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Summary

The energy-saving benefits of two lighting control strategies -- scheduling and daylighting -- were investigated at demonstration sites in two large commercial buildings. A continuously-dimmable lighting control system was installed at the Pacific, Gas & Electric Co. building in San Francisco and an on/off switching system was installed at the World Trade Center building in New York City. By automatically scheduling the operation of the lighting systems to conform with occupancy patterns, lighting energy consumption was reduced 10 to 40%. Several scheduling techniques were investigated and the influence of switching zone size on energy savings was examined. Using photo-electrically controlled lighting systems which switch or dim lighting in accordance with available daylight, the energy consumed for lighting in daylit areas was reduced 25 to 35%. The influence of clear and overcast conditions on the energy savings associated with daylight- linked controls is discussed.

1. INTRODUCTION

As the cost of energy continues to rise, increasing effort has gone into minimizing the energy consumption of lighting installations. This effort has evolved principally along three lines: the development of new, more efficient lighting equipment, the utilization of improved lighting design practices (e.g. task/ambient lighting systems) and finally, improved lighting energy management practices. This paper is concerned with lighting energy management practices and how effective lighting control strategies can minimize the excessive use of electric lighting in buildings.

Two frequently-encountered examples of excessive use of electric lighting are 1) the provision of electric lighting during periods when a building is partially or completely unoccupied and 2) the supply of full electric lighting in daylit portions of a building despite the availability of daylight to partially satisfy lighting requirements. The waste associated with the first example has been exacerbated by the construction of buildings without even wall switches for the control of lighting. In these buildings, lighting circuit breakers are activated when occupants first arrive and switched off at some point after the workers and cleaning crew leave. Such building operation clearly invites waste since inaccessible controls such as circuit breakers (which are often in a locked electrical closet) are less frequently used than more accessible controls.[1] In regards to the second example, the widespread use of inexpensive dedicated fluorescent lighting without the means to control lighting has discouraged the use of daylighting as a practical source of illumination for visual tasks.

Many types of lighting control products are available to reduce the unnecessary expenditure of energy for lighting, but little data have been collected to quantify the energy savings which results from the implementation of lighting control strategies in real building environments. In this report, we will describe the energy-savings that were measured when two lighting control strategies -- scheduling and daylighting -- were applied in two large-scale lighting energy management demonstrations in San Francisco and New York City.

2. LIGHTING CONTROL STRATEGIES

The energy consumed for lighting in buildings is a function of two variables: energy (kWh) = power (kW) x time (hour). The purpose of lighting controls is to allow the building manager dynamic control over these two parameters so as to satisfy the lighting needs of the building occupants with a minimum expenditure of energy. Several lighting control strategies are available to manage lighting energy use in buildings, although in this paper we are concerned with only two: scheduling and daylighting. We will limit the discussion to fluorescent lighting systems since these are the prevalent source of lighting in commercial buildings.

Scheduling

The purpose of scheduling is to provide appropriate illumination levels and lighting patterns when required and to switch lighting off when it is not. Lighting control hardware which can automatically schedule lighting operation fall into roughly three categories:

- Personnel detectors which activate a lighting circuit according to the presence or absence of personnel in the area.
- Mechanical time-clocks which turn on lighting in an area for a pre-set period of time.
- Computer-based, programmable control systems which turn lighting on and off according to a pre-programmed schedule.

The present study is concerned with the performance of computer-based, programmable control systems which are useful for scheduling light levels in buildings where occupancy patterns are reasonably well-defined and predictable. For example, in commercial office buildings, the lighting system can be programmed to switch on prior to the arrival of the occupants, (e.g. on at 7:30 am) and, upon departure of the occupants, can be switched to reduced illumination levels for custodial and security personnel. Most programmable control systems incorporate a manual override mechanism so that occupants who need to work outside normal operating hours can obtain lighting in their particular zones as necessary. Manual overrides are typically wall switches although systems are available which utilize telephone-computer interfaces so that lighting can be overridden by occupants using their telephones.

Daylighting

In areas near windows or skylights, natural daylight can be used to partially satisfy lighting requirements. Contemporary lighting design practices, however, require that illumination meeting some specified design illuminance criterion be provided at all times a building is occupied. The sole use of natural daylight does not lend itself to such criterion since daylight is not available in the evenings and daylight illumination levels continually change with time, season, and sky conditions.

To exploit daylight as a source of illumination, it is necessary to establish an interactive link between the ambient lighting conditions and the electric lighting system. This can be achieved with a photo-electrically controlled lighting system which, by means of a photo-sensitive device, adjusts the output of the electric lighting system based on the amount of prevailing daylight. Lighting control hardware which link electric lighting to available daylight generally fall into two categories depending on whether the hardware is continuously-dimmable or digitally switched:

- Continuously-dimmable electric lighting systems controlled by photosensors which continually adjust the electric lighting level based on the amount of daylight striking the control photosensors.
- Photo-relay-based systems which automatically switch off perimeter lighting when daylight is sufficient to meet lighting needs.

