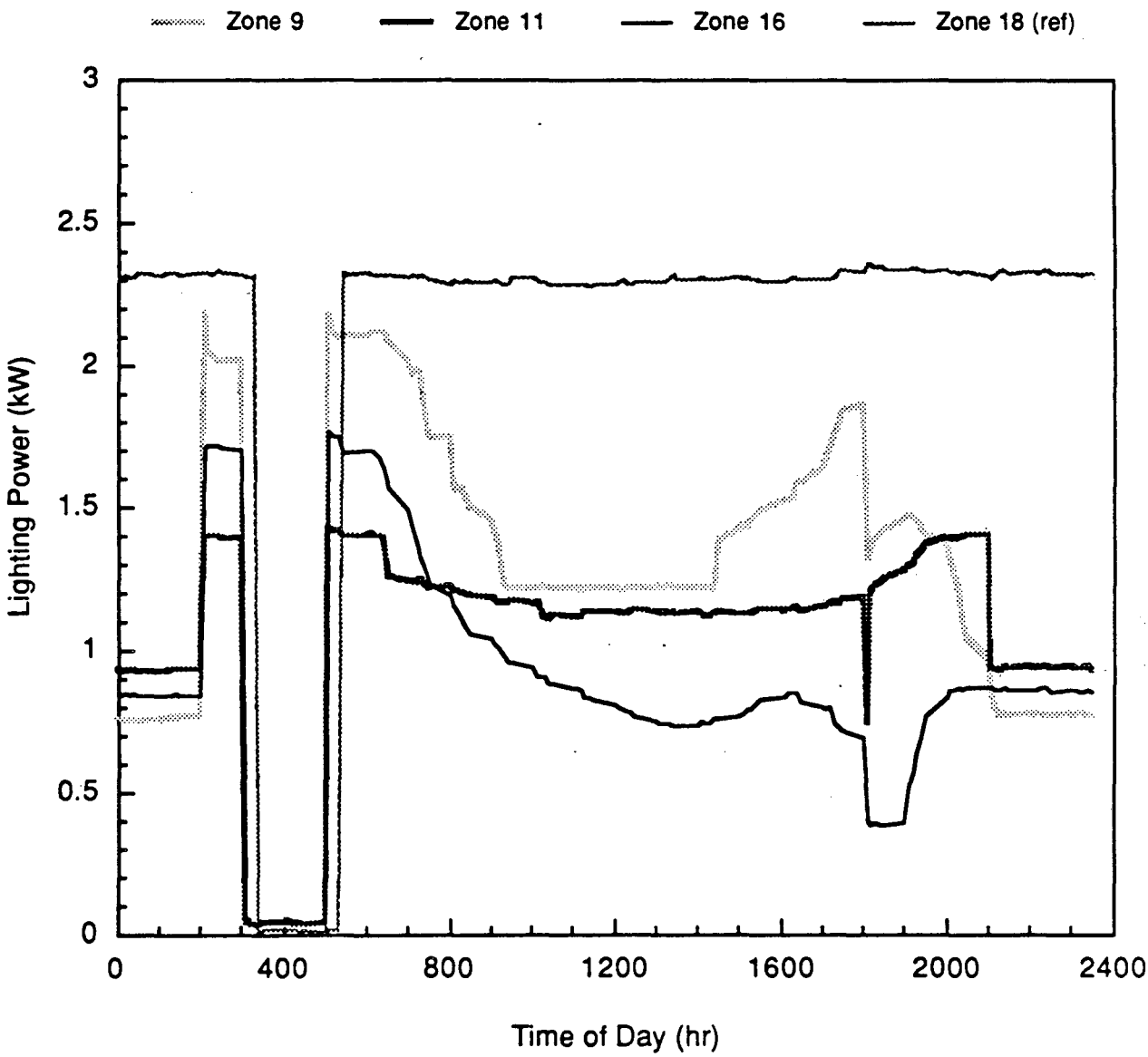


Figure 3-7. Lighting power as function of time of day for weekday (August 15) demonstrating photocell control for daylighting and lumen maintenance and scheduling.

## Daylighting (winter)

The data for a typical winter day (November 27) are shown in Figure 3-8. Note the sharp drop in load in circuit zone 9 between 8:00 am and 9:00 am. This was caused by the sun penetrating the south zone (the south zone actually faces south-by-southwest and therefore tends to be brighter before noon). The subsequent increase (at 9:00 am) is caused by the occupants closing the drapes to block the low winter sun. It is interesting to note that

despite the obvious differences in the load shapes of the south and north daylight zones (zones 9 and 16, respectively), the energy use when integrated over core operating hours is virtually identical (15.2 and 15.5 kWh/12-hr, for zones 9 and 16). The north daylight zone, because of its more benign conditions, permits as much exploitation of daylight as the south zone, despite the higher daylight levels in the latter.

As was observed for the summer data, some dimming occurs in the interior zone (circuit zone 11) even though this zone is well over 15 feet from the window, the classically accepted limit to useful daylight penetration from vertical glazing.

(The small notches seen in the load profile for circuit zone 18 [reference zone] during the evening were due to the cycling of the thermal protection switch in a defective magnetic ballast. The cycling tended to occur in the evenings when the air conditioning system was switched off causing abnormally high temperatures in the ceiling plenum.)

Figure 3-9 shows the light levels measured by the monitoring photometers mounted at varying room depths in the north zone for the same day as shown in Figure 3-8. It is significant that, despite the substantial electric dimming observed in Figure 3-8, the light levels shown in Figure 3-9 remained relatively constant throughout the day. This is clear evidence that the daylighting controls were properly functioning by providing a reasonably constant illuminance at the workplane while permitting substantial reductions in lighting load. The data from the photometers at 4.5' and 8.5' from the window indicate that the light levels provided at these locations were about 20% above the level provided at night. In principle, this discrepancy could be reduced by a more careful calibration of the photocells. In practice, this discrepancy may actually be desirable since maintaining a slightly higher light level during the day will tend to mitigate the effect of the apparently bright outside relative to the dimmer interior.

To put this load reduction into another context, we calculated that the lighting power density at noon on this same winter day, in both north and south daylight zones was only 0.95 W/ft$^2$ compared to the power densities measured in these zones during the preinstallation measurements (1.83 and 2.12 W/ft$^2$ for the south and north zones, respectively). On some days, especially in the summer months when peak demand is a more serious problem, lighting densities were around 0.75 W/ft$^2$ for several hours a day.

