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Publication Date
1998-03-01

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**Environmental Energy
Technologies Division**

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March 1998

Preliminary Results from An Advanced Lighting Controls Testbed

Francis Rubinstein, Judith Jennings, Douglas Avery and Steven Blanc

Abstract

Preliminary results from a large-scale testbed of advanced lighting control technologies at the Phillip Burton Federal Building at 450 Golden Gate Ave. in San Francisco are presented. The first year objective of this project is to determine the sustainable energy savings and cost-effectiveness of different lighting control technologies compared to a portion of the building where only minimal controls are installed. The paper presents the analyzed results from six months of tests focused on accurately characterizing the energy savings potential of one type of daylight-linked lighting controls compared to the lighting in similar open-planned areas without dimming controls. After analyzing a half year's data, we determined that the annual energy savings for this type of daylight-linked controls was 41% and 30% for the outer rows of lights on the South and North sides of the building, respectively. The annual energy savings dropped to 22% and 16% for the second row of lights for the South and North, respectively, and was negligible for the third rows of lights.

Introduction

Previous research has shown that "second generation" (post 1988) lighting controls have the potential to reduce lighting energy use in commercial buildings by up to 35% compared to conventional lighting systems without controls [1-5]. The second generation lighting control strategies include: daylighting (automatically dimming the lights in response to available daylight), scheduling (dimming or switching fixtures on and off according to occupancy), and lumen maintenance (automatic compensation for long-term lumen losses). However, these systems proved difficult to calibrate and commission in actual practice and lack the distributed intelligence of emerging third generation systems. Furthermore, some studies [1,7] have hinted that the savings from lighting controls may not be persistent, i.e., the savings achieved in the first year of operation may not be realized in subsequent years due to bypassing of the controls.

Third generation lighting controls that are now becoming available offer a potential solution to the commissioning problems of earlier lighting controls, while providing many additional benefits, specifically: 1) lighting energy monitoring capabilities, 2) more accessible dimming and 3) ability to respond to real-time utility pricing methods.

In 1995, a partnership of the General Services Administration (GSA), Pacific Gas & Electric Co. (PG&E), and Lawrence Berkeley National Laboratory/U.S. Department of Energy (LBNL/DOE) was established to implement a large scale test of different lighting control systems at a major high-rise office building in San Francisco. The purpose of this lighting controls testbed was 1) to demonstrate whether existing, second generation lighting controls are an energy- and cost-effective means of meeting Federal energy efficiency directives while maintaining occupant comfort and satisfaction and 2) to demonstrate the additional energy savings benefits, operational advantages, and improved occupant response resulting from the application of more intelligent (third generation) controls.

Commercially-available lighting controls from several manufacturers (dimming ballasts, photosensors and controls) were installed throughout three floors of the building and the energy

performance of these controls is being measured using a third generation lighting control system that is connected to energy monitors that record lighting use data in all the 186 zones of the testbed. (A zone is a group of lights that are dimmed and switched together. Zones correspond to individual rooms, open-plan spaces on one switch or entire quadrants). The entire 4th floor (one third of the 18,000 gross square meter testbed) serves as a monitored basecase, allowing for defensible comparisons of the lighting energy usage in areas where different types of lighting controls are installed (floors 3 and 5) and where only manual switches are provided (floor 4).

This paper presents initial results from this lighting controls project with emphasis on the successful operation of one type of daylight-linked lighting controls that has resulted in significant and sustainable energy savings in some of the open-planned spaces within the larger test site. Detailed analysis of the energy-savings potential of the occupant detectors installed at the site as well as less-than-successful daylight-linked controls in individual offices will be presented in follow-on papers.

Methods

Determining the sustained energy performance of controlled lighting systems in a manner that will withstand scientific scrutiny requires sound experimental design and data analysis while recognizing that an operating building is not a laboratory experiment and not all experimental variables can be controlled.

To understand how well lighting controls save energy in an existing building, it is first necessary to understand how energy would be consumed in the absence of any additional controls (i.e. the baseline or basecase condition). "Measuring" energy savings is an imprecise science since all one can really do is compare the energy usage between different areas with varying controls treatments against areas without such controls. Alternatively, one can compare the same areas before and after installation of controls. In this study, we avoided the "before" and "after" approach because of inevitable changes in occupancy over time as well as the fact that the building across the street was under construction during the project. Some earlier case studies of lighting controls were flawed because the energy savings were calculated by comparison to baseline conditions that were not adequately measured or were dissimilar to the controls case. In our study, we have addressed this problem by establishing a large baseline area (the entire 4th floor) where only building standard light switches are used.

The room sizes and occupant activities (which consist of typical office tasks such as reading and word processing) are relatively homogeneous across all the floors of the testbed and energy usage in the baseline floor is measured using the same instrumentation methods and at the same time intervals as floors 3 and 5, where the different control systems are installed. With this approach, the effect of the adjacent building construction, for example, would equally affect the control zones and the basecase zones thus reducing the effects of this confounding variable.

Because of the inherent variability in lighting energy usage from zone to zone and day to day, lighting energy usage in multiple spaces must be monitored for extended periods in order to obtain a reliable estimate of the potential energy savings between the different examined space types and controls treatments. Furthermore, the influence of daylight will cause the savings from zones with daylight-linked controls to vary according to the time of year. To reach statistically significant conclusions concerning sustainable energy savings, measurements must be made for relatively long periods of time (on the order of months to capture seasonal effects).

Building and environs

The testbed site is three floors of the San Francisco Federal Courthouse (also known as the Philip Burton Federal Building)— a 21 story office building in downtown San Francisco. The building houses multiple Federal clients including the Federal Courthouse, the General Services Administration, the Federal Bureau of Investigation, the Internal Revenue Service and the U.S. Marshall's Office. The entire building (built in 1962) is 130,100 square meters (1.4 million square feet) and occupies one whole city block. There is a large building on the North side which comes up to the 8th floor. There is also a 15 story building under construction on the South side. Both these adjacent buildings have an effect on the availability of daylight within the test site.

Fenestration

The building envelope is conventional with single-glazed windows running from 1 meter above the floor up to the dropped ceiling (NEMA Type G at 2.7 meters (9 ft). Each window is fitted with mini-blinds that are operated by the occupants as necessary to block direct sun and glare. The windows on all elevations except North have been retrofitted with solar film which reduces the window transmittance to about 40%.

Overhead lighting system

The overhead lighting for the three floors of the testbed consists primarily of 3-lamp direct parabolic-type luminaires. T-8 fluorescent lamps and electronic ballasts (non-dimming) have become building standard since 1993. In a few areas, 2x2 3-lamp luminaires are used. Changes had to be made in the ceiling wiring system for all three floors to accommodate the requirements of the testbed. With one exception (see below), only 2-lamp dimming electronic ballasts were available in 1995 when the testbed equipment was specified so the 3-lamp fixtures had to be "tandem" wired. That is, the inboard lamps of two adjacent luminaires were wired to be operated by one 2-lamp ballast while the outboard lamps where operated by two additional 2-lamp ballasts. In order to be able to dim luminaires in rows running parallel to the window wall, the tandem wiring was applied to pairs of fixtures in each row (rather than transversely as is common in other parts of the building).

