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ENERGY-SAVING BENEFITS OF AUTOMATIC LIGHTING CONTROLS

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ABSTRACT

The energy-saving potentials of various lighting control strategies were investigated at two demonstration sites. A continuously dimmable system was installed at the Pacific Gas & Electric building in San Francisco and an on/off switching system was installed at the World Trade Center in New York. Automatically switching the lights on the basis of occupancy reduced daily lighting energy use by 10 - 26%. Using natural daylight to supplement electric lighting reduced lighting energy consumption an additional 16 - 30% in daylit areas.

A simple cost/benefit analysis is presented that allows building energy managers to determine the cost-effectiveness of different lighting control strategies for particular design applications.

1. INTRODUCTION

Automatic lighting controls can reduce the energy consumed for lighting in buildings. Using a variety of strategies and techniques that range from having lights turn off according to a set schedule to schemes that utilize natural daylight, automatic controls can meet lighting needs with less expenditure of energy than dedicated lighting systems. However, these lighting management systems have only recently been introduced and few data are available to quantify the energy-saving potential of the various lighting control strategies. For the past year, the U.S. Department of Energy has conducted two demonstrations in an effort to determine the magnitude of the energy savings associated with different strategies and techniques.

This paper documents the energy-saving benefits of three major lighting control strategies--scheduling, daylighting, and tuning. Experimental data were gathered at two lighting control demonstrations to allow comparison of the strategies using both dimming and switching techniques. In the first section, the major strategies are defined. The next section describes the two demonstration sites and the operation of the lighting control hardware installed. In the third section, data from the demonstrations are presented and used to quantify the energy savings for each control strategy. Finally, a simple cost/benefit analysis is presented.

2.0 LIGHTING CONTROL STRATEGIES

The energy used for lighting in buildings is a function of power and duration of use. Automatic lighting controls enable the building energy manager to dynamically alter both these parameters according to the visual needs of the occupants, thus saving energy. Four major lighting control strategies are defined below.

2.1 Scheduling

Scheduling is a strategy that adjusts the lighting levels on the basis of expected building occupancy. Light levels can be decreased or lights switched off during periods when the building is unoccupied. A typical scheduling technique provides full lighting during the work day but reduces levels for cleaning and security personnel. Since there are always deviations from the routine, some provision must be made to override the system. Some techniques incorporate a telephone/control system interface while others employ manual override switches.

2.2 Daylighting

Natural daylight can provide useful illumination in building areas near windows or under skylights. To exploit this source of illumination, an interactive link can be established between the ambient lighting conditions and the electric lighting system using photocells that sense light levels (daylight plus electrical) and feed the information back to the control system. With photocell-feedback, a near-constant, predetermined light level can be maintained by dimming the electric lighting in proportion to the amount of available daylight. Such control systems save energy throughout the day because electric lighting will be substantially dimmed and will therefore use less power than undimmable systems.

2.3 Tuning

With the tuning strategy the light output of individual fixtures or groups of fixtures is adjusted to match the visual requirements in an area. By "tuning" light levels to suit visual tasks, lighting loads are reduced in circulation areas, corridors, and other areas where non-critical visual tasks are performed. This adjustment can be done either directly at the fixture with ballasts incorporating a manual dimming potentiometer or with control systems capable of independently controlling individual fixtures or small groups of fixtures. Tuning is semi-permanent and allows low-cost readjustment if lighting needs change because the space is re-arranged.

2.4 Lumen Maintenance

The initial light output of a system decreases over time due to the decrease in the light output of the lamps and the accumulation of dirt on fixture and wall surfaces. These light losses, termed recoverable because lamps can be replaced and fixtures and walls washed, are the reason initial light levels are typically 50% above the specified design level. Control systems can dim lamps to provide the specified design level initially and, as lamps age and dirt accumulates, increase the power to the lamps, thus maintaining the correct light level throughout the maintenance period. This lumen maintenance strategy saves energy because maximum power is applied only near the end of the maintenance period and not throughout the life of the system as is the case for a dedicated lighting system. In fact, the increasing power level is a signal to the building operators that it would be prudent to re-lamp or wash the fixtures to minimize energy consumption.