3. DEMONSTRATION SITE DESCRIPTIONS

In order to measure the potential energy-savings associated with scheduling and daylighting under real field conditions, two demonstration sites were selected. The 30th floor of the Pacific, Gas & Electric Co. building in San Francisco was selected for installation of a continuously dimming lighting control system while a programmable switching system was installed on the 58th floor of One World Trade Center in New York. The system at the P.G.&E. building was designed to continuously dim large blocks of luminaires using centralized power units to electrically accomplish the dimming. The programmable lighting control system at the World Trade Center used microprocessor-controlled relays to switch lighting loads on and off. (By connecting one relay to each ballast in the lighting system, we could control individual fixtures in this installation). Thus the lighting controls at these two sites were functionally dissimilar: the hardware at the P.G.&E. site permitted continuous control over large blocks of lights while the controls at the W.T.C. allowed only digital switching but of individual fixtures. By using different lighting control hardware in these two demonstrations, we were not only able to measure the energy-savings with daylighting and scheduling at two buildings under different building operating conditions, but could also examine the control strategies using different techniques.

World Trade Center

Physical Site Description. The 58th floor of the World Trade Center is located approximately half way up the north tower of the World Trade Center complex. The 58th floor occupies a 40000 ft^2 area but only 29000 ft^2 is usable office space. The remaining 11000 ft^2 is core space where airshafts, elevators and corridors are located (Fig. 1).

Approximately 95% of the usable space is open-office landscaped with 5 ft high partitions located between adjacent work stations to provide privacy. The remaining 5% of the usable floorspace is used for conference rooms and a library which are enclosed by ceiling-high partitions.

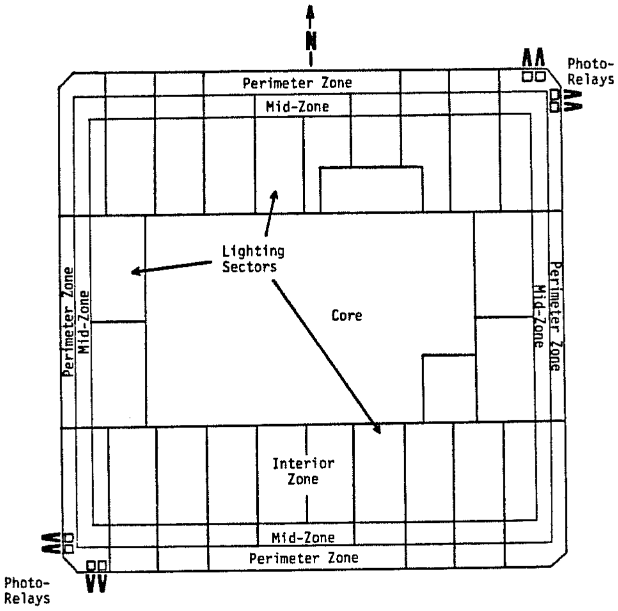


Fig. 1. Floor plan of 58th floor World Trade Center showing 1000 square foot lighting sectors and daylighting zones.

The window wall enclosing the 58th floor is identical to the other floors of the tower and consists of 58 window elements per side. Each window is 15" wide and 87" high with adjacent windows on 34" centers. The window-to-wall ratio is about 0.4. Windows are fitted with diffusing, low-transmittance fabric drapes which can be drawn by the occupants when required to limit the direct solar gain into the perimeter.

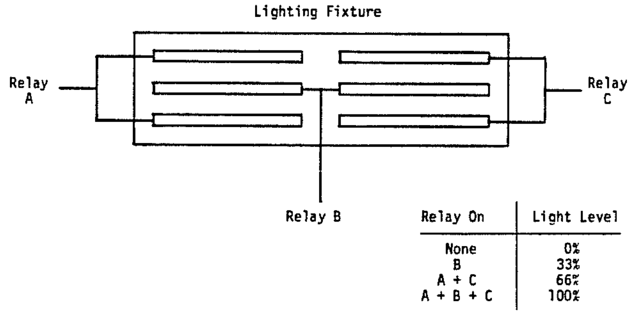
The 58th floor housed part of the engineering staff of the Port Authority of New York. The staff consisted of engineers, architects, draftsmen, administrators and clerical support. Visual tasks included drafting, writing, reading, and typing.

The lighting system on this floor consists of 450 six-lamp recessed fluorescent fixtures with prismatic diffusers. The fixtures are 8 feet long and approximately 18 inches wide. Each fixture houses six 35-watt lamps: pairs of lamps are connected to two-lamp ballasts as shown in Fig. 2.

The power density of the lighting system originally installed on this floor was approximately 4.4 watt/ft^2. In 1973, however, the Port Authority relamped the floor with 35 watt lamps and delamped over areas requiring less illumination. Thus the lighting power density at the time of the demonstration project was 2.6 watts/ft^2.

Lighting Control Hardware. A programmable lighting control system was installed on the 58th floor. This computer-controlled switching system used low-voltage relays to switch lighting loads on and off. A centrally located microprocessor communicated with remote transceivers via a low-voltage data link. Each transceiver controlled up to 32 relays which actually accomplished the load switching. The transceivers could accept inputs from occupant-activated switches and photo-relays as well as from the central computer. These occupant-activated switches permitted authorized personnel to override the computer control when necessary. The photo-relay inputs allowed appropriate lighting loads to be switched off when daylight falling on the photo-relays exceeded a certain level. Overrides could also be accomplished by means of a telephone/computer interface. This allowed workers to change the lighting pattern by using their own telephones.