The luminaires for all three floors are identical except for ballast type. The ballasts installed in the 4th floor (basecase floor) overhead lighting system were of the instant-start, non-dimming type. As the dimming ballasts on the 3rd and 5th floors were, of necessity, rapid-start, this introduces some unavoidable differences in the performance characteristics between the basecase floor lighting system and the 3rd and 5th floor systems.

T-8 fluorescent lamps (Philips TL-735) were installed throughout all three floors of the test site. These lamps were seasoned on site by operating continuously for 100 hours at full intensity immediately after re-lamping.

Based on an photometric survey conducted at night immediately the re-lamping and burn-in, we measured the interior illuminance in open-planned spaces without partitions to be 800-900 lux. In the partitioned, open-planned areas and in the individual offices (which have ceiling-high partitions separating the rooms), the measured illuminance at the workplane was 500-700 lux (initial).

Partitions

In all open-planned areas, building standard partitions were installed separating the individual workstations. The partition heights between the workstations were not identical and generally varied between 1.2 and 2.1 meters (4-7 ft). The partition surfaces are a beige fabric with a

reflectivity of about 60%. Workstations are also equipped with individual task lights that are mounted underneath storage cabinets. These task lights are under occupant control.

In the individual offices, there are no internal partitions or additional task lights.

Installed lighting controls

Lighting controls equipment from eight different manufacturers was installed on floors 3 and 5. Several different control system configurations are being tested. In the single- and multiple-person offices we are testing: 1) occupant sensors (OS) only, 2) OS plus daylight-linking and 3) OS with manual dimming (wall slider and infrared remote). In the open-planned areas we are testing 1) daylight-linking and 2) wide area OS. Dimming, 2-lamp, electronic ballasts (Advance Mark VII and Motorola Helios), occupancy sensors, photocells and manual dimming controls were installed throughout the third and fifth floor ceiling lighting systems, respectively.

Dimming 3-lamp electronic ballasts were available from only one manufacturer (Lutron ECO-10) at the time of installation. These ballasts, associated controllers and photocells and were installed in the 273 m^2 (2900 ft^2) open-planned office spaces on the North and South sides of the 3rd floor. Only the sustained energy performance of the Lutron daylight-linked control systems has been analyzed to date and this data is presented in this paper. (Results from the tests of other lighting controls equipment will be presented in future papers).

The Lutron Microwatt controller uses the open-loop proportional control algorithm [6] to dim the electric lights in synchrony with the available daylight detected by the ceiling-mounted photosensors. Each zone of lights (see Table 1 for list of all zones reported in this paper) is controlled by a single photosensor and controller. Adjustment of system gain, minimum dim level and maximum output are all set from the controller after installation of the lighting controls.

The first and second rows of controlled lights shown in Table 1 are 1.5 and 4 m, respectively (5 and 13 ft.) from the window wall. The third row of lights is 6.5 m (21 ft.) from the window wall which is beyond the manufacturers' recommendation for effective daylighting. Nonetheless, for this test project, we thought it important to test the feasibility of daylighting at this distance even though we suspected that daylighting would not prove effective for this row of lights.

Table 1. Daylight-linked lighting control zones and comparable basecase zones

Zone	Description	Number of fixtures[†]	Max. Power (watts)	Notes
312	1st Row South	9	781	Manual wall switch controlled row
313	2nd Row South	9	745	Manual wall switch controlled row
314	3rd Row South	5	442	Manual wall switch controlled row
320	1st Row North	7 + (1) 2x2	660	Manual wall switch controlled row
321	2nd Row North	7 + (1) 2x2	750	Manual wall switch controlled row
322	3rd Row North	7	642	Manual wall switch controlled row
401	1st Row North, basecase	(7) 2x2	500	2x2 fixtures. Manual wall switch controlled row
402	2nd+3rd Row North, basecase	14	1265	Manual wall switch controlled two rows
407	1st+2nd+3rd Row South, basecase	23	1968	Manual wall switch controlled three rows

[†] 2x4 3-lamp parabolic-type direct luminaire unless otherwise noted

Data acquisition

The need to measure lighting energy usage of many zones at frequent intervals over extended times led us to an unusual data collection solution. Rather than installing an entirely separate data acquisition system (which we had estimated would cost about $200,000 for the number of measurement points we have), we took the novel path of use a newly available distributed intelligent control system (Matrix 4000 from Thomas Lighting), to collect the experimental data. The M4000 is a third generation lighting control system that consists of independent "smart panels" that are distributed throughout the areas of the building to be controlled. Each panel can be connected to a large number of switch inputs (e.g., wall switches or occupancy sensors) or analog inputs (such as light sensors) and can independently control the operation of multiple dimming lighting zones. All the panels can be individually programmed and operate independently from one another which provides a robust, reliable switching system for the building lighting. The panels are connected to one another via a simple network which lets all the panels send data to a computer connected to the network (Figure 1). The energy consumption of all the lighting zones in the testbed is measured using energy monitors (E-Mon D-Mon Energy Monitor Demand Monitor from E-Mon Corp.) that produce a number of electrical pulses proportional to the electrical energy consumption of each connected zone.
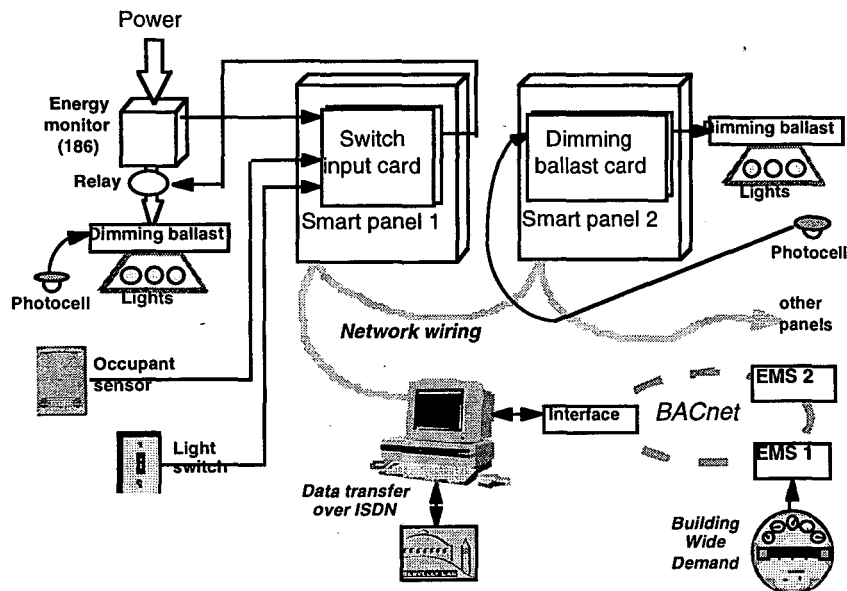
Fig. 1. Data collection system overview.