3.0 DEMONSTRATION SITES AND LIGHTING HARDWARE

For both demonstration sites, lighting control hardware was selected that had the flexibility to allow testing of the scheduling, daylighting, and tuning strategies. At the Pacific Gas & Electric site, a centralized dimming system was installed. This allowed continuous dimming of light levels and was used to control large groups of fluorescent lamps. A programmable switching system, which employed relays to switch lamps on and off, was installed at the World Trade Center. While permitting only incremental changes in light levels, this system allowed independent control of individual fixtures. The selection of two control systems permitted the investigation of the strategies using different techniques.

3.1 Pacific Gas & Electric Building

The continuous dimming system was installed on the 30th floor of the Pacific Gas & Electric building in San Francisco. Dimming was accomplished by phase-control systems located in the electrical closet. Special core-coil ballasts were required. Two control photocells mounted at selected ceiling locations monitored the light levels for each area. Using the photocell-feedback technique described in the previous section, the amount of electric lighting provided by the fixtures was altered by the control system in response to changing ambient light conditions.

Figure 1 is a plan view of the 30th floor showing the orientation of the demonstration site and the location of the control zones. The lighting fixtures were grouped into six zones: four perimeter and two interior. This arrangement allowed the light levels in each zone to be controlled independently using photocells in a closed-feedback mode. A small computer was interfaced with the controls to allow the lighting to be switched automatically according to a programmed schedule.

3.2 World Trade Center

A programmable lighting control system was installed on the 58th floor of the World Trade Center in New York. 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 inputs permitted authorized personnel to override the computer control when necessary. They also 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.

The lighting system on this floor consisted of 450 six-lamp fixtures. Multi-ballasted fixtures of this type can be wired so that groups of fixtures can be set to any of four lighting levels. Such a switching configuration was used here, as shown in Fig. 2. 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.

To allow maximum flexibility for this test program, one relay controlled each ballast. For many tests, however, the floor was divided into 1000-sq. ft. sectors, and each sector was independently controlled to one of the four light levels. This zoning simulates a pragmatic installation of this kind of control system in a commercial building. Each sector was controlled by the central computer, which altered the light levels according to a programmed schedule or in response to the signal from exterior-mounted photo-relays which sensed the amount of daylight falling on each face of the building. Figure 3 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.

4.0 TEST RESULTS

A series of lighting control experiments was conducted at both demonstration sites. This report presents the results of those tests which show the energy-saving potential of three control strategies — scheduling, daylighting, and tuning.

4.1 Scheduling

The lighting control systems at the World Trade Center and the Pacific Gas & Electric building were used to control light levels on the basis of occupancy. Different schedules were used at each site to conform with building operation requirements.

4.1.1 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 was turned on and off from the circuit-breaker panels by building security personnel. Because the lighting was switched manually, lighting operating hours were highly variable, ranging from 11 hours a day to 23 hours a day when the lights were left on all night. Baseline lighting use prior to scheduling was measured over a four-month period. The results are shown in Fig. 4, which plots 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.

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 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 timed override switches). With this scheduling profile, only lighting operation periods of 13.5 and 15.5 hours per day were observed (dashed lines in Fig. 4). 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%.

4.1.2 World Trade Center

The energy-saving benefit of scheduling was also evaluated at the World Trade Center by comparing the daily energy use before and after installing the control system. Previously, the lighting had been operated by an existing building automation system only able to switch all the lighting for the floor on and off. Limitations on the existing system and the variable working hours of the cleaning crew had resulted in relatively long operating hours. The baseline lighting load as a function of time of day is represented by the top line in Fig. 5.

With the demonstration control system, a scheduling technique was selected to provide for the lighting needs of the floor occupants. As shown in Fig. 5, full lighting was provided for the personnel between 7:00am and 5:30pm. Since the regular operating staff typically left by 5:30pm, the lighting at 5:30 was reduced to 1/3 level by switching off all outboard fixture tubes. The reduced illumination level was adequate for the lighting needs of the cleaning and security personnel. This scheduling technique reduced the energy consumed for lighting by 26%.

4.2 Daylighting

4.2.1 Pacific Gas & Electric Company

At the P.G.&E building, the daylighting strategy was tested using the dimming capability of the demonstration control system. Ceiling-mounted photocells, located in selected perimeter offices, monitored the available light levels in each zone. When daylight contributed to the illumination level, the control system automatically reduced the supplied electric lighting to maintain the prescribed light level.