Installation of Lighting Control System. The multi-ballasted fixtures were wired so that groups of fixtures could be set to any of four lighting levels. By using the relays to switch the two pairs of outboard tubes separately from the inboard tubes, four light levels -- 0, 1/3, 2/3, and full lighting -- could be provided (Fig. 2).



Relay On	Light Level
None	0%
B	33%
A + C	66%
A + B + C	100%

Fig. 2. Six-lamp luminaire from World Trade Center showing relay connections for 4 light level operation.

To allow maximum flexibility for this test program, one relay controlled each ballast. For many tests, the lighting fixtures were grouped into 1000 ft^2 independently-controllable sectors, simulating a pragmatic installation of this control system in a commercial building in which two relays would control 1000 ft^2 of lighting. Each sector was controlled by the central computer, which altered the light levels according to a programmed schedule and in response to the signal from exterior-mounted photo-relays which sensed the amount of daylight falling on each face of the building. Fig. 1 is a plan view of the demonstration site at the World Trade Center and shows the lighting arrangement used for most of the lighting control tests.

Instrumentation. The microprocessor used to control the lights in this installation was also used to collect the experimental data. When the microprocessor changed the lighting arrangement for the floor (by switching groups of relays on or off) it simultaneously recorded what that change was and at what time it occurred. In this manner, a running record was kept of the status of all the relays throughout the system. Because there was a one-to-one correspondence between relays and ballasts, the lighting load for all the lighting or any subset of lights could be determined by analyzing the relay activity record. In a typical commercial building installation, this control system outputs the activity record only to a hard-copy printer. In this demonstration, relay status activity was also recorded onto a magnetic data cartridge system. After each experiment, a magnetic tape cartridge imprinted with the experimental data was shipped to Lawrence Berkeley Laboratory for processing and reduction.

In addition to the data collection system described above, calibrated photometers were placed at selected locations to measure daylight and electric light illuminance levels during different experiments. Electrical signals from the photometers were recorded onto a multi-channel strip chart recorder.

Pacific, Gas & Electric Building

Physical Site Description. The 30th floor of the Pacific, Gas & Electric Company building occupies 26000 ft^2 of gross floorspace. Of this total area, approximately 19000 ft^2 is usable office space, 4000 ft^2 is corridors and 3000 ft^2 is core space. The core space, which includes airshafts, stairwells and elevators was not included in the lighting project (Fig. 3).

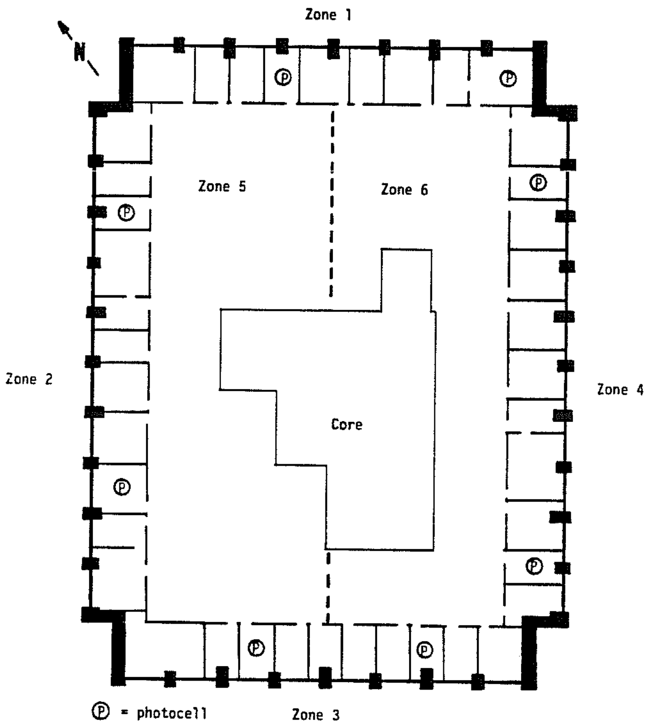


Fig. 3. Floor plan of 30th floor Pacific, Gas & Electric Co. building showing daylighting zones and placement of control photosensors.

About 92% of the usable office space consists of individual or group offices separated by ceiling-high partitions. All perimeter offices have the same depth - 17 feet measured from the back wall to the window wall (Fig. 3). The widths of these offices vary from 12 to 22 feet. Window-to-wall ratios for the perimeter offices range from .35 to .55. The occupants can limit the direct solar through the windows by drawing diffusing fabric drapes.

The 30th floor of the Pacific, Gas & Electric building houses engineers, managers and clerical support. Visual tasks include drafting, reading, filing, and typing.

Standard recessed 2 x 4 fluorescent fixtures make up the lighting system for this floor. While the lighting system originally installed on this floor used 3.7 watts/ft^2, a recent de-lamping program had reduced lighting power densities in the daylit and interior zones to 1.5 and 2.0 watts/ft^2, respectively.

Lighting Control Hardware. The lighting control hardware installed on the 30th floor consisted of four major components.

- A photosensor which generates an electrical current in direct proportion to the illumination impinging on its surface
- An electronic control unit which sends a control signal to the dimming panels based on the current from the photosensors
- A dimming panel which uses triacs to modulate the current flowing in the lighting feeders
- Special dimming core/coil type ballasts which drive the fluorescent lamps in the lighting system

The control signal from the electronic control unit changes the phase triggering of the dimming panel triacs thus varying the output of the electric lighting system based on the amount of light falling on the photosensors.