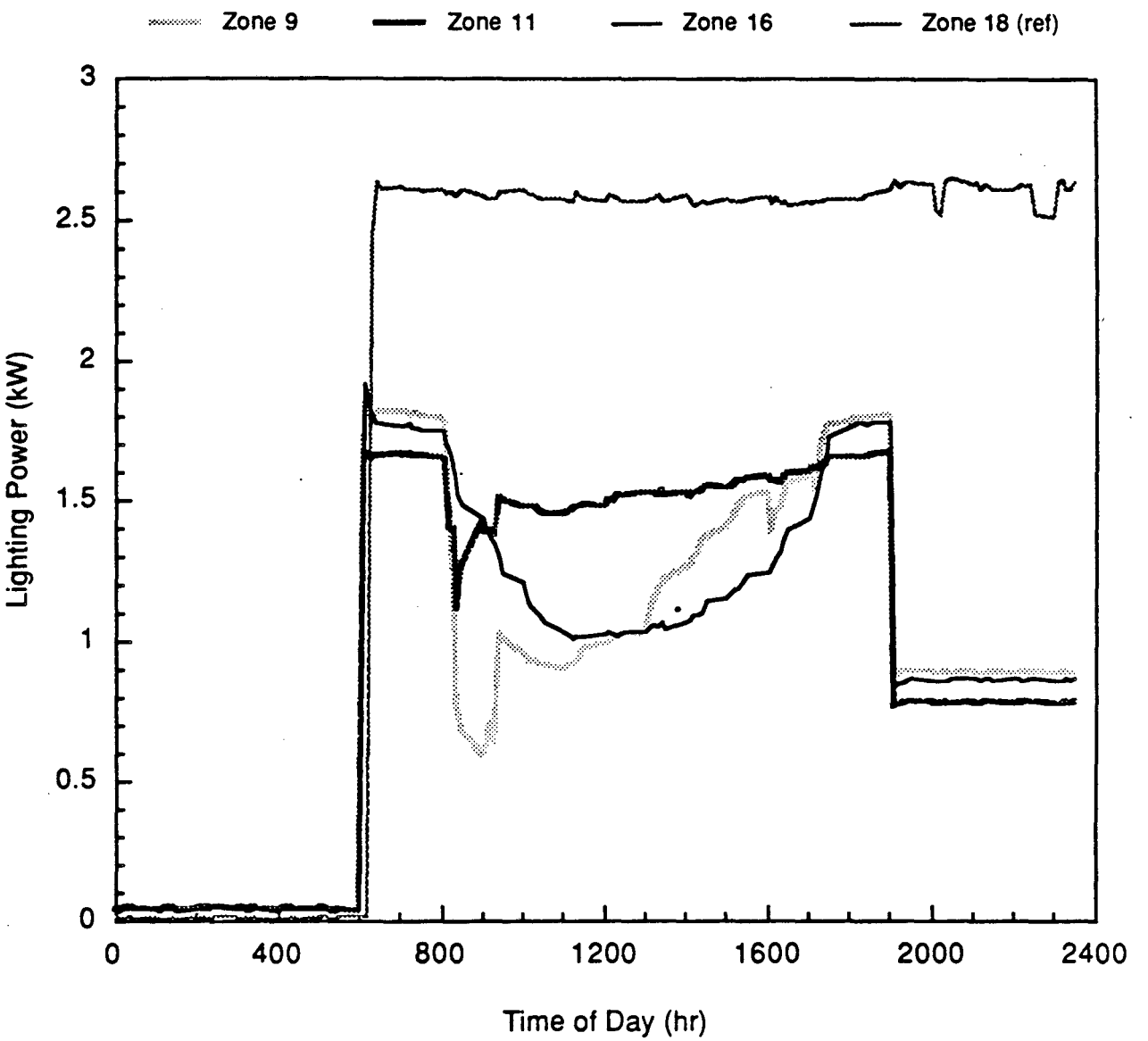


Figure 3-8. Lighting power as function of time of day for weekday (November 27) demonstrating photocell control for daylighting and lumen maintenance and scheduling.