To an M4000 panel, the pulses from the E-Mon energy monitor looks just like a switch input, which it is well suited to process. By keeping a running count of the pulses produced by all the connected energy monitors, the M4000 becomes a high-performance data acquisition system capable of monitoring and reporting on the energy consumption from the hundreds of energy meters. In addition, the M4000 also records the on-off states of all manual light switches and occupant sensors used throughout the three floor testbed. Because the testbed control system can measure the energy usage in every zone and record the states of all the connected manual switches and occupant sensors throughout the testbed, the resolution and quality of the lighting data extracted from this site is unequaled. Thus the testbed represents unique example of using a lighting control system to monitor as well as control connected lighting loads.

All the data collected by each of the "smart panels" is automatically saved to a PC that is connected to the M4000 network. The data stored on the PC is periodically downloaded through a high speed ISDN line to Berkeley Lab for analysis.

Data collection

Although installation of the lighting controls hardware and the M4000 control/monitoring system was completed in May 1996, data collection on the operation of the lighting control testbed did not commence until January 1997 because of delays in delivery of the data collection cards. Energy use data from the 185 installed energy monitors has been collected at 1 hour intervals since January 1997. (In February 1998, we increased the data collection rate to 15 minute intervals). In addition, the system automatically records the time, date and location of every switch closure (wall switches and occupancy detectors, if installed) within the 3-floor test site.

Due to misinstallation of the energy monitors, accurate data was collected from only 25 zones between January and July 1997. In July 1997, we completed repairs to the energy monitoring wiring, including changing out the current transformers (CTs) that measure the current in each zone with more sensitive CTs. Since August 1997, we have been collecting validated data from over 90% of the 185 monitored zones.

Analysis of data

The data is analyzed and reduced using a series of customized PERL scripts (running on a UNIX workstation computer) that check the validity of the data files, apply calibration constants to the raw data, display lighting power as a function of time of day for selected zones, compute maximum and minimum power per day and compute energy usage statistics such as average, maximum and daily power per zone.

In this paper, we report the results from only one type of daylight-linked lighting control system installed in the testbed. Six months of data (from July 1, 1997 through December 31, 1997) from the nine zones listed in Table 1 was analyzed and is presented. Since this period covers essentially from the Summer Solstice through the Winter Solstice, the energy usage averaged over this six month period should provide a reasonable estimate of the annual energy usage patterns from the basecase zones as well as the average annual energy savings from the six daylight-linked control zones.

Figure 2. An interior view of the third floor taken during commissioning of the lighting system before installation of the furniture system. Note the luminance pattern on the far wall which shows that the row of lights nearest the window is heavily dimmed while the second row is at near full intensity.

Results

Basecase zones results

Initially, we present the energy usage results from the basecase zones. Figure 3 shows the lighting power for the Basecase (South) zone as a function of time of day for six representative days in July, September, and December, 1997. Lighting power for the Basecase (North) zone is given in Figure 4 for the same six days. These figures show that there is some variation in the lighting operating hours between different days. The lights in these zones may be switched on as early as 5am and off as late at 10pm. However, 14 hours of operation is a reasonable average for weekday operation for both basecase zones. The slightly lower power levels evident in the two shown December days (Figure 3) is thought to be due to a failed ballast although this has not been verified.
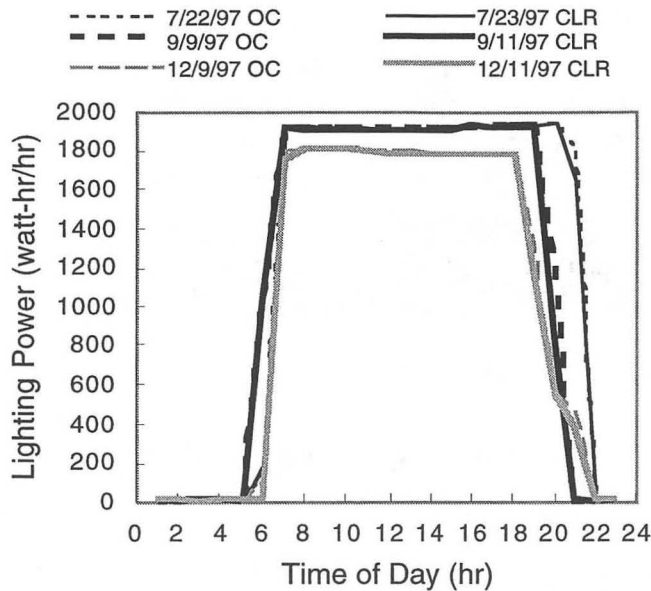
Figure 3.   Lighting power for Baseline (South) zone vs. time of day for clear (CLR) and overcast (OC) days in July, September and December.
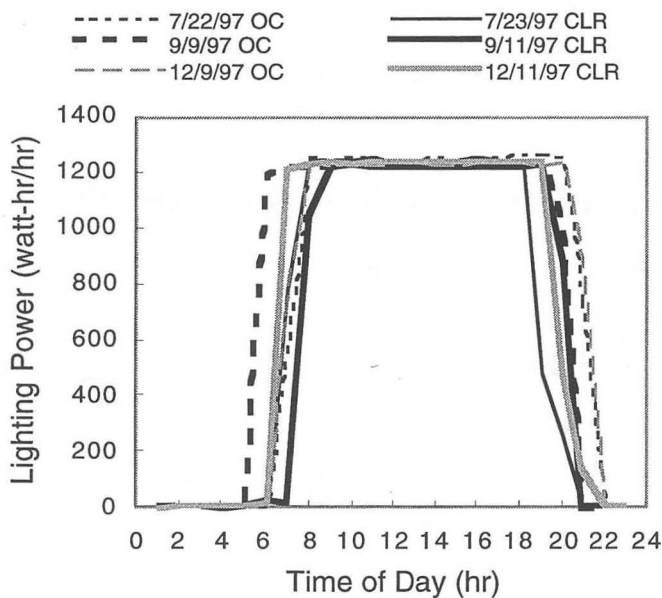
Figure 4.   Lighting power for Baseline (North) zone vs. time of day for clear (CLR) and overcast (OC) days in July, September and December.