Installation of Lighting Control System. Installation of the lighting control system used at this demonstration site required the following steps: 1) replacing the existing ballasts with special dimming ballasts 2) installation of dimming panels on each feeder serving the overhead lighting system 3) rearranging the branch circuit wiring and 4) installation of control photosensors in selected offices in each zone. All the branch circuits for the electric lighting on the 30th floor are supplied by six main feeders. Six lighting zones were created -- four perimeter and two interior -- by re-arranging the branch circuit wiring so that each main feeder supplied power to only one zone. By installing a dimming panel on each feeder, the output of the electric lighting system in each zone was independently controllable.

Since some offices allowed more daylight than others, two offices typifying the range of daylight conditions were selected from each perimeter zone and control photosensors were installed in the ceilings of these offices (Fig. 3). For each daylit zone, one photosensor was installed in a maximally daylit room (window-to-wall ratio .55) and the other sensor was placed in a minimally daylit room (window-to-wall ratio .35). Each pair of control photosensors were wired to the control circuitry in parallel so that the light output of the lighting system in each zone was controlled according to the average of the light impinging on both sensors.

Instrumentation. Power transducers were installed on each of the six feeders so that the lighting load for each zone was measured independently. The transducers were connected on the line side of the dimming circuitry so that any power losses due to heat dissipation in the control circuitry were measured. Voltage signals generated by the six power transducers were recorded at 15 minute intervals onto magnetic tape using a datalogger and a data cartridge system.

4. EXPERIMENTAL RESULTS

Scheduling

World Trade Center. A series of one and two week experiments were conducted at the World Trade Center to determine the energy-savings resulting from several scheduling techniques and the dependence of energy-savings on switching zone size. Each series of experiments was designed to isolate the effect of one variable by keeping other factors as constant as possible. In one set of experiments, the scheduling sequence was changed but the switching zones were held fixed. In a second set, the schedule was kept constant but different switching zone sizes were used.

An initial test was performed to simulate the baseline operation of the lighting system before scheduling. The lighting on the 58th floor had (along with the other floors) been switched on and off by a building automation system. All the electric lighting for the floor had been switched on at 7:00 am and switched off at 1:00 am the following morning.

1. Three Scheduling Techniques. In this set of experiments, the three lighting schedules summarized in Table 1 were investigated. The lighting fixtures were grouped into independently- controllable zones of 1000 ft^2 and these same sectors were used for all three schedules described below.

The loose and tight schedules were similar except that with the tight schedule the lights were turned on slightly later in the morning and turned off slightly earlier in the late afternoon as indicated in Table 1. The tight schedule also included a 2/3 reduction in illumination level during the lunch-hour.

TABLE 1

SCHEDULE	TIME PERIOD	STATE	COMMENTS
Loose Schedule	<7:30	all off	early arrivers can override
	7:30-5:30	all on	
	5:30-11:00	1/3 on	late workers can override
	11:00-1:00	stumble lights	
	>1:00	all off	
Tight Schedule	<7:30	all off	early arrivers can override
	8:00-12	all on	
	12-1	1/3 on	Lunch time workers can override
	1- 4:30	all on	
	4:30-11:00	1/3 on	late workers can override
	>11:00	all off	
Off-Only Schedule	12-1	1/3 on	Each sector lights activated by first arriving person
	4:30-11:00	1/3 on	
	>11:00	all off	late workers can override

In the off-only schedule, rather than turning the lights on automatically with the control system, the first person to arrive in his or her sector in the morning turned on the lighting for that sector manually using the telephone overrides described in the preceeding section. At noon, the control system reduced the lighting in all sectors by 2/3 and, as individuals returned from their lunch-break, they restored the lighting in their sector to full level using the overrides. At 4:30 pm, the control system reduced all sectors to 1/3 level for the cleaning personnel and switched all lighting off at 11:00 pm.

Figures. 4-6 show the number of relays on versus time of day for typical days from each of the tests summarized in Table 1. (Since there was a one-to-one correspondence between relays and ballasts, the number of relays on is proportional to the lighting load). The effect of overrides by early and late workers are seen on the graphs. Fig. 6 shows the results for the off-only schedule in which the first worker to arrive in a sector turned on all the lights for that entire sector.

Relative to the baseline lighting operation in effect prior to these tests, the percent reduction in lighting energy consumption was 30.5, 36, and 40.5% for the loose, tight, and off-only schedules, respectively.

2. Switching zone size. In a second set of experiments, the effect of zone size on the energy savings associated with scheduling was investigated by applying the off-only schedule described in Table 1 to zones of different sizes. The first test used large switching zones in which entire quadrants of the floor (about 7000 ft^2) could be set to one of four levels (off, 1/3, 2/3, or on). The first occupant to arrive in each quadrant would turn on all the lights in that quadrant. In the second test, switching zones of 1000 ft^2 were used. The functional dependence of energy savings on switching zone size is illustrated in Fig. 7 which shows that, relative to baseline consumption, energy use was decreased 28% with 7000 ft^2 zones and 41% with 1000 ft^2 zones. The increased energy savings observed with the smaller zones is a result of the reduced impact of overrides on noon-hour and after-hours lighting loads when the smaller zones were employed. Note also that with 1000 ft^2 zones, not all zones were switched on during the afternoon. This is attributable to either zone vacancies when occupants were out on site visits or the availability of sufficient daylight in some zones to satisfy the needs of those occupants.