Figure 6 shows the effect of daylighting on electric lighting power level for a typical winter day. The power used for lighting in the inner offices (shaded area in Fig. 6) is unchanged since daylight made no contribution to the illumination level in these areas. Electric lighting for the daylit perimeter offices shows a significant reduction. Compared to baseline power (upper dashed line), daylighting reduced lighting power for the outer offices by as much as 50% during the day. For regular operation hours 6:30am to 8:00pm, the energy consumed for lighting was reduced 27% in daylit areas. During the summer (data not shown) the average energy savings were 32%. The average daily savings throughout the year is about 30% in daylit areas. By averaging the daylighting savings for the entire floor lighting (inner and outer offices), it was found that daylighting reduced energy consumption by 13%.

4.2.2 World Trade Center

The switching system installed at this site utilized photo-relays to sense outside light levels. Before a suitable daylight control technique could be devised, it was necessary to empirically determine the relationship between the exterior light levels sensed by the photo-relays and the daylight levels inside the building. Based on an analysis of this relationship, eight daylit zones were layed out--one perimeter and one mid-zone per building face (Fig. 3). Two photo-relays of different sensitivities were installed on each building facade pointing outwards. The more sensitive relays tripped when the sky brightness exceeded a pre-set value. The less sensitive relays did not trip until direct sunlight fell on the building face. With this array of photo-relays, several daylight switching schemes were investigated. The optimum arrangement cut the perimeter lighting from full to 1/3 when exterior daylight levels exceeded the set point of the more sensitive relay. As even more daylight became available (i.e., with direct sun on the building face) the second relay switched the mid-zone lighting from full to 2/3 level. While several other switching techniques were also tested, the described technique proved best able to maintain the design illumination level.

Figure 7 shows the effect of the daylight switching technique on the total lighting power levels for a typical day in March. The lighting load in the daylit area was reduced approximately 30% when daylight was available. Because a switching technique was employed at this site, the reduction in lighting load appears as discrete steps in the figure. Compared to the baseline condition, daylighting reduced energy use in the daylit zone by 16%. Averaged over the lighting for the entire floor, energy consumption was reduced 7%.

4.3 Tuning

The control system at the P.G.&E. building could not independently control the light level of small groups of fixtures; thus, the lighting system could not be "tuned." At the W.T.C. building, however, each fixture could be independently addressed to provide four levels of light, so the lighting could be finely tuned to the requirements of individual work stations.

Using the programmable controller, the lighting above non-critical tasks was reduced to levels appropriate to the task. The lighting fixtures over circulation areas were reduced from full lighting to 2/3 level. Tuning the lighting in this fashion reduced the lighting load 30% relative to the baseline conditon.

4.4. Discussion

Table 1 summarizes the energy-saving benefits of the various lighting control strategies as measured at the P.G.&E. and the W.T.C. demonstration projects. The percent energy savings for each strategy are different for each site. This is a result of the different operational characteristics of the two buildings and differences in the control techniques employed.

The percent energy savings attributed to scheduling was higher at the W.T.C. than at P.G.&E. because the scheduling technique employed at the W.T.C. reduced light levels after 5:30pm for the cleaning crew whereas at P.G.&E. lighting was simply turned off after the cleaning crew left.

Table 1

Energy Savings at Demonstration Sites

Strategy	Site Pacific Gas & Electric	 World Trade Center
scheduling	10%	26%
daylighting	30%*	16%*
tuning	-	30%

* savings apply to daylit areas only

Table 1 also shows that the percent energy reduction due to daylighting was found to be greater at the P.G.&E. building than at the W.T.C. This result is consistent with calculations of other investigators who have determined that dimming systems are inherently more efficient at exploiting natural daylight than switching systems.[1]

The tuning strategy reduced lighting energy consumption by 30% at the W.T.C. This is a good illustration of the large savings that can result from tuning. In this case, average lighting requirements at the time of the test program were well below those for which the lighting system was originally intended. The lighting system was designed to provide 100 to 150 footcandles for drafting tasks; much of the area, however, was eventually used for secretarial and managerial tasks requiring less illumination. Since the magnitude of the energy savings with tuning depends on the degree to which lighting requirements change, the situation at the W.T.C. probably presented a greater potential for reducing energy use than is usually the case. In the subsequent section, which discusses the costs and benefits associated with different strategies, a more conservative

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[1] Hunt, D.R.G., 1977, "Simple Expressions for Predicting Energy Savings From Photo-Electric Control of Lighting", Lighting Research and Technology 9(29):93-102.

estimate of 15% will be used for the energy savings attributable to tuning.