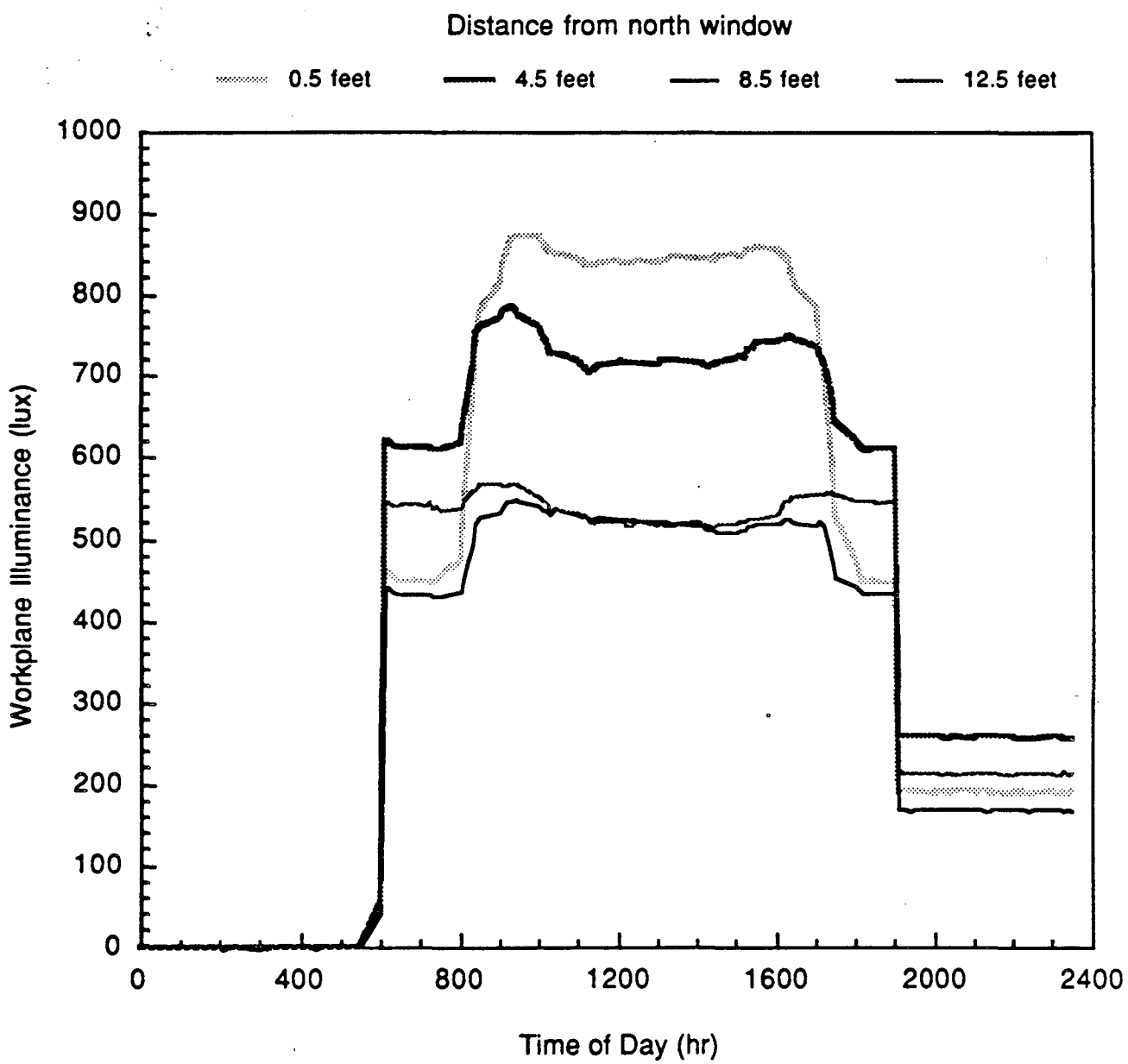


Figure 3-9. Total illuminance (one foot above 30" workplane) at varying distances from north window as a function of time of day for daylighting/lumen maintenance/scheduling control scenario for November 27.

## LUMEN MAINTENANCE

Clearly, a significant portion of the base energy savings from this combined strategy test is attributable to the fact that the power levels could be set to 75% of full power during core hours and still supply sufficient illumination. In time, however, the lamps will gradually produce less light and the ballasts will have to supply more power to the lamps to maintain the same light level (approximately 50 fc). Thus, under similar daylight conditions a year from now, the lighting demand (and daily energy use) is expected to be slightly higher simply because the electric lighting system will be somewhat less efficacious. This trend should continue until the system is relamped and cleaned, at which time this year's savings pattern would repeat itself.

Lumen maintenance is a long-term strategy and its use and effectiveness is virtually undocumented in the literature. As a result, we were interested to see whether this slow increase in lighting power could be discerned from the data. Coupled with workplane illuminance data, this would conclusively demonstrate that lumen maintenance and daylighting can be successfully implemented simultaneously with the same equipment. Unfortunately, the exigency of starting with a "clean slate" after solving the lamp-blackening problem (see section 2), required that we re-lamp the entire demonstration site in mid-October. This left us with only about 2-1/2 months of clean data with which to attempt to discern the lumen maintenance effect. A preliminary analysis of the data revealed no statistically significant increase in lighting power during this short period.

## ENERGY SAVINGS SUMMARY (AS MEASURED)

Table 3-3 summarizes the average weekday energy use for the various control scenarios and the preinstallation condition. Also shown is the variability of the daily energy use expressed as the standard deviation of the individual daily energy use calculated over the number of days in the test period. Compared to the preinstallation condition, the energy savings calculated both over the entire day as well as just during core hours are in the 31-52% range. The core hours savings during the summer test is especially significant because of the potential for reducing summer peak demand.

As shown in Table 3-3, the average daily energy savings calculated relative to the preinstallation condition ranged from 40-52% depending upon the specifics of the control scenario tested. For core operating hours, the energy savings range from 31-46%. The energy savings calculated for circuit zone 9 was generally slightly lower than that for the other two zones because it had the largest number of non-functioning ballasts prior to the installation of the demonstration system. The standard deviations for the average daily energy usage was generally small compared to the average.

Table 3-3

Average weekday energy use for three dimming circuit zones
for various strategy combinations

| Strategies | Period | # days | Average energy use (core hours only) [kWh/zone/12-hr] Zone 9 | Zone 11 | Zone 16 | Average energy use (all day) [kWh/zone/day] Zone 9 | Zone 11 | Zone 16 |
|---|---|---|---|---|---|---|---|---|
| Preinstallation | 4/12-5/4 | 13 | 25.4 * | 29.4 | 29.3 | 47.9 | 57.5 | 54.2 |
| | | | 0.29 | 0.51 | 0.17 | 1.95 | 2.18 | 3.04 |
| Tuning | 5/8-6/4 | 20 | 16.6 | 17.4 | 16.5 | 30.5 | 32.9 | 29.7 |
| | | | 3.97 | 0.77 | 3.43 | 5.72 | 3.13 | 5.32 |
| Scheduling + Tuning | 7/13-8/2 | 15 | 20.2 | 13.4 | 19.2 | 30.5 | 22.2 | 28.2 |
| | | | 0.24 | 0.45 | 0.80 | 2.12 | 1.66 | 1.80 |
| Daylighting+ Lumen Main.+ Scheduling | 8/14-8/28 | 11 | [18.4] | 14.5 | 12.5 | [29.3] | 24.5 | 21.3 |
| | | | [1.72] | 0.54 | 0.69 | [3.51] | 1.78 | 1.79 |
| Daylighting+ Lumen Main.+ Scheduling | 11/7-12/29 | 38 | 15.7 | 17.6 | 15.6 | 26.1 | 27.7 | 25.1 |
| | | | 2.20 | 2.34 | 1.97 | 3.49 | 3.95 | 2.93 |

* Upper number is average energy use, lower number is standard deviation
[ ] denotes flawed test data.

## ENERGY SAVINGS SUMMARY (CORRECTED)

In the previous sections, we made no attempt to correct the measured energy savings to take into account the rehabilitation of the lighting system that resulted from the retrofit. These uncorrected energy savings, though impressive, understate what the lighting savings would have been relative to the preinstallation condition had all the ballasts been initially operational. In this section, we calculate the baseline energy usage and correct it to account for the ballasts that were non-functional prior to the retrofit. We then recompute the energy savings for each zone relative to the corrected baseline energy usage.