Figure 5 shows the relative average daily lighting energy consumption for the large basecase zone on the 4th floor South (Basecase (South) in Table 1). Each data point represents a day's measured lighting energy use (calculated over the entire day or just between 6am-6pm) relative to how much energy would be used if the lights operated at full power for 24 hours. Data for non-holiday weekdays only are shown. Weekends, holidays and otherwise anomalous days have been excluded. Two series are plotted in Figure 5: the 6am-6pm series indicates the lighting energy measured between 6am-6pm divided by how much energy would be required if the lights were operated at full power for the entire day. In the entire day series, the daily energy use is for the full 24 hours. Separating the energy usage during the operating hours only (6am-6pm) allows a better

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estimate of the energy savings potential of daylighting alone, since it reduces the effect of random differences in the actual lighting hours each day. The lights in this open-planned space (as well as open-plan spaces on floor 3) are switched on and off at somewhat different times at the beginning and the end of the day by the occupants, not by timeclock.
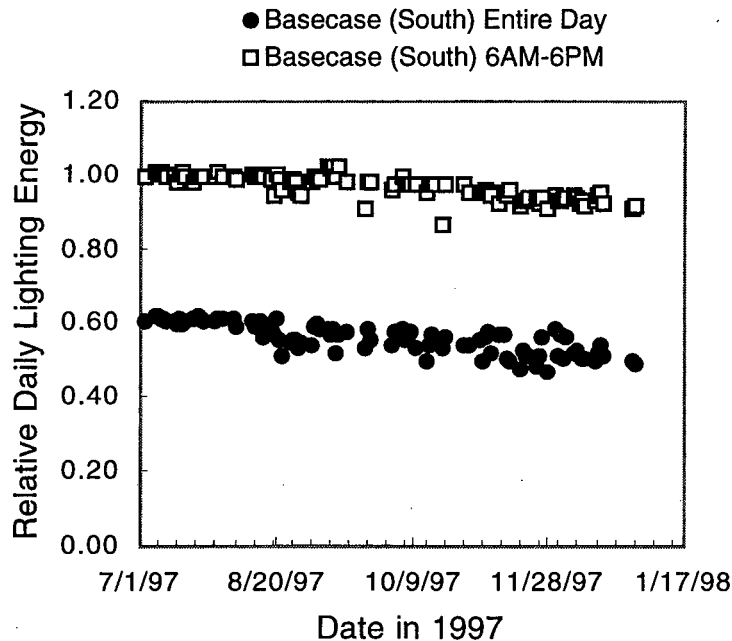

● Basecase (South) Entire Day
□ Basecase (South) 6AM-6PM

Figure 5.   Relative daily lighting energy for the basecase (South) zone for non-holiday weekdays. Relative daily lighting energy is calculated for the entire day and for 6am-6pm only.

Figure 5 indicates that the daily lighting energy use is quite similar from weekday to weekday even though the lights are manually switched. The lights in this zone don't dim; thus differences in energy use (entire day series) are caused by changes in hours of operation only. The data in Figure 5 can be used to derive an accurate estimate of the average annual operating hours for this space. Since the relative average weekday lighting energy is approximately 0.6, the hours of operation are 14.4 hr/day. Thus annual hours (excluding weekends and holidays) are 3754 hr/yr (14.4 hr/day x 365 days/yr x 5 weekdays/week / 7 days/week).

Daylight-linked zone results

The next series of figures (Figs. 6 - 11) show the lighting power as a function of time of day for the 1st, 2nd, 3rd Row South, and the 1st, 2nd, 3rd Row North, respectively for the same six selected days in July, September and December as were shown for the basecase results. Figure 6 shows that on clear days, the lighting power in the 1st Row South drops from about 780 watts in the early morning to about 200 watts for several hours each day. This lower limit on the lighting power (about 25% of maximum) is an attribute of this particular dimming ballast and controller. This value can be adjusted upwards by tweaking the controller. For this installation, we set the minimum value to the lowest possible. According to the manufacturer, 25% power corresponds to about 10% light output, but we have not confirmed this with measurement. For the shown clear day in December, the lighting power does not quite reach minimum during the day. For the shown overcast days, the power also does not quite reach minimum but approaches it for several hours each day.
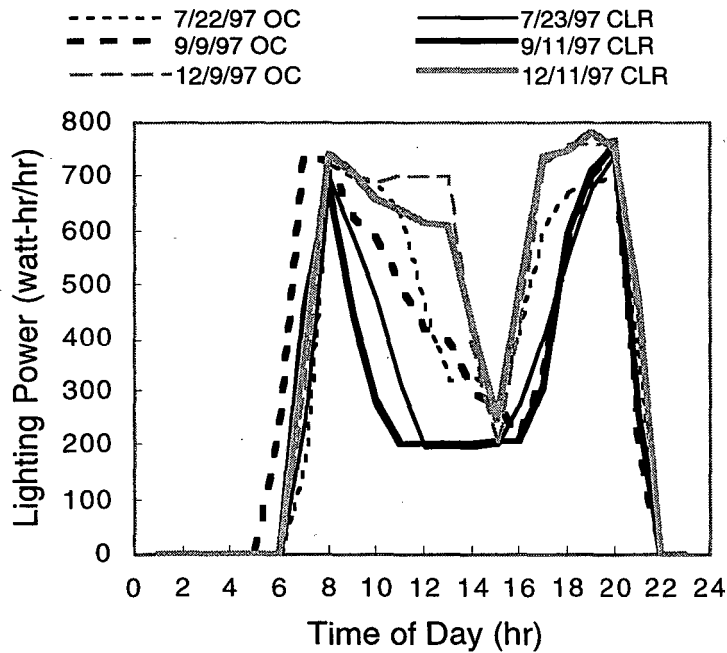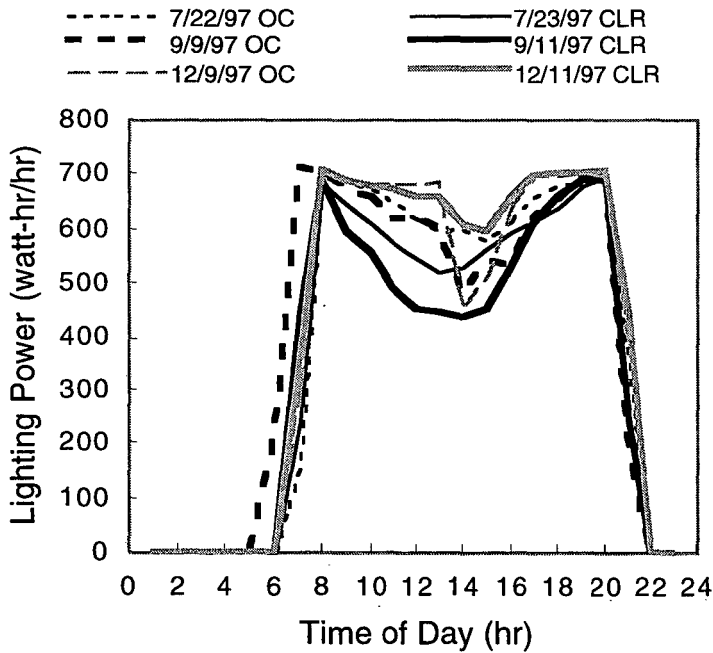
Figure 6.   Lighting power for 1st Row South vs. time of day for clear and overcast days in July, September and December.

Note that even on overcast winter days, there is still significant reduction for 2 hours. Figure 7 shows the lighting power for the second row of lights from the South window. The reduction in lighting power is less significant than for the lights nearest the window. Nevertheless, loads are 60% of maximum for a few hours during September, during which energy prices here often spike. The third row of lights from the South window (Figure 8) shows virtually no reduction in lighting power because of the highly attenuated daylight at this distance from the window.