5.0. COST/BENEFIT ANALYSIS

The analysis presented below provides an estimate of the energy cost savings that can result from applying one or more control strategies for the sites studied. Since the two sites examined (individual offices at P.G.&E. and an open office space at the W.T.C.) are somewhat typical, the results represent a reasonable estimate of the possible savings for other office space. The methodology developed can be used by buildng managers to determine the cost-effective price for control hardware that would meet their particular needs.

The return on investment for lighting control products can be found using the following expression:

$$\text{Return on Investment} = \frac{\text{annual cost savings}}{\text{initial investment cost}}$$

The above expression is used to determine the simple return on investment for energy-conserving equipment of known price and capability. For the purpose of this analysis, it is more convenient to re-write the expression in the following form:

$$\text{Cost-effective Price of Strategy} = \frac{\text{annual cost savings with strategy}}{\text{required return on investment}}$$

From the above expression, the cost-effective price of any combination of control strategies can be determined.

The analysis is applied to a building that is assumed to use 3 watts/ft^2 for lighting, with an annual usage of 3200 hours. The above is typical of a modern commercial building. Table 2 will be used to calculate the reduction in annual lighting costs that results from applying various combinations of strategies to the selected building example. The table was generated based on the experimental results previously discussed. The energy reduction attributable to scheduling has been estimated by averaging the results of the scheduling tests at both demonstration sites.

Table 2

Energy-Savings in Typical Buildings

	Type of Control	
Strategies	Switching	Dimming
scheduling	18%	18%
daylighting	18%*	30%*
tuning	-	15%
scheduling daylighting	33%*	43%*
scheduling daylighting tuning	-	51%*

*daylit areas only

Cost-effectiveness curves (Figs. 8 - 14) were generated for the combinations of strategies listed in Table 2. The cost-effective prices determined from these figures are shown in $/ft^2. This is a convenient way to show costs since one may find the total cost of an appropriate control system simply by multiplying the cost in $/ft^2 by the building area. Since these figures are similar in form , one example will suffice to illustrate the use of all. We take the case of a building manager considering retrofitting a building by adding a switching control system to schedule the lighting. By selecting the appropriate figure (Fig. 8), the cost-effective price of the installed controls may be readily determined. If a 50% return on investment is required (equivalant to a two-year simple payback) and the cost of energy is $0.10/kWh, the cost-effective price to install the controls should not exceed $0.35/ft^2. There are switching systems presently on the market which may be installed at a cost lower than this.

The reader should be aware that the costs determined from the cost-effectiveness curves shown in Figs. 8 - 14 represent the total cost of installing the controls including labor and design charges as well as hardware cost. For most retrofit applications, scheduling is the most cost-effective strategy, since switching hardware that exploits this simple strategy can usually be installed in central locations such as the electrical closet, thus minimizing installation costs.

The costs shown in Figs. 8 - 14 are conservative since, for most buildings, the reduction in lighting energy costs is accompanied by a further cost savings due to reduced air-conditioning loads.

6. CONCLUSIONS

The energy-saving benefits of scheduling, daylighting, and tuning have been evaluated at two lighting control demonstration sites. Scheduling was found to reduce the energy consumed for lighting by 10 - 25%. The energy savings attributable to daylighting was measured to be 16% for a switching system and 30% for a dimming system. By combining scheduling and daylighting in daylit areas, lighting energy use was reduced 33% and 43% with switching and with dimming systems, respectively.

The effective cost of different control schemes was estimated using a simple methodolgy based on return on investment. For a building with an annual usage of 3200 hours, to obtain a 50% ROI, the effective cost of a control system using scheduling is $0.35/ft^2 assuming energy costs $0.10/kWh. For a building using all the strategies (scheduling, daylighting, and tuning), the effective cost is $1.00/ft^2 assuming the above conditions.

7. ACKNOWLEDGEMENT

The work described in this paper was supported by the Assistant Secretary for Conservation and Renewable Energy, Office of Building Energy Research & Development, Building Equipment Division of the U.S. Department of Energy under Contract No. W-7405-ENG-48.