The measured data from the reference zone cannot be used directly to obtain the corrected baseline energy usage for two reasons: 1) the lighting load in the reference zone changed throughout the demonstration period (as discussed in the beginning of the results section) because of the gradual failures of seven of the old magnetic ballasts, and 2) the reference circuit zone includes only 17 fixtures while the three dimming zones contain 18. To obtain the baseline energy use, we need to know a) what the lighting load would have been were all ballasts operational, b) the number of hours the lights were on per day, and c) a way to correct for the difference in the number of ballasts. The corrected lighting load (2.6 kW) is known from data gathered during November and December when all the ballasts in the reference zone were working (2.6 kW for 17 fixtures or 34 ballasts). Rather than use just the pre-installation data to obtain the hours of operation, we used the more precise method of counting the number of data records in which the lights were on in the reference zone throughout the entire course of the demonstration. (This is valid because the reference zone continued to be switched in the same manner throughout.) We found that, during the 194 days between April 5 and December 5, the lights in the reference zone were on 89% of the time on weekdays (21.4 hr /day) and 57% (13.7 hr/day) of the time on weekends. From the corrected lighting load (2.6 kW x18/17=2.75 kW) we obtain that the baseline energy use on weekdays is 58.8 kWh/day and 37.7 kWh/day on weekends. The corrected baseline energy usage during core hours on weekdays is 33 kWh/12-hr (58.8 kWh x 12 hr ÷ 21.4 hr).

From the above calculation, we can also immediately determine the corrected lighting power density for all of the zones prior to the installation. With eighteen fixtures in zones 9, 11, and 16, the corrected lighting load is 2.75 kW/zone with a power density of 2.39 W/ft$^2$ (2.75 kW/zone ÷ 1,152 ft$^2$/zone).

Figures 3-10 and 3-11 show the energy use data given in Table 3-3 plotted relative to corrected baseline energy use for both core and all operating hours for weekdays.

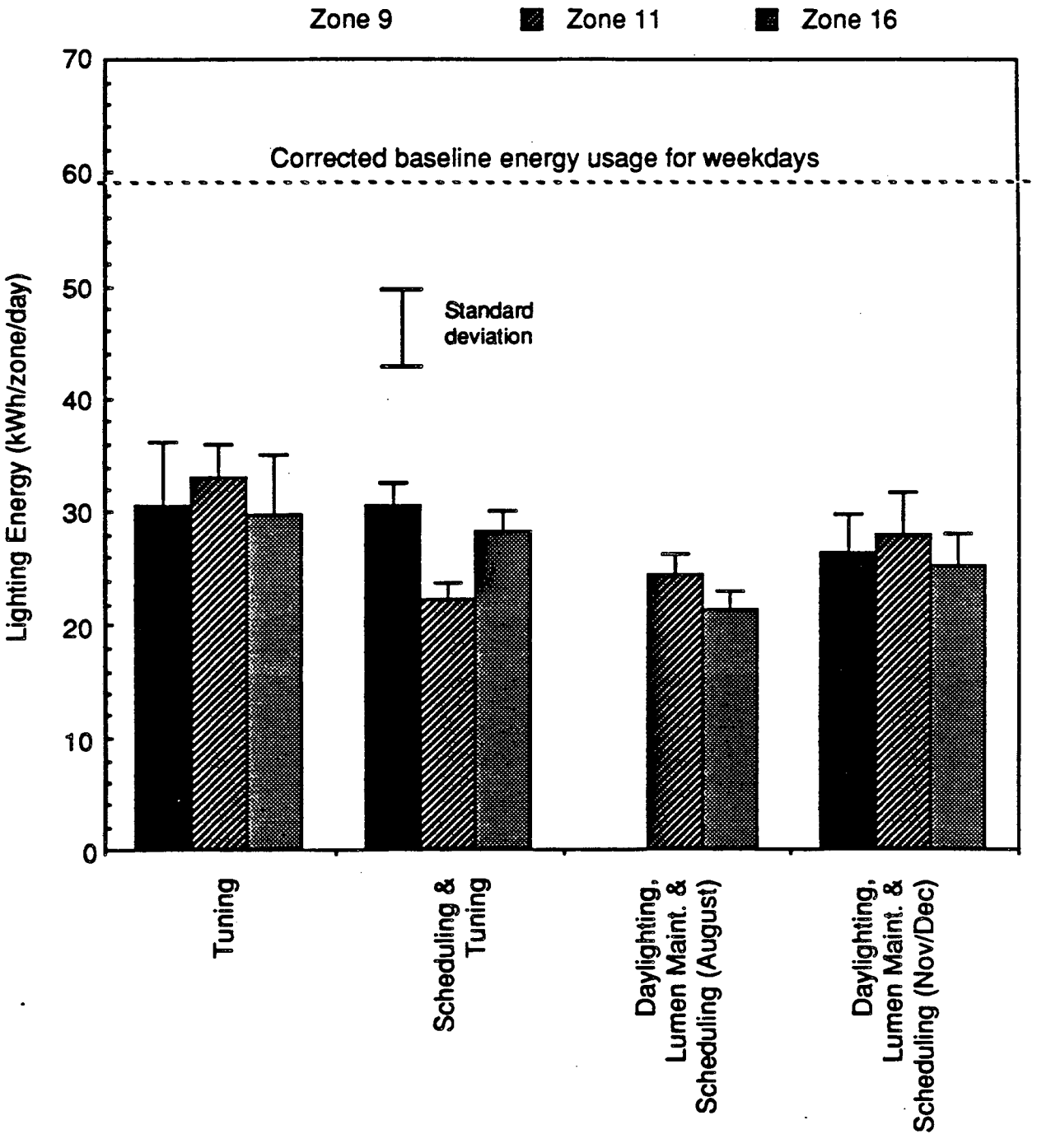


Figure 3-10. Average weekday lighting energy usage for various control scenarios. Standard deviations are calculated over the number of days in each test as given in Table 3-3. Zone 9 average for daylighting test in August not shown.