Figure 7.   Lighting power for 2nd Row South vs. time of day for clear and overcast days in July, September and December.
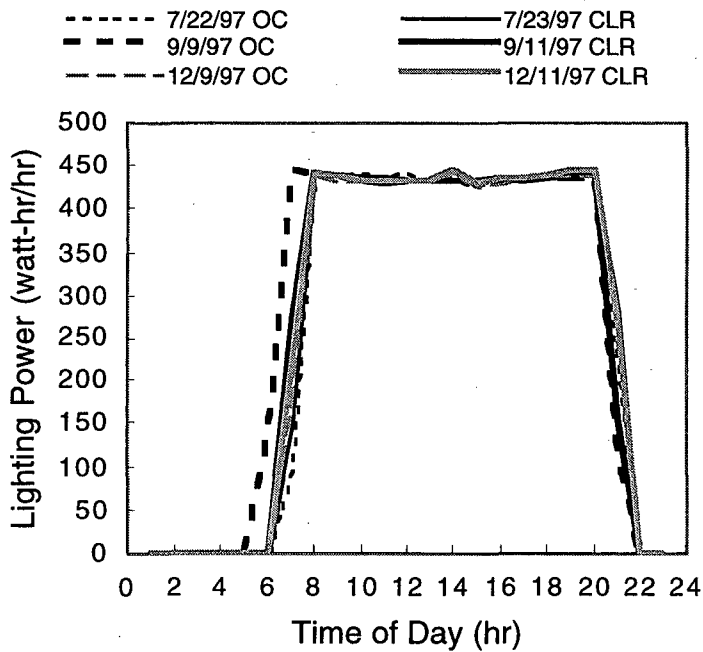
- 10 -

Figure 8. Lighting power for 3rd Row South vs. time of day for clear and overcast days in July, September and December.

Figures 9-11 show analogous plots as previous figures 6-8 but for the North side of the building. The first row of lights show significant dimming during daylight hours but not as much as the South side. For the second row (Fig. 10), the dimming is more modest still but there is still some reduction in power even at the 3rd Row (Fig. 11).
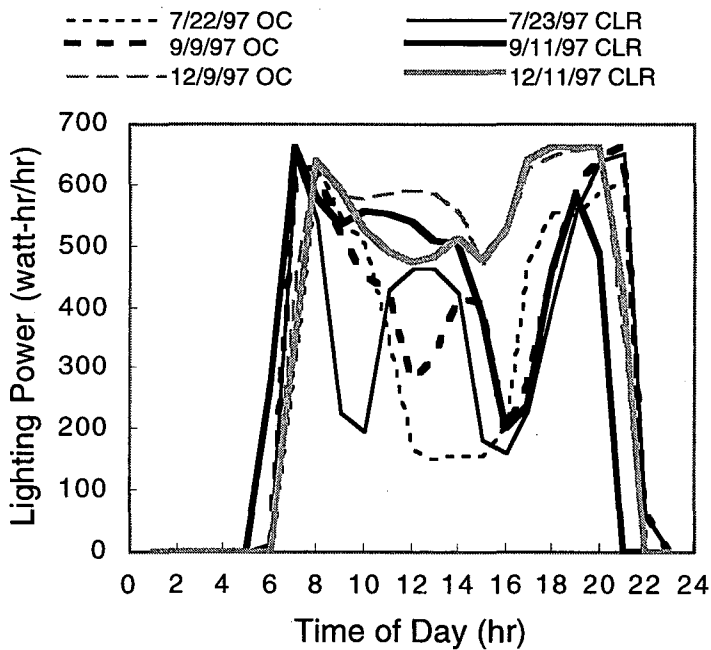
- - - - - 7/22/97 OC   ————7/23/97 CLR
■ ■ ■ 9/9/97 OC   ————9/11/97 CLR
— — — -12/9/97 OC   ═══════12/11/97 CLR

Figure 9. Lighting power for 1st Row North vs. time of day for clear and overcast days in July, September and December.
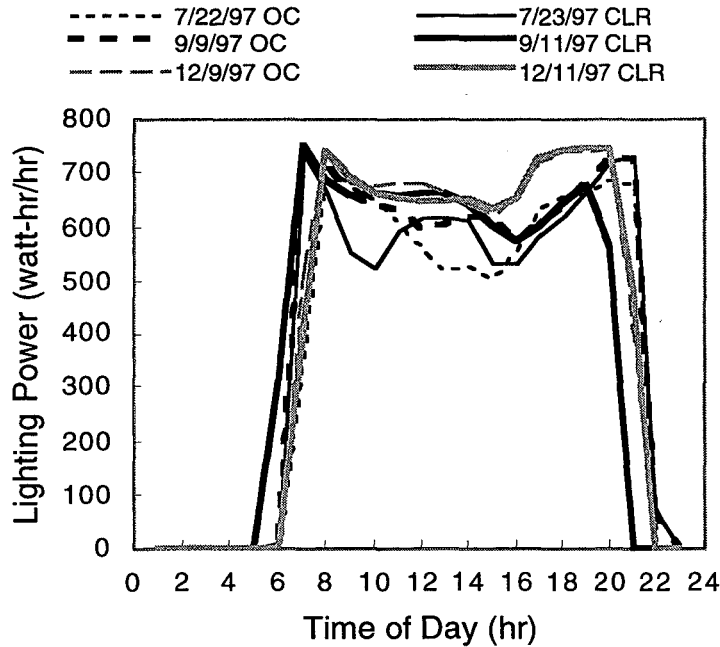
Figure 10. Lighting power for 2nd Row North vs. time of day for clear and overcast days in July, September and December.
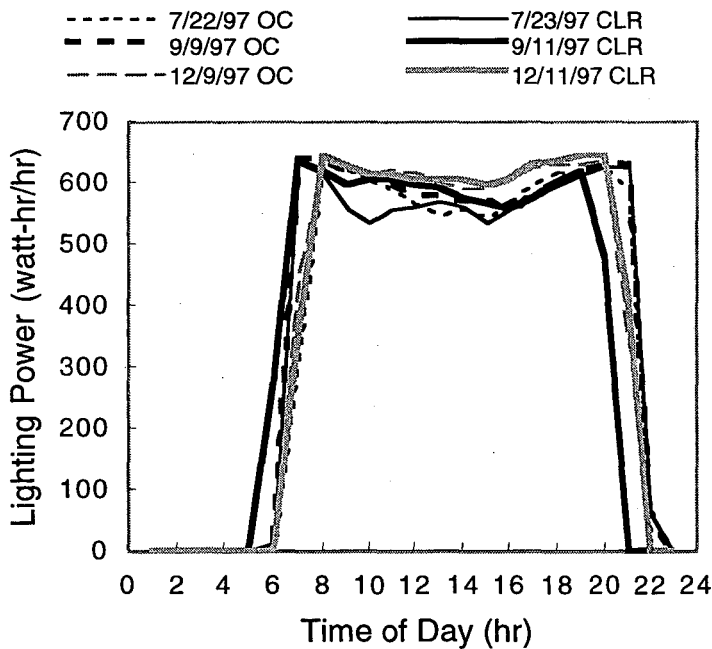

Figure 11. Lighting power for 3rd Row North vs. time of day for clear and overcast days in July, September and December.