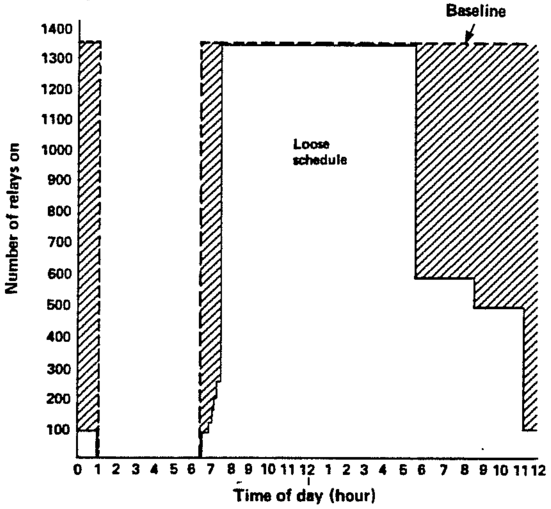


Fig. 4. Lighting load using loose schedule (World Trade Center).

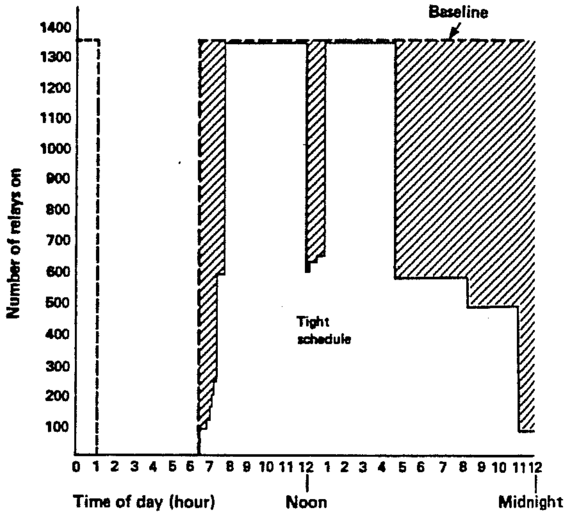


Fig. 5. Lighting load using tight schedule (World Trade Center).

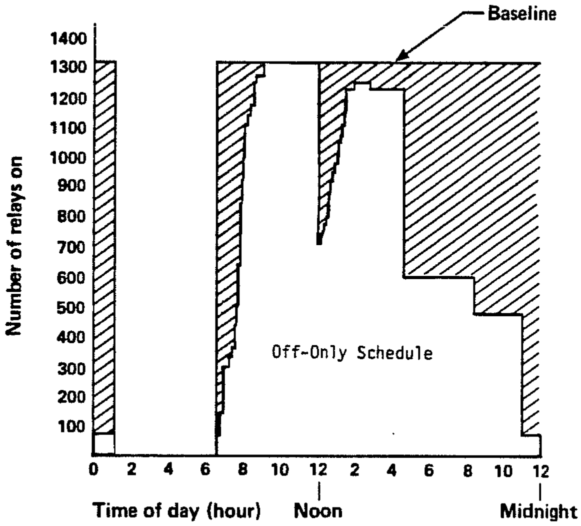


Fig. 6. Lighting load profile for manual-on/automatic-off operation (World Trade Center).

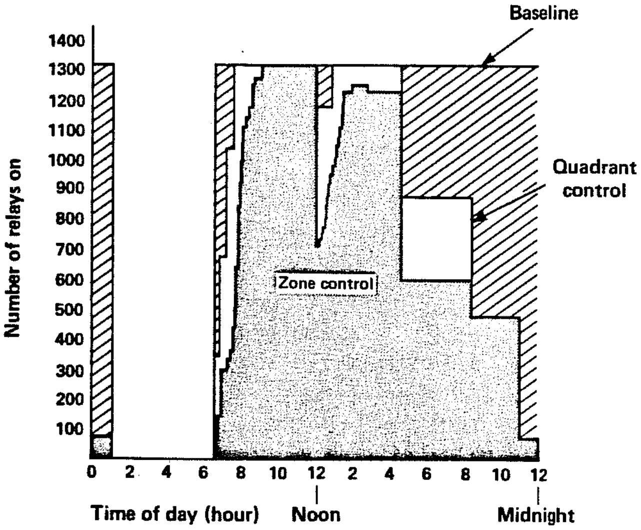


Fig. 7. Effect of different switching zone sizes on lighting load profile for manual-on/automatic-off operation (World Trade Center).

Pacific Gas & Electric Building. The energy savings attributable to scheduling were determined by comparing the average number of hours the lights were on daily before and after implementing the schedule. Prior to scheduling, the lighting system had been turned on and off from the circuit-breaker panels by building security personnel. The lighting system had been manually switched resulting in operating hours that were highly variable, ranging from 11 hours to 23 hours a day. Baseline lighting use prior to scheduling was measured over a four-month period. The solid line in Fig. 8 is a plot of the number of work days during this period the lights were on for a given number of hours. The figure shows that 16 hours of lighting per day was most common. Sixteen hours of lighting per day was also the statistical average for the 80 weekdays examined. (This analysis does not include the lighting use on weekends and holidays).