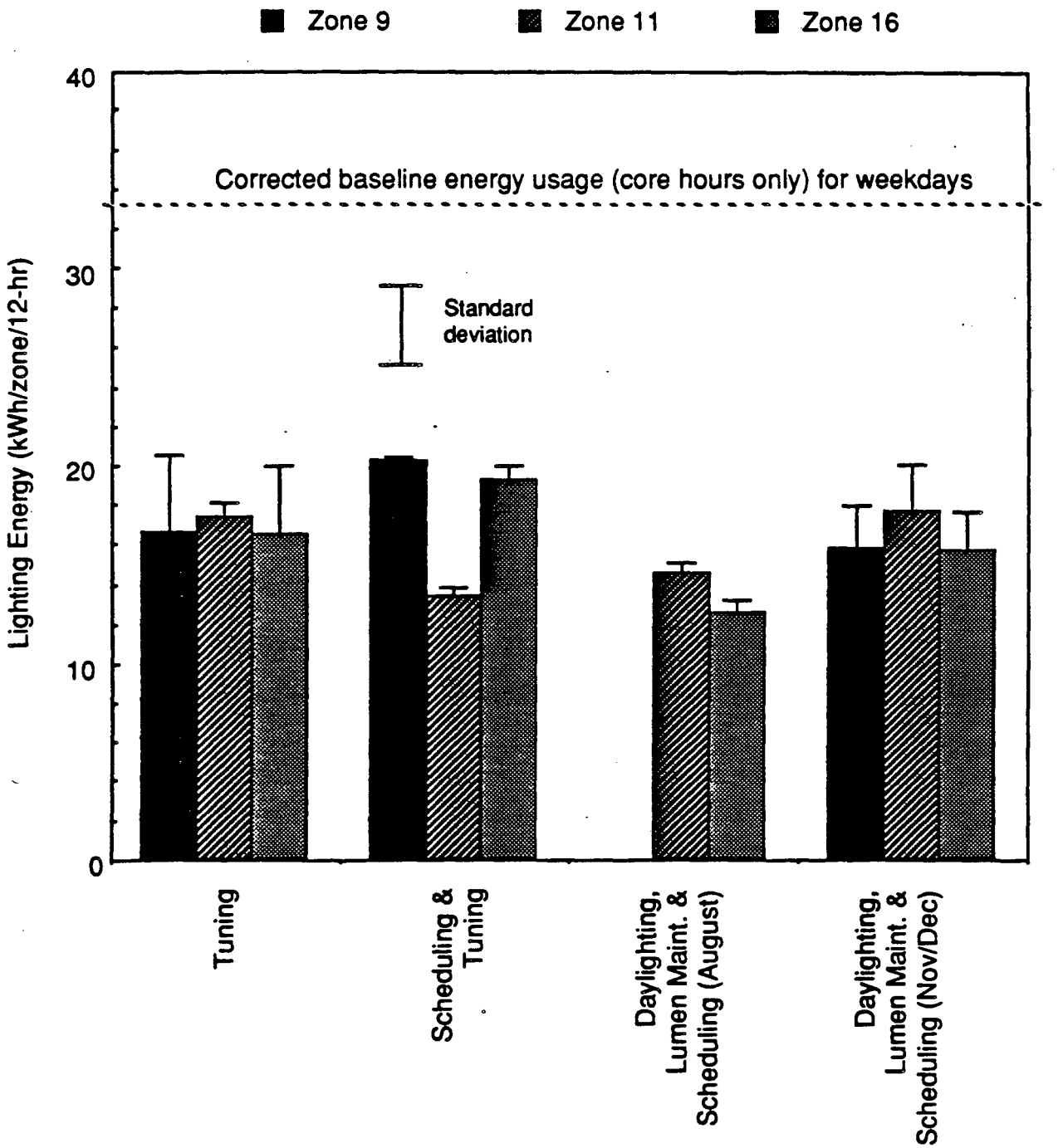


Figure 3-11. Average weekday lighting energy usage for core hours only for various control scenarios. Standard deviations are calculated over the number of days in each test as given in Table 3-3. Zone 9 average for daylighting test in August not shown.

## Energy savings on weekends

The energy savings measured on weekends were also very significant but show far greater variability than the savings on weekdays. For the 62 weekend days measured over the entire test period (April 5 to December 31), the daily energy use averaged 7.05, 12.13, and 7.3 kWh/day for circuit zones 9, 11, and 16, respectively. Compared to the corrected baseline energy use for weekends (37.7 kWh/day), this represents a savings of 81%, 68%, and 80.5%.

Section 4

# DISCUSSION

## SCHEDULING

The impressive energy savings obtained with the use of scheduling was largely due to the reduction of light levels during non-core operating hours. In this project, we implemented this reduction by dimming the lamps at appropriate times, but this technique could also be accomplished by simpler switching gear. For example, lighting systems consisting of multi-ballasted luminaires can be "split-wired" to a programmable relay-based switching system to provide 2 or 3 discrete light levels in each appropriately wired zone. Switching systems are much less expensive on a per square foot basis than dimming systems and this difference is likely to persist even in a mature market.

The scheduling savings look particularly impressive because of the long operating hours of the lighting system without automatic controls. Most buildings do not require lighting for nearly 90% of weekday hours. But the reason the lights stay on is that the activities of all the occupants cannot be accurately predicted. This in turn brings about the "conservative" practice of simply keeping the lights on when there is a chance that someone might be working in the area. Thus, while the magnitude of the savings with scheduling found here are not necessarily applicable to all building types, the reason for the waste as well as the usefulness of scheduling for alleviating it have widespread applicability.

## PHOTOCELL CONTROL

The two-part photocell system worked remarkably well in maintaining a constant workplane illuminance. To our knowledge, this is the first demonstration of a closed-loop photocell-controlled system that can correctly compensate for both changes in daylight as well as lumen depreciation in the electric lighting system. (In the Lockheed building, an open-loop system is used for the daylighting control. Because that system uses open-loop, the system is unable to compensate for lumen depreciation effects and thus cannot take advantage of the lumen maintenance strategy.) The use of a control photocell whose response can be adjusted so that the relationship between photocell output and workplane illuminance is the same for daylight and electric light is one of the unique features of this system. Without this type of photocell, system response can be optimized for either daylighting (by using open-loop control as at Lockheed [Benton 1989] or with closed-loop proportional control [Verderber 1989] or lumen maintenance) but not both simultaneously. The natural integration of these two photo-linked strategies is of great significance since the overlapping hardware requirements (i.e., dimmability with photocell control) and the sizeable energy savings are necessary to justify the premium cost of dimming hardware.

From an experimental standpoint, one might think it preferable to implement daylighting and lumen maintenance initially separately and then later in combination to test interactive effects. In practice, this is not possible. The photocells don't "know" if a change in measured light is due to a short term increase in daylight or due to long-term changes in lamp lumen output.

Regardless, during the daylighting/lumen maintenance/scheduling scenario, there is a certain ambiguity as to whether tuning was also in effect. After all, lighting was not at full power during this or the previous test, scheduling/tuning, in which there was no photocell link. Here we differentiate between tuning to a given light level by manually changing the light level and maintaining a given light level automatically using a photocell feedback control.

## OVERRIDE USE PATTERNS

We found that the overrides were used primarily to raise the light level from the default reduced level to the nominal full during very early morning hours. It is also significant that all three zones were often overridden, not just one. This could be due to the occupant using the master override sequence instead of the individual zone sequence (perhaps out of ignorance). It may also be that the occupant intentionally overrode the lights in all three zones because he or she needed to work in more than one zone. Regardless, one can deduce from the switching pattern that at least a few individuals work in parts of this site in the very early morning hours and that they leave between 2 and 3 am. Since the reduced cleaning crew level is rarely overridden until 2 am (when the scheduling system would have the lights dimmed off), one can speculate that some individuals may find the reduced level adequate to work by at night and that they use the overrides just when the lights are switched off. (The occupants had no way of obtaining the reduced level; their overrides would only restore to full lighting.)