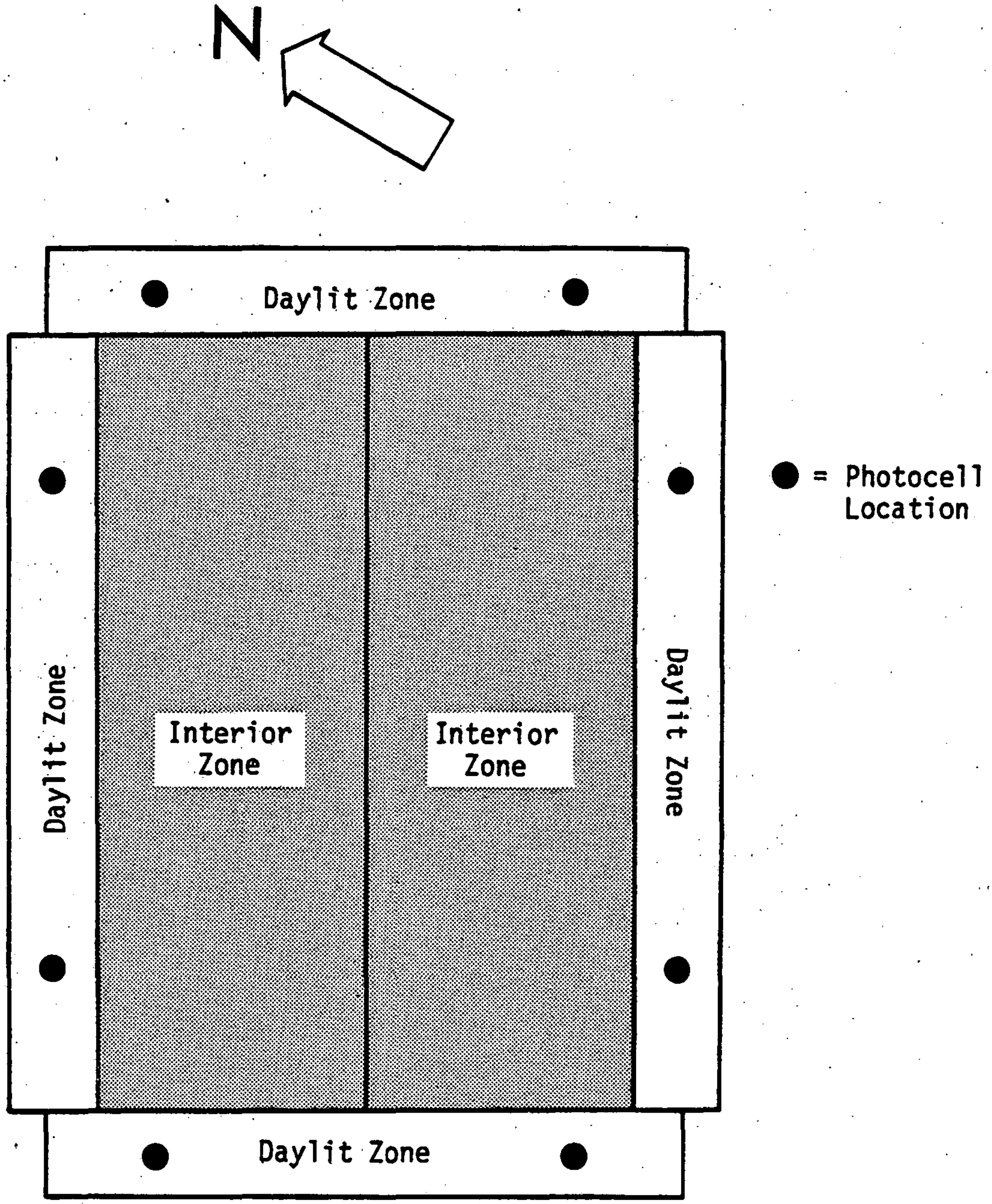
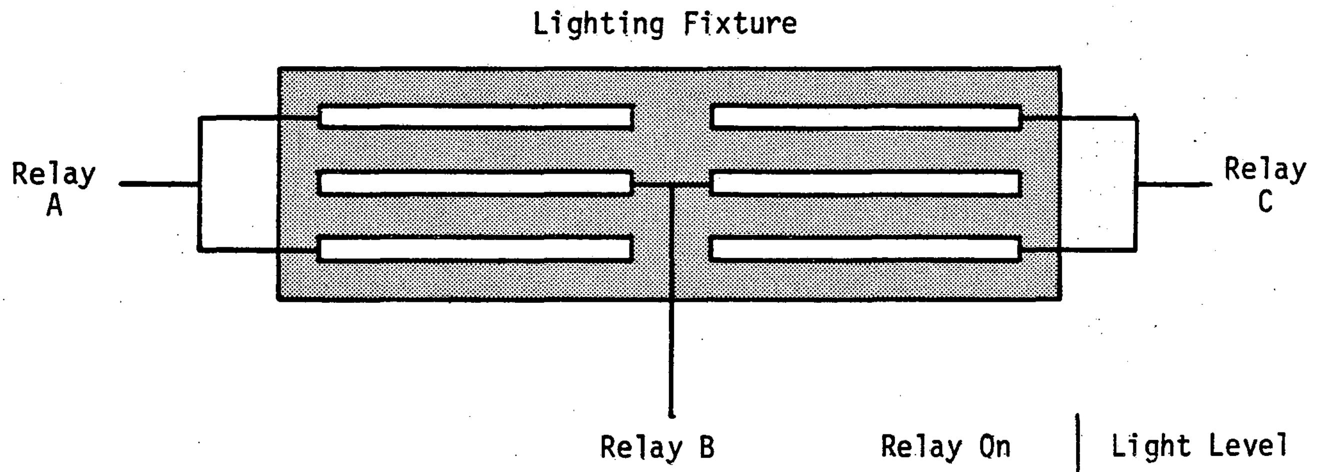