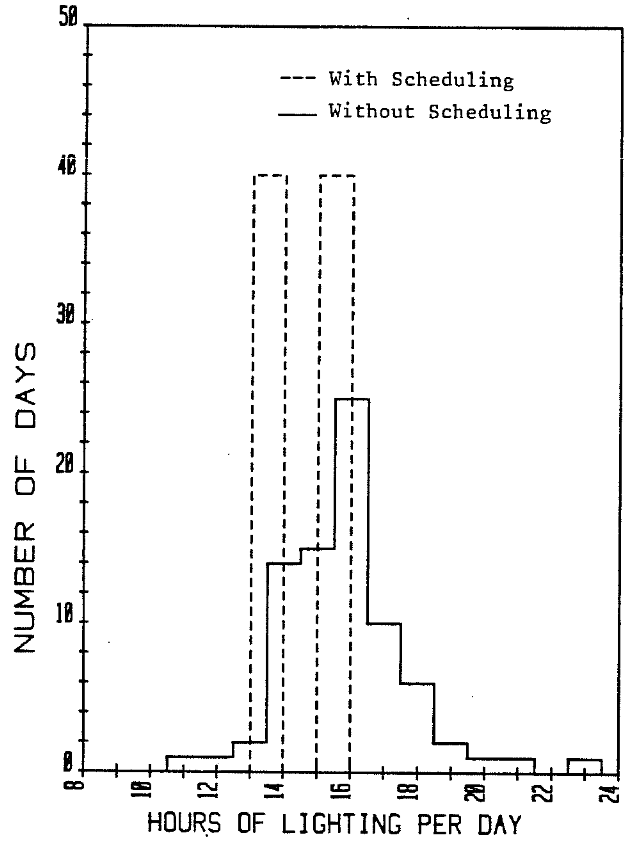


Fig. 8. Effect of scheduling on hours of lighting per day at the Pacific, Gas & Electric building

The scheduling hours used for this demonstration were selected to accommodate the needs of the office workers and cleaning crew. Lighting for the floor was turned on automatically at 6:30am on weekdays and switched off at either 8:00pm or 10:00pm, depending on the requirements of the cleaning personnel. (On weekends, the lighting was scheduled to be off although lighting could be provided when necessary by means of override timer switches). With this scheduling profile, 50% of the weekdays had lighting for 13.5 hours a day while the remaining weekdays had lighting for 15.5 hours (dashed lines in Fig. 8). Since this reduced the average weekday lighting hours from 16 to 14.5, the change from manual operation of the lights to the use of the scheduling strategy with the control system reduced the lighting energy consumption by 10%.

Daylighting

World Trade Center. The lighting control system at the World Trade Center utilized photo-relays to detect exterior illuminance levels. The relationship between exterior illuminance levels and the amount of daylight penetrating to various depths within the building was analyzed using the Lumen-II computer program. Based on this relationship the size of the perimeter and the mid-zone on each side of the building was determined (Fig. 1). These eight zones constituted the daylit zones in our analysis. Two photo-relays of different sensitivities were installed on each building facade pointing outwards. A compound switching scheme was devised in which the lighting control system executed a two-level lighting reduction depending on the amount of daylight falling on the photo-relays. The lighting control system was programmed to reduce the perimeter lighting from full to 1/3 level when the more sensitive photo-relay tripped (at approximately 300 footcandles). A second reduction was programmed to take place in the midzone when the less sensitive photo-relay tripped (at approximately 1000 footcandles) reducing the mid-zone lighting from full to 2/3 level. While other switching techniques were also tested, the technique described above proved most capable of maintaining the design illumination level at the daylit zones.

While the programmable switching system adjusted lighting levels based on the illumination levels measured at the photo-relays, the occupants were allowed to override the programmed lighting pattern in their zones and restore their lighting to full level if necessary.

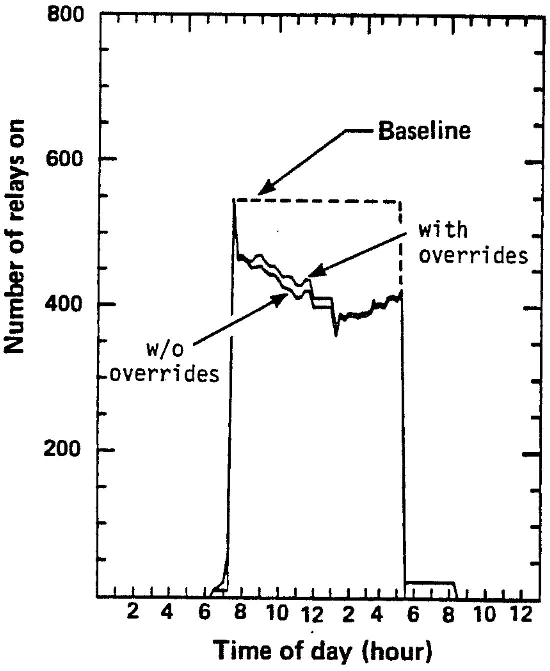


Fig. 9. Effect of daylight-activated switching on lighting loads in daylit areas averaged over eight weekdays in March

Fig. 9 shows the effect of the compound daylight switching technique on the lighting loads for all the daylit zones (both perimeter and midzones) as averaged over 8 working days in March. The lower line is the load that would have resulted if overrides were not permitted, while the upper line shows the lighting load actually measured. Between the hours of 7:30 am and 5:30 pm, daylight-activated switching would have reduced the lighting consumption in the daylit area by 28%, however, due to overrides, the actual reduction measured was 26.4%. These figures translate to 8% and 9% energy savings when applied to the entire floor (which included both daylit and non-daylit zones) since only 32% of the floorspace can be daylit.