It is also clear from the detailed profiles that some individuals (especially in zone 11) use their overrides to restore just their own zone's lights after the 6 pm reduction. This is significant since it indicates that the scheduling system with overrides can minimize energy waste while accommodating the occupants' unpredictable working hours.

## COST-EFFECTIVENESS

No energy conservation measure (ECM) will be successful unless one can demonstrate cost-effectiveness. Since this system is an advanced commercial prototype with a price that is not yet fixed, we use the calculated energy savings to estimate what the cost of the ballast and ancillary controls should be to achieve an acceptable payback for a commercial building

(< 2 years simple payback). We derive target costs for both existing buildings and new construction assuming that a 50% energy savings can be achieved in both cases.

In an existing building using 2.5 W/ft$^2$ for lighting for 4,000 hrs/yr, lighting costs \$1.00/ft$^2$/yr if energy costs \$0.10/kWh. This study indicates that we can (conservatively) save half of this cost using a lighting control system: \$0.50/ft$^2$/yr. If the first cost of retrofitting the control system is to be recovered in two years, then the total installed first cost must not exceed \$1.00/ft$^2$ or \$64/fixture (each fixture lights 64 ft$^2$.) Allowing \$20/fixture for the labor cost to retrofit each fixture and install the controls (see Section 2 for how this estimate was derived), and an additional \$5/fixture for the controls cost (photocells, EMS linkage, override switches and wiring) leaves us a target cost premium of \$39/ballast. Note that this is a premium cost. Since two energy-efficient ballasts cost ~\$20, that gives us a ballast target cost of \$59. We believe that this is well within the range that such a system can be profitably marketed. For example, Advance Transformer Company, one of the nation's leading manufacturers of ballasts, has recently begun marketing a two-lamp dimming electronic ballast (Advance Mark VII) with performance specifications somewhat similar to the Braydon ballast examined in this demonstration. The cost adder for the Advance ballast is \$42 for large orders, placing it close to the target costs deduced above.

For new construction, we need to adjust the above figures to account for the fact that the installed lighting power density is lower in a Title 24 office building than in a non-Title 24 building. In the new construction case, the building lighting energy costs without controls would be expected to be about \$0.80/ft$^2$/yr (2.0 W/ft$^2$ x 4000 hrs/yr x \$0.10/kWh)†. Again assuming that the control system can save 50% of the lighting energy costs gives us a total installed first cost of \$51.20/fixture if the system is to pay back in two years. For new construction, we may assume that the labor to install the controls is only \$5/fixture to reflect the low costs of installing a control system when it is incorporated into the design plans from the start. Allowing, as before, an additional cost of \$5/fixture for the controls cost results in a target cost premium of \$41.20/ballast. The end-user cost, therefore, should not exceed \$61.20/ballast. Again this cost is within a reasonable range especially when one accounts for reduced production costs in a mature market and any applicable utility rebates.

It is interesting to speculate what the savings would be to the owners of Watergate Tower 1 if this system was installed throughout the building. If we modify the above estimate to

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† Although a Title 24 office building may only use 1.5 W/ft$^2$ for lighting, we have used 2 W/ft$^2$ to account for the allowed power adjustment credit for controls. We have used 35% for this credit, which is intended to be a weighted average value over the building.

account for the (possibly) lower operating hours in other parts of the building, we estimate that the cost for lighting energy is $0.96/ft$^2$/yr (2.4 W/ft$^2$ x 4000 hr/yr (est.) x $0.10/kWh). Assuming that the controls can produce an energy savings of 40%, the cost to light the building could be reduced by nearly $100,000 annually.

### Cost of conserved energy

The final way we present to examine the economics of this system uses a method known as the cost of conserved energy (CCE) [Geller 1987]. This method expresses the cost of an ECM in terms of $/kWh so that it can be compared directly with the cost of buying the energy. If an ECM has a CCE that is less than the cost of buying energy, the measure makes economic sense. Assuming that the end-user cost of the ballast is $60, the cost of the controls is $5/fixture and the installation labor cost (retrofit) is $20, the total cost to install the ECM is $85/fixture. Let us also assume that the retrofit occurs at a time when the existing ballasts would otherwise be replaced with energy-efficient core-coil ballasts (which cost ~$10 each). Finally, the present value of the saved operating and maintenance costs (O&M) is $5 (because only three, less expensive 40-watt lamps are used per fixture rather than four, more expensive 35-watt lamps). Thus the present value of the incremental investment is $60/fixture ($85 - $20 -$5). On a yearly basis, each ballast saves 538 kWh (2.4 W/ft$^2$ x 7000 hr/yr x 64 ft$^2$/fixture x 50%). Assuming a system life of 45,000 hours with a usage of 7,000 hr/yr, the measure lasts for 6.4 yr. Given an annual real discount rate of 7%, we find that the cost of conserved energy is $0.022/kWh. Clearly, this compares very favorably with the present cost of electric energy.

For new construction, we assume that the installed power density is 2.0 W/ft$^2$ (see previous paragraph) and that the annual hours of operation are only 4,000 hrs rather than 7,000. Further, we take the installation labor cost to be only $5/ballast to reflect the lower cost of installing the ballasts and controls when the ECM is undertaken as part of the construction process. Using the same discount rate as above, and the same savings in O&M costs, we calculate that the cost of conserved energy is only $0.023/kWh, which again compares favorably to the present cost of electricity.

The above economic analyses are believed to be conservative since we have not accounted for the additional cost savings that takes place as a result of reducing the cooling load.

## RELIABILITY

### Ballasts

Throughout the course of this project, seven of the electronic ballasts either failed or exhibited sufficiently anomalous behavior that they had to be replaced. Most of the failures appear to be attributable to quality assurance errors in sorting out defective devices

(particularly diodes in the diode bridge) rather than intrinsic design. We are therefore reasonably certain that these types of problems are resolvable in the manufacturing process.

### Controls

Except for a faulty switch on the string 5 controller board, the controls have functioned satisfactorily. Our results suggest that the two-part photocells are an elegant and effective way to detect and control light levels so that both daylighting and lumen maintenance can be simultaneously implemented with the same hardware. To our knowledge this is the first demonstration of such an integrated system in which long-term performance has been measured.