Figure 1. Plan View of 30th Floor of PG&E Building Showing Control Zones and Photocell Locations.



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

Figure 2. Switching Configuration Used at World Trade Center.

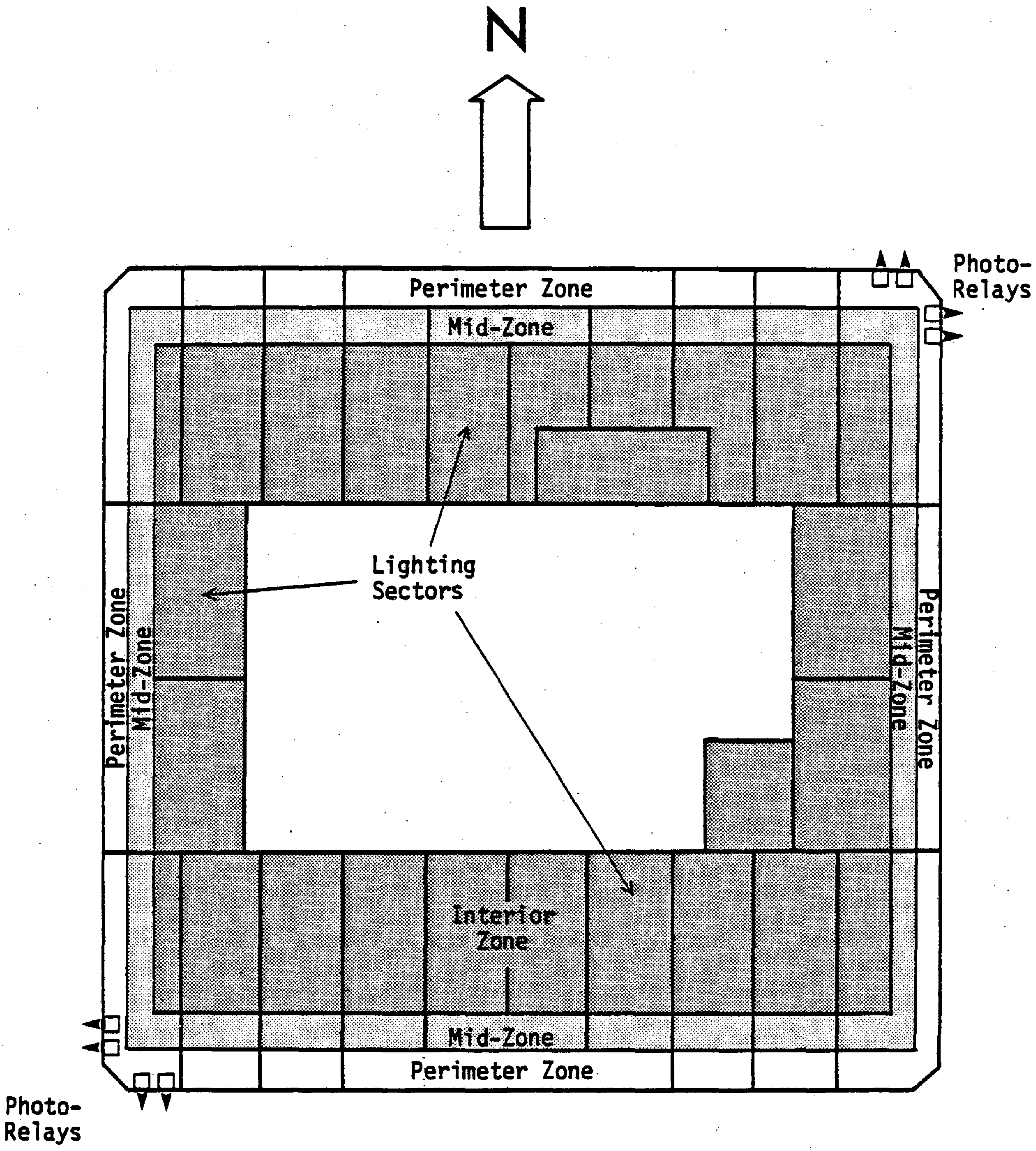