Figure 12 shows the relative average daily lighting energy consumption for the daylight-linked 1st Row South zone and the basecase zone on the 4th floor South for comparison. Each data point represents the ratio of the measured lighting energy use between 6am-6pm and how much energy would be used if the lights operated at full power for 12 hours. Data for non-holiday weekdays only are shown. Weekends, holidays and otherwise anomalous days have been excluded. The daily lighting energy for the daylighting control zone is only 50% of that of the uncontrolled zone for at half of the 6 month period. During the winter time, the savings is about 20%.
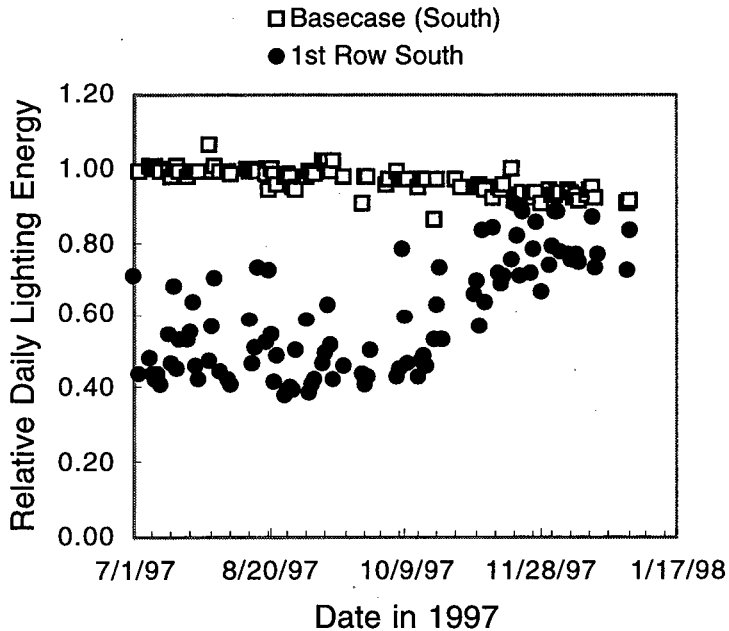
Figure 12. Relative daily lighting energy (6am-6pm only) for the 1st Row South and basecase (South) zones for non-holiday weekdays.

Figure 13 shows the relative average daily lighting energy consumption for the daylight-linked 2nd Row South zone. For this row of lights, the daily energy savings is about 25% for about 4 months of the six-month period and 15% for the other 2 months.
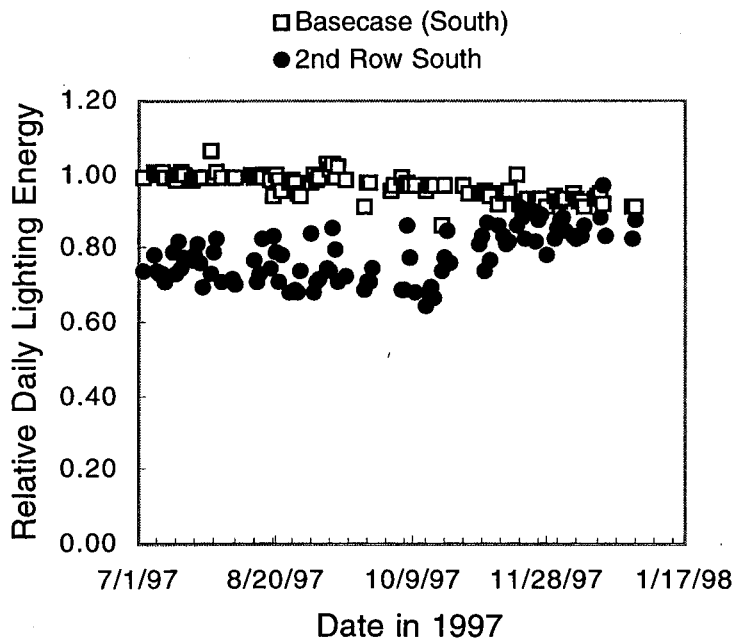
□ Basecase (South)

● 2nd Row South

Figure 13. Relative daily lighting energy (6am-6pm only) for the 2nd Row South and basecase (South) zones for non-holiday weekdays.

Figure 14 shows the relative average daily lighting energy consumption for the daylight-linked 3rd Row South zone. For this row of lights, the daily energy savings is negligible throughout the year.
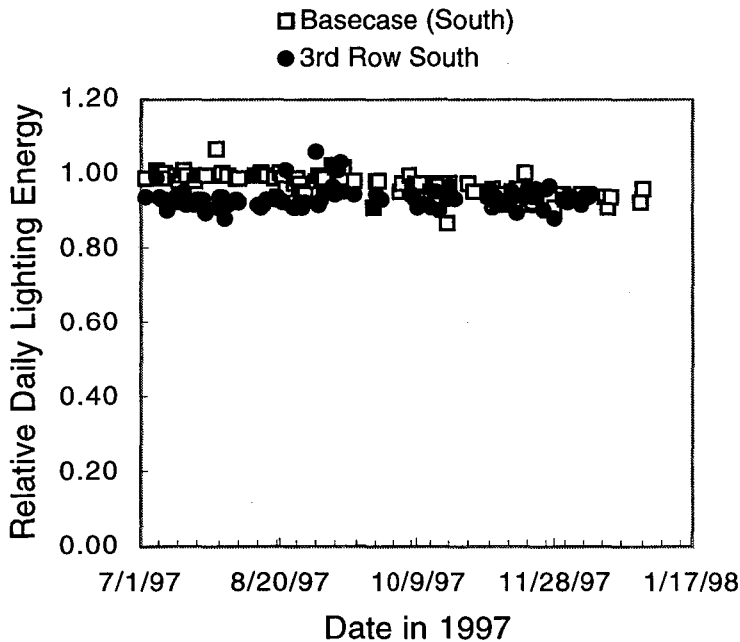
□ Basecase (South)
● 3rd Row South

Figure 14. Relative daily lighting energy (6am-6pm only) for the 3rd Row South and basecase (South) zones for non-holiday weekdays.