Pacific, Gas & Electric Building. A one month test centered around the time of the winter solstice was performed at this installation to measure the energy-saving benefit of using natural daylight to partially displace electric lighting in the daylit areas of the floor.

The lighting control system was designed to automatically adjust the output of the luminaires as daylight levels changed in a zone so that a constant level of light (electric plus daylight) was always maintained at the zone's control photosensors. The illumination level to be maintained at the photosensors was set by calibrating the control system at night when the daylight contribution at the control photosensors was zero. In addition to the calibration procedure described above, the dimming circuitry was adjusted so that the lighting system never dimmed below about 45% of maximum light output. This precaution was taken to minimize the possibility of harsh shadows and large contrast ratios between the inside and outside environments which might have occurred if the electric lighting was allowed to dim very low.

The average effect of daylight dimming on the electric lighting load is shown in Fig. 10 for the a) northeast and b) southwest perimeter zones. The plots labelled "average" in the figure were generated by measuring the electric lighting demand at fifteen minute intervals and then averaging that demand over the 20 days of the test. To facilitate comparison between different daylight zones, the electric lighting demand shown in these figures has been normalized so that the baseline lighting load (i.e. without daylighting) is numerically equal to 1. For the northeast perimeter zone, the average energy-savings between 7:30am and 5:30pm is calculated to be 24% while, for the southwest zone the energy-savings is calculated to be 28%. Similar results were obtained for the other daylit zones (data not shown).

The reduction in average electric lighting demand shown in Fig. 10 was greatest between the hours of 11:00 am and 3:00 pm when time-of-day electricity rates are often at their highest and when peak demand charges are most likely to occur.

Since it was observed that a diverse range of daylight conditions occurred during the test period (ranging from densely overcast to bright sunny days), the measured lighting power data was disaggregated based on the prevailing daylight conditions. Such a disaggregation was possible at this test site since paralleling the daylight dimming tests on the 30th floor, daylight availability data was also being concurrently taken on the rooftop of the building using a multiple array of pyronometers and photometers. A pair of pyronometers, one shaded from the direct sun by means of a shadow band, the other unshaded, were used to classify the daylighting conditions according to the criterion given below:

$$\text{overcast:}\quad \frac{E_g - E_d}{\sin\theta} < 200 \text{ watts/meter}^2$$

$$\text{clear:}\quad \frac{E_g - E_d}{\sin\theta} > 200 \text{ watts/meter}^2$$

where E_g is the global (sun and sky) horizontal irradiance, E_d is the diffuse (sky only) horizontal irradiance and θ is the solar altitude measured from the horizon. Rooftop pyranometric data and lighting power data from each daylight dimming zone were recorded simultaneously. Consequently, the lighting demand data could be sorted into two categories - overcast or clear - according to whether the direct normal solar component exceeded 200 watts/meter^2. (This criterion was selected to be consistent with results from the Campbell-Stokes sunshine recorder which is used for measuring percent clear conditions.[2])

The average lighting demand data broken down into clear and overcast categories is plotted for the a) northeast and b) southwest zones in Fig. 10. These data clearly show that the energy-savings due to daylight is greatly influenced by the intensity of the direct normal solar component. In the southwest zone,