Figure 3. Plan View of 58th Floor of World Trade Center Showing Lighting Sectors and Daylit Zones.

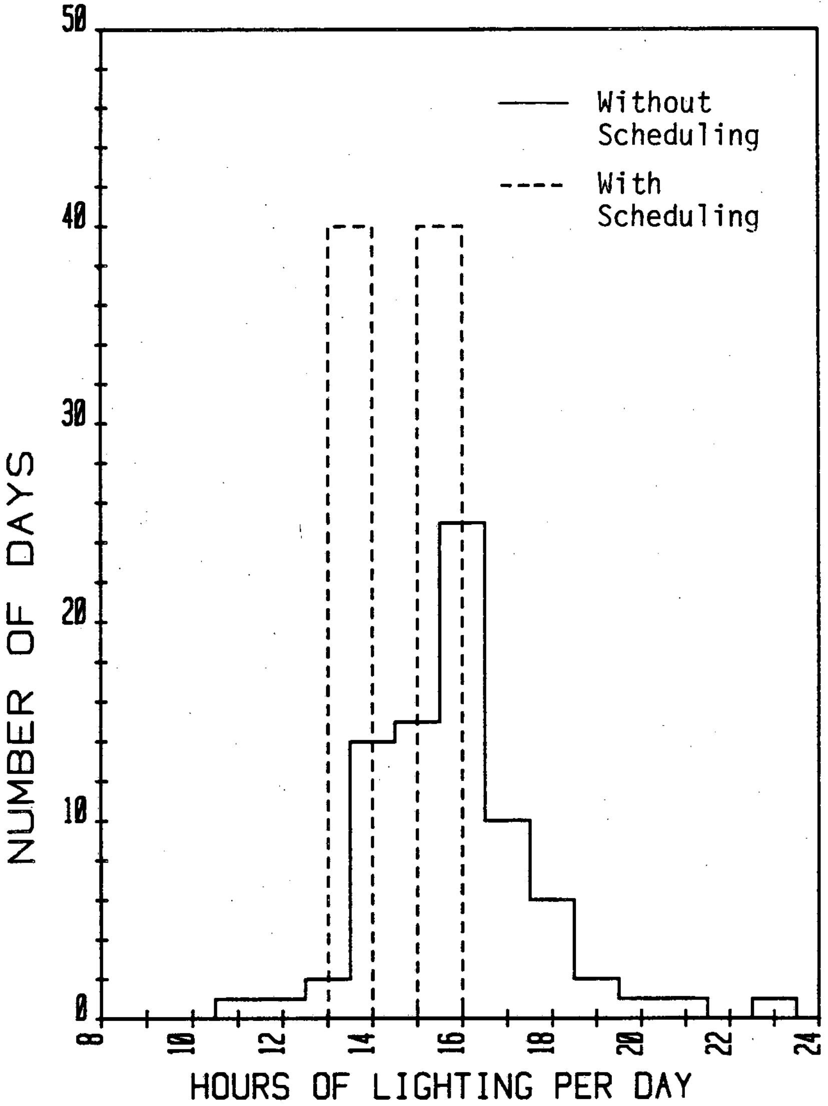


Figure 4. Effect of Scheduling on Hours of Lighting Per Day at 30th Floor of PG&E Building.