Figure 15 shows the relative average daily lighting energy consumption for the daylight-linked 1st Row North zone and the 2nd+3rd Row basecase zone on the 4th floor North for comparison. Each data point represents the ratio of the measured lighting energy use between 6am-6pm and how much energy would be used if the lights operated at full power for 12 hours. As before, data for non-holiday weekdays only are shown; weekends, holidays and otherwise anomalous days have been excluded. Around the time of the summer solstice, the daily lighting energy for this controlled 1st Row from the North window is only 50% that of the uncontrolled zone. Around the autumnal equinox (Sept 21), the savings is about 30%, dropping to 20% during the winter months.
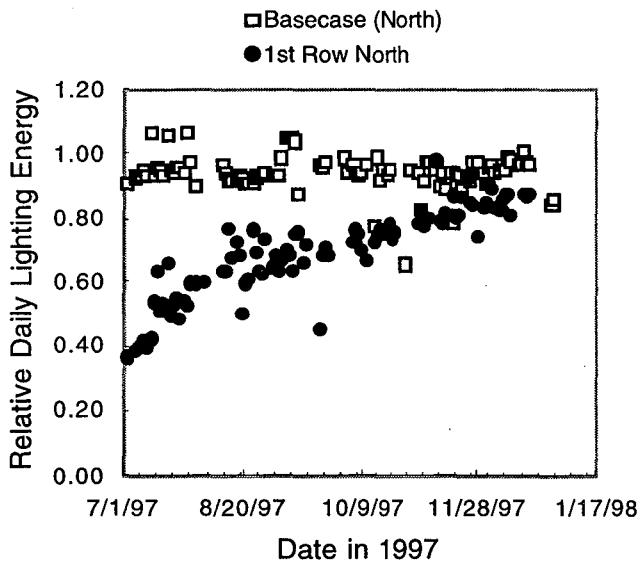

□ Basecase (North)
● 1st Row North

Figure 15. Relative daily lighting energy (6am-6pm only) for the 1st Row North and basecase (North) zones for non-holiday weekdays.

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Figure 16 shows the relative average daily lighting energy consumption for the daylight-linked 2nd Row South zone. For this row of lights, the daily energy savings is only about 20% during the summer falling to less than 10% during the winter.
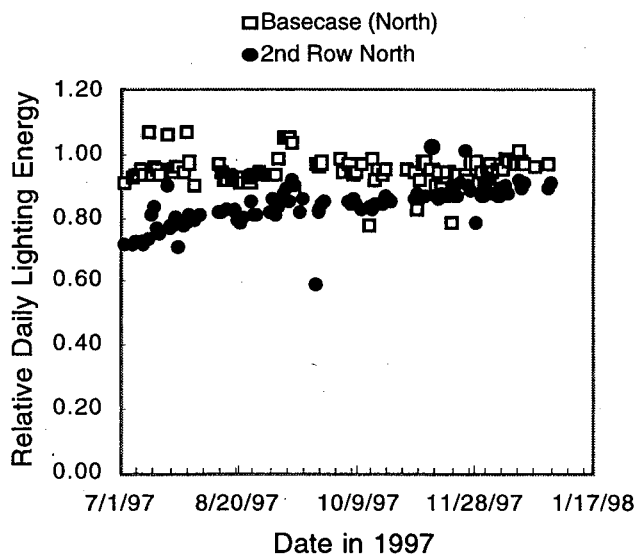
□Basecase (North)
●2nd Row North

Figure 16. Relative daily lighting energy (6am-6pm only) for the 1st Row North and basecase (North) zones for non-holiday weekdays.

Figure 17 shows the relative average daily lighting energy consumption for the daylight-linked 3rd Row North zone. For this row of lights, the daily energy savings is negligible throughout the year. However, there is evidence of a small savings during the summer that was not observed in the 3rd Row South (Fig. 14).

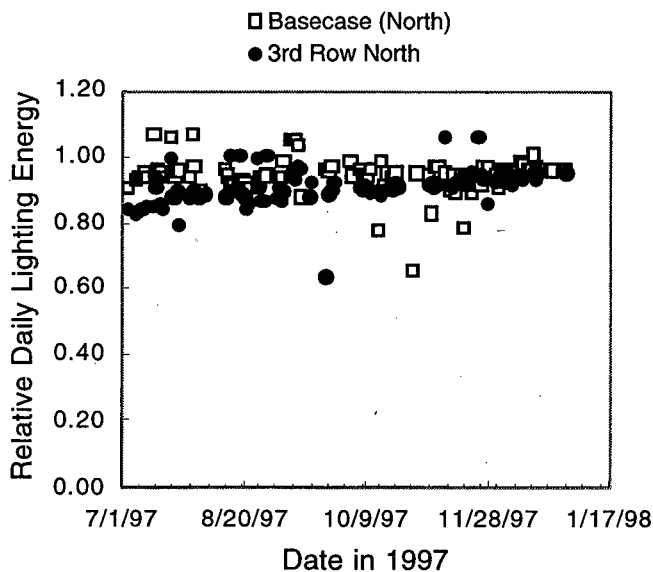□ Basecase (North)
● 3rd Row North

Figure 17. Relative daily lighting energy (6am-6pm only) for the 1st Row North and basecase (North) zones for non-holiday weekdays.

Finally, fig. 18 presents the relative daily lighting usage (6am-6pm) binned into monthly intervals showing all 3 South rows on one summary plot. Six-month averages and standard deviations for each row of lights are also displayed. Since the data interval examined in this analysis covers between the summer and winter solstices, the six-month averages should provide an accurate estimate of the annual savings (except for weather effects). The 1st and 2nd Rows South had six-

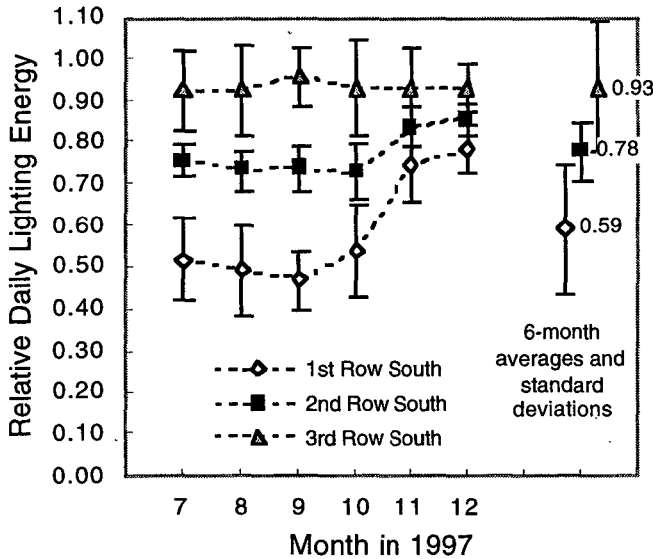month average savings of 41% and 22%, respectively. The average savings for the 3rd row was under 10%.

Fig. 18. Relative daily lighting energy usage (6am-6pm only) for 1st, 2nd and 3rd Rows South averaged over the last six months of 1997. 2/3 of the measured values for each month fall within the indicated standard deviation error bars. Semi-annual averages and standard deviations for each row are shown at the right of the plot.