The calibration procedure for the daylighting control clearly needs to be simplified. Instead of moving the photocell stalk up and down to obtain the correct photocell response for daylight and electric light, it would be preferable to fix the photocell in one location in selected fixtures shipped to the job site and to balance the signals from the two sensors electrically. Furthermore, we recommend placing the adjustment controls in a location where they can be easily reached from the controlled space.

### Lamps and auxiliary equipment

As described in Methods, we encountered problems with severe lamp blackening and premature lamp failure under heavy dimmed operation for substantial periods of time when the ballasts provided only 2-2.5 v to the cathode heaters. Once the ballasts were modified to supply 3.5 - 4 V cathode heating voltage, the problem with lamp operation was completed resolved. During the four months since the ballasts were modified (9/23/89), we have observed no signs of any lamp blackening on even the most heavily dimmed lamps and we have had no lamp failures since that time. The hazards of operating lamps at high frequency in dimmed mode with low cathode voltage is not unknown in the literature [Verderber 1984], although exact specifications for a lower limit have not been suggested. In our lab, we have seen lamp life of 40,000+ hours in high frequency driven lamps at substantially dim levels with cathode voltage of 4.1 volts. Clearly, then, 3.5 - 4 v on the cathodes is sufficient to prevent premature lamp failure, but we do not know whether this limit could be relaxed slightly. It is significant that once the lamps were provided with sufficient cathode voltage, that good performance was achieved without the use of special lamps or lampholders.

## OCCUPANT RESPONSE

Although we undertook no formal solicitation of occupant reaction to the new lighting system, in informal conversations the occupants reacted with neutrality or mild curiosity. We received no negative comments on the lighting system or its operation although one

individual complained that he was sometimes on the phone when the light levels dropped to reduced level at 6:00 and consequently could not reactivate the lights in his zone immediately. This problem could be easily solved by instead briefly dimming the lights five minutes before the level change to allow the occupant time to activate the override. (In fact, the GE system that was used to handle the overrides is capable of flashing the relays in a designated manner to accomplish just such an effect. Unfortunately, the CR-10 could not be programmed to process these switch inputs with the requisite precision.)

Because the dimming was very smooth, most occupants seemed unaware of the fact that the lights would dim substantially during the day. When one woman was informed as to exactly how the lights were dimming with available daylight, her paraphrased response was "well, that makes sense" as if daylight dimming should be a commonplace occurrence!

## WHY CONTROLS AREN'T UNIVERSALLY USED

We know of no other energy conservation measure (ECM) with potential energy and demand savings comparable to those obtained from the lighting controls in this demonstration. Given this fact, why aren't controls used more universally? One reason is that integrated lighting control systems, especially those built around electronically-ballasted technology, are just emerging. The fact that the system demonstrated here was a pre-commercial prototype some 8-10 years after the first integrated electronically ballasted control system was developed is testament to the immaturity of this market. The second reason is that methods for selecting appropriate combinations of control strategies, laying out the control groups and installing, calibrating and maintaining the controls have not been well articulated. As a result, designers are reluctant to specify controls because they lack adequate knowledge about how the controls work and how they can be effectively employed in their designs. The implementation of control strategies needs to be simplified so that the potential of controls can be routinely realized in practice. The use of controls may never be as simple as the operation of dedicated (i.e., non-dimming) systems, but a series of appropriately-crafted design aids, diagnostic procedures and related tools would go a long way to encouraging their effective use.

Section 5

# RECOMMENDATIONS

Based upon the nine months of data collected at the demonstration site and the very significant measured savings in lighting energy use and demand, we make the following recommendations:

- Continue the testing and data collection at the Watergate demonstration site in order to assess long-term changes in energy consumption due to the lumen maintenance control strategy, and project the long-term energy savings and peak demand reduction potential attributable to daylighting. Continuing the data collection would provide PG&E with the necessary data to address utility concerns that the demand savings with daylighting can be reliably counted on to counteract summer peak demand.

- Commence a new research effort directed towards developing simplified methods for zoning and installing lighting controls systems in new buildings. This effort might be developed along the lines of the "Power by Design" program currently being conducted by New England Electric in which the utility plays an active role in ensuring that energy efficient lighting measures are aggressively pursued during the building design stage.

- Assist in the development of educational programs for building management personnel to help these individuals understand the importance of a properly operated and calibrated control system.

- Assist the research and design community in developing simplified procedures for specifying and installing cost-effective lighting control measures in existing buildings.

- Reduce the perceived risk of investing in controls by developing aggressive rebate programs that help decrease the initial added cost of controls to building owners.

With respect to the demonstration site at this building, we would recommend that the data collection and analysis continue at least until mid-summer 1990 to permit the collection of a full year's data on the long-term impacts of daylighting and lumen maintenance. This information is sorely needed by the lighting community to convince specifiers that the controls savings are consistent and robust. In this regard, we recommend that the load shedding technique be tested in follow-on work designed to demonstrate the feasibility of

shedding lighting loads in response to building demand monitors. Another technique to be explored is tuning individual fixtures according to local needs, a strategy to which this type of ballasted system is ideally suited.

Section 6

# CONCLUSIONS

The project has demonstrated that a state-of-the-art electronically ballasted dimmable lighting system can reduce energy and lighting demand by at least 50% using various combinations of control strategies. The data collected during the late summer (though limited) suggests that energy savings of 75% relative to the original lighting usage is achievable. The energy savings were found to be both significant and robust. Equally important, the measured demand reduction during core operating hours, up to 70% during the summer months, argues forcefully for the consideration of lighting control techniques for moderating peak demand.

A novel two-part control photocell was shown to be effective in providing appropriate control allowing daylighting and lumen maintenance strategies to be implemented simultaneously with the same hardware. With this photocontrol system, design light levels were maintained at the workplane regardless of the daylight contribution.

The energy savings documented in this demonstration were accomplished without compromising the quality of the lighting in any way. In fact, since these electronic ballasts eliminate flicker, it could be argued that lighting quality actually improved. While we did not attempt to qualify this potential improvement, other studies have suggested that high-frequency lighting can reduce eyestrain and the number of headaches.

It is difficult to overstress the importance of the measured energy and demand reductions. Buildings are the most significant users of electrical energy in the nation, and lighting is the major contributor to total electrical loads in buildings. It would not seem to be too extreme a viewpoint to state that the use of appropriate lighting controls is probably the most cost-effective method to significantly reduce electrical energy use and peak demand in buildings.

Section 7

## REFERENCES


Abesamis, R., P. Black, and J. Kessel, *Field Experience with High Frequency Ballasts,* Proceedings of the IEEE-IAS Annual Conference, San Diego, October, 1989.