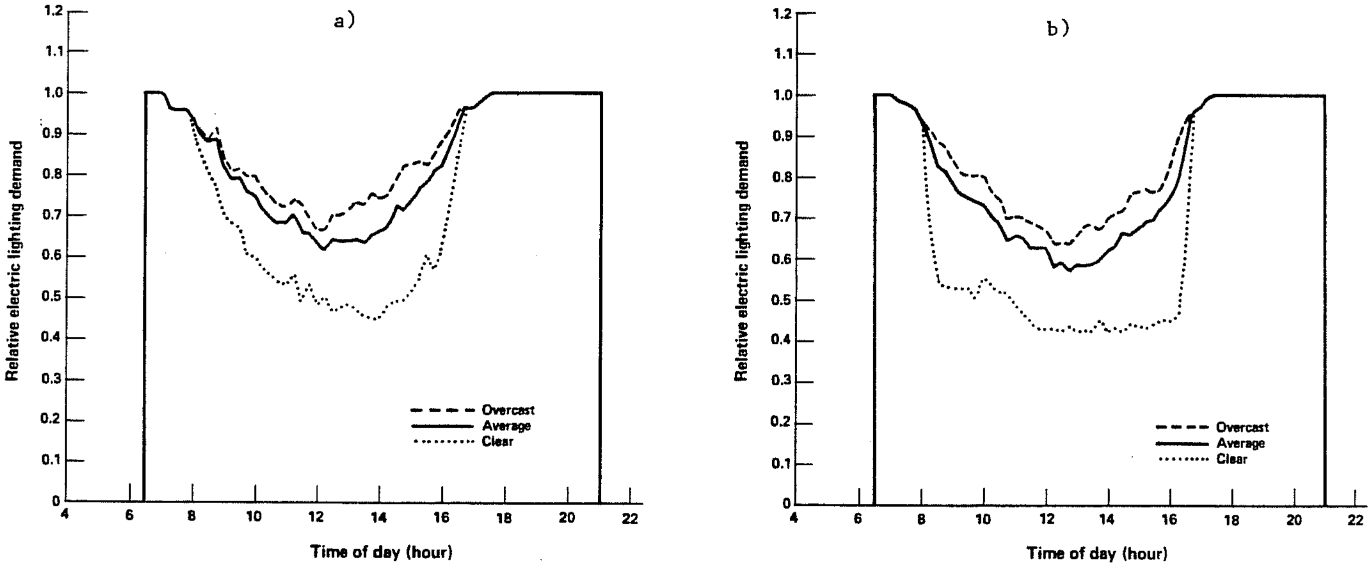


Fig. 10. Effect of daylighting on lighting loads for a) northeast and b) southwest perimeter zones using daylight-linked dimming system at P.G.&E. building during winter. Curves show lighting demand averaged for all days and disaggregated by clear and overcast conditions.

TABLE 2

Energy Savings at Demonstration Sites

		SITE	
Strategy		Pacific, Gas & Electric	World Trade Center
Scheduling		10%	30 - 40%
Daylighting*	Daylit zones	26%	27%
	Entire floor	10%	9%

* Savings calculated for 7:30am - 5:30pm.

the energy-savings calculated between 7:30am and 5:30pm on average clear conditions is 44%, twice the savings (21%) calculated for average overcast conditions.

The similarity of the overcast curve to the average curve suggest that overcast conditions were predominant during the winter test. This interpretation is consistent with typical Bay Area weather conditions.

5. DISCUSSION

Table 2 summarizes the energy savings accrued from daylighting and scheduling as measured at the two demonstration sites. The values given in the table are the percentage reductions in lighting energy consumption relative to the baseline consumption. The percent energy savings attributable to scheduling was significantly larger at the World Trade Center than at the Pacific, Gas & Electric building since the baseline lighting operating hours before scheduling were longer at the World Trade Center. The reduction in energy consumption due to scheduling at the WTC is given as a range to reflect the range of savings from the three scheduling techniques examined there.

The energy savings attributable to daylighting as measured at World Trade Center and the Pacific, Gas & Electric buildings are also shown in Table 2. If one considers just the daylit zones, then the percent energy reduction due to the use of daylighting is roughly equivalent at both demonstration sites. This result was somewhat unexpected since daylighting performed with a switching system as at WTC is a discrete approximation of the continuous dimming technique. Hence, under equivalent test conditions, one would expect the dimming technique to yield a larger reduction in energy consumption.[3] However, the daylighting tests at WTC and P.G.&E. were performed at different times of the year. One can assume that, since the daylighting tests at WTC were performed around the time of the vernal equinox (when the length of day and night are equal), the results measured then represent a reasonable approximation of the energy-savings that would accrue for the entire year. The daylighting tests at the Pacific, Gas & Electric building, though, were performed during the winter solstice and therefore reflect the minimum savings possible.

In order to permit meaningful comparisons between the daylighting results from the two buildings we have taken the energy savings measured at P.G.&E. and extrapolated the results over the entire year. Such an extrapolation is possible since we have measured the relative frequency of clear and overcast conditions for approximately three years at P.G.&E. and we have characterized the energy-savings with daylighting for clear and overcast conditions in the previous section. By weighting the energy savings under clear and overcast conditions with the relative frequencies of clear and overcast conditions for each month of the year, we have calculated that, summed over all the daylit zones, the energy savings attributable to daylighting range from a low of 26% (as measured during the winter) to a high of 34% (as calculated for the summer). These calculations are consistent with daylighting tests conducted during the summer and fall (data not shown). Based on these calculations, the dimming system at P.G.&E. is seen to be more energy-conservative than the switching system employed at the WTC.

In these studies we have only considered the energy savings for lighting loads even though scheduling and daylighting would also affect heating and cooling loads. Computer simulation of commercial building energy loads indicate that reducing lighting loads also reduces the cooling loads. Although this increases heating loads, studies have shown that with properly designed window systems, the increased heating load can be offset by decreased cooling loads especially in large buildings which are usually dominated by cooling loads.[4]

6. CONCLUSION

As a result of these tests, we have shown that there exists considerable potential for reducing lighting energy consumption using daylighting and scheduling as lighting control strategies. The use of computer-based lighting control systems for scheduling light levels on the basis of occupancy was shown to positively impact lighting loads outside the core operating times (7:30 am to 5:30 pm). These savings were significant, ranging from 10 to 40% depending on the lighting system operating hours measured before scheduling. Using available daylight as a source of illumination to displace electric lighting loads was shown to reduce the energy consumed for lighting in daylit areas by 25% to 35%. Moreover, the lighting load reduction with daylighting occurred during the core operating hours when peak demand charges and higher time-of-day rates would be in effect.

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