Fig. 19 presents the relative daily lighting usage (6am-6pm) binned into monthly intervals showing all 3 North rows on one plot. Six-month averages and standard deviations are also shown. The 1st and 2nd Rows North had six-month average savings if 30% and 16%, respectively, with negligible average savings in the 3rd Row.
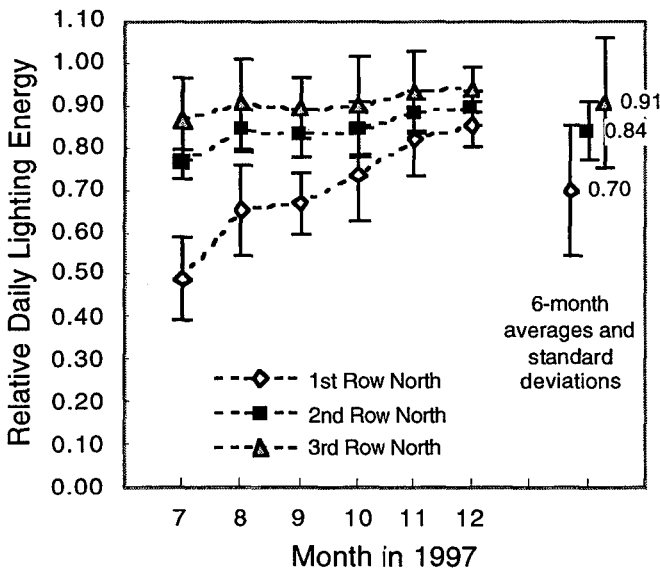

Figure 19. Relative daily lighting energy usage (6am-6pm only) for 1st, 2nd and 3rd Rows North averaged over the last six months of 1997. 2/3 of the measured values for each month fall within the indicated standard deviation error bars. Semi-annual averages and standard deviations for each row are shown at the right of the plot.

Discussion

In particular, we noted that the reduction in electric lighting demand from these daylight-linked systems was coincident with the utility's peak load profile. Thus this system saved the most lighting power at just that time of day when the utility's more expensive on-peak energy prices were in effect. The coincidence of the reduction in lighting power with the utility's peak load

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profile is one of the most compelling reasons for considering daylight-linked controls in commercial building applications.

The curious central hump in the power profiles for the 1st Row North (Fig. 9) deserves an explanation. We observed that on clear days the building itself blocked direct sunlight from striking the lightly colored building across the street for a few hours in the middle of the day. During this time, there was less light entering through the window so the lighting system compensated by providing more light (and thus more power as shown in the plot).

Although only six months of performance data has been presented in this paper, this daylight-linked system has perform satisfactorily, without occupant complaints, since July 1996, when it was first commissioned. It should be considered that the calibration and commissioning of the daylight-linked system reported here was performed by one of us, rather than by the contract lighting maintenance company that installed the lighting controls equipment for the testbed. It took us approximately 30 minutes to calibrate the response of each of the individually controlled zones although we believe that the calibration time could be significantly reduced with experience. The particular daylight-linked system reported here uses an open-loop proportional control algorithm [6] which must have its sensitivity adjusted to match the specific daylight distribution in the space. The system tested provides this adjustment on the lighting controller, which, in our installation, was located above the dropped ceiling. Because the controller was located some distance from the photosensor, proper adjustment of system sensitivity required two people: one watching the display on a light meter located at a selected location on the workplane (we call this a stationpoint) and a second working the calibration controls on the controller. We calibrated the system response on a clear summer day and set the response so that the total illuminance at the stationpoint was between 750-800 lux. This is easily done with a light meter. Without such a meter, it would have been very difficult to set the light levels precisely. (The reader is referred to [7] for a more complete discussion of the problems of calibrating and commissioning lighting control systems).

Although we have documented significant and sustainable energy savings with this daylight-linked system, whether such systems can be considered cost-effective will depend on a number of factors, particularly the cost of the dimming equipment and the lighting power density of the basecase system against which the savings are calculated. For this GSA building, it is appropriate to use 15 w/m^2 (1.4 w/ft^2) as the basecase lighting power density since that is the LPD of the lighting on the basecase floor (4th floor) as well as other recently renovated floors in this building. To compute cost-effectiveness for this particular application, we first compute the lighting energy cost per unit area per year for the basecase. Then we use the energy savings reported above to calculate the lighting energy costs for the daylight-linked control zones. The incremental cost of the lighting controls equipment (again on a unit area basis) divided by the annual energy cost savings gives the simple payback time for the lighting controls investment in this application.

The lighting energy cost per unit area per year for the above basecase is fairly low (15 w/m^2 (1.4 w/ft^2) x 4125 hr/yr x $0.09/kWh x 1 kWh/Wh = $5.48/m^2-yr ($0.51/ft^2-yr)). For the daylight-linked controls measured and reported above, the lighting energy costs are $3.33, $4.41, $3.33 and $4.73/m^2-yr ($0.31, $0.41, $0.36 and $0.44/ft^2-yr) for the 1st Row South, 2nd Row South, 1st Row North and 2nd Row North, respectively. These relatively modest savings translate into very long payback times (9-24 years) if the incremental installed cost of the lighting controls is $21/m^2 ($2/ft^2). If the cost of the lighting controls equipment is $10/m^2 ($1/ft^2) (which we believe is achievable using currently available equipment), the paybacks are 4.7 and 6.4 years for the 1st Row South and North, respectively. Since GSA can use a 10-year discounted payback time for its

energy efficiency investments, daylight-linked controls for the outermost rows of lights could be considered cost-effective at an installed cost of $10/m^2 ($1/ft^2).

Because GSA now requires energy efficient lighting in its buildings, the basecase lighting power density at this building may not be representative of other commercial buildings. For example, in many existing commercial buildings, where older, less efficient lighting equipment is still in use, LPDs are often 21 - 27 w/m^2 (2-2.5 w/ft^2) rather than 15 w/m^2 (1.4 w/ft^2). For a typical building with a basecase LPD of 27 w/m2, the payback times for daylight-linked controls would be considerably shorter than we have estimated above (2.5 - 3.5 yr for controls costing $1/ft^2 or 5 - 13 yr for controls at $2/ft^2). Finally, in our study we only investigated how well the control system exploited daylight-linking. In more typical applications, the same control hardware would be used to implement multiple control strategies (such as scheduling or even load shedding), which would increase the annual energy cost savings without increasing first costs. By using multiple strategies, lighting controls can be quite cost-effective.

Nonetheless, these economics should sound a cautionary note to lighting controls equipment manufacturers. If dimming lighting controls are to be sold based solely on their ability to effect a cost-effective reduction in lighting energy costs, the incremental installed cost of the lighting controls should not exceed about $10/m^2 ($1/ft^2) if a typical payback of 3-4 years is required.

Conclusion

This investigation has shown that currently available daylight-linked control systems can bring about significant and sustainable reductions in electrical energy in a typical high-rise office building. We found that the annual energy savings from these controls was 30-41% for the outermost row of lights and 16-22% for the second row of lights from the window wall. This study shows that daylight-linking controls should be considered as an energy savings strategy for reducing lighting energy consumption in commercial buildings.

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Acknowledgment