Benton, C., *The Lockheed Building 157 Monitoring Project Phase II: The Lighting Control System,* PG&E Research and Development Report 008.1-89.7, 1989.

Geller, H., J. Harris, M. Levine, and A. Rosenfeld, *The Role of Federal Research and Development in Advancing Energy Efficiency: A $50 Billion Contribution to the US Economy,* Annual Review of Energy, Vol. 12, pp. 357-395, 1987.

Jewell, J., S. Selkowitz, and R. Verderber, *Solid-state Ballasts Prove to be Energy Savers,* Lighting Design & Application, Vol. 10, No. 10, pp. 36-42, Jan., 1980.

Rubinstein, F., R. Verderber, and M. Karayel, *Field Study on Occupancy Scheduling as a Lighting Management Strategy,* Lighting Design & Application, Vol. 14, No. 5, pp. 3-19, May, 1984.

Rubinstein, F., and M. Karayel, *The Measured Energy Savings From Two Lighting Control Strategies,* IEEE Transactions on Industry Applications, Vol. IA-20, No. 5, pp. 1189-1197, 1984.

Verderber, R., O. Morse, and F. Rubinstein, *Effect of Filament Power Removal on Fluorescent Lamp Systems,* Proceedings of the IEEE-IAS Conference, Ontario, Canada, Oct. 1985.

Verderber, R and F. Rubinstein, *Photoelectric Control of Daylight-Following Lighting Systems,* Electric Power Research Institute Final Report CU-6243, 1989.

Verderber, R., O. Morse, and F. Rubinstein, *Performance of Electronic Ballast and Controls with 34- and 40-Watt F40 Fluorescent Lamps,* IEEE Transactions on Industry Applications, Vol. 25, No. 6, pp. 1049-1059, Nov/Dec 1989.

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

Appendix A

# NOTIFICATION MEMO TO OCCUPANTS

# Announcement

## Lighting Controls Study

Over the next few months, P.G.&E., with your management's support, will be conducting a lighting controls study in your area. The study is being managed by the Lighting Research Staff of the Lawrence Berkeley Laboratory with the cooperation of the building managers, Goldsmith and Lathrop. The weekend of May 6, the existing ballasts and lamps in the overhead lighting system will be replaced with a dimmable lighting control system that uses high-frequency ballasts.

During the test period, various lighting control strategies will be demonstrated. These tests are being conducted to determine how much energy can be saved with this control system. In certain areas, we will be installing photocells in the ceiling to control the lighting system. In addition, light meters will be installed near a few desks to assure that proper light levels are maintained. These meters are being installed only to measure the performance of the lighting system and will not intrude on your privacy.

During some tests, the lighting system will be dimmed after working hours to reduce energy during unoccupied times. Should you need full lighting after hours, you will be able to conveniently obtain it using your push-button phone. You will receive instructions on how to do this before we begin any of these tests.

PG&E and LBL have considerable experience in conducting these types of on-site demonstrations. With Goldsmith and Lathrop's participation, we are taking every effort to assure that your work routine will not be altered or that your work environment will be compromised in any way. In fact, a recent study in Britain showed that a lighting system similar to the one being installed here actually improved occupant comfort and reduced fatigue.

We welcome your comments and suggestions and will be pleased to provide interested people with a copy of the final report.

Should you have any problems or questions, please contact:

Tom Sheehan
Goldsmith and Lathrop
547-4770

Thank you for your cooperation.

Appendix B

# GLOSSARY OF TERMS

## Appendix B: Glossary of Terms

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| Ballast: | A device used with a fluorescent lamp to provide the correct starting voltage and maintain the appropriate current conditions for operating the lamp. |
| Ballast factor: | The lumen output of a lamp operated by a commercial ballast divided by the lumen output of the same lamp operated on a reference circuit. |
| Control group (also control string): | A group of light fixtures controlled together to provide the same illumination level. |
| Control zone: | All fixtures on one lighting branch circuit. |
| Daylight: | Light from the sky and sun used to provide illumination for the performance of visual tasks. |
| Daylight control (also daylighting): | An energy-saving lighting control strategy in which a photocell is used with a dimming system to provide a fixed light level at the workplane by increasing the amount of electric light with decreasing daylight levels and decreasing the amount of electric light with increasing daylight. |
| Dimmer: | A control device for varying the light output from lamps. |
| Efficacy: | The ratio of light output from a lamp to the electrical input power, expressed in lumens per watt (L/W). |
| Electronic ballast: | A solid-state ballast that converts 60 cycle electric power to high frequency (20- 60kHz) power to drive a fluorescent lamp. |
| Footcandle: | A unit of illuminance; the illumination on a surface one foot square on which there is a uniformly distributed flux of one lumen. |
| IESNA: | Illuminating Engineering Society of North America. |
| Illuminance: | Lighting level, expressed in footcandles (English unit) or lux (metric unit). |
| Lamp: | Engineering term for light source, commonly referred to as a bulb or tube. |
| Lighting control: | General term referring to the devices and techniques necessary to provide the right amount of light where and when needed. |
| Load shedding: | A lighting control strategy for selectively reducing the output of lighting fixtures on a temporary basis as a means to reduce peak demand charges. |
| Lumen: | Basic unit of light flux. |

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| Lumen maintenance: | An energy-saving lighting control strategy in which a photocell is used with a dimming system to provide a fixed light level over the maintenance cycle. |
| Luminaire: | A complete lighting unit consisting of a lamp (or lamps), together with a housing, the optical components to distribute the light from the lamps, and the electrical components (ballasts, starters, etc.) necessary to operate the lamps. |
| Lux: | A unit of illuminance; the illumination on a surface one meter square on which there is a uniformly distributed flux of one lumen. |
| Override: | A switch that can be used by occupants to obtain lighting when required outside of normal operating hours. May be activated using a touch-tone telephone. |
| Photocell: | A light sensitive device for measuring a quantity of light. |
| Photometer: | An instrument for measuring lighting quantities such as illuminance and luminance. |
| Scheduling: | An energy-saving lighting control strategy for dimming or otherwise reducing light levels during hours when a building space is unoccupied or occupied by individuals with less stringent lighting requirements. |
| Troffer: | A recess-mounted lighting fixture. |
| Tuning: | An energy-saving lighting control strategy in which the light output of an individual fixture or group of fixtures is adjusted to provide the correct amount of light for a local task. |
| Workplane: | The plane at which work is performed and at which illumination is specified and measured. Usually taken to be 30" above floor. |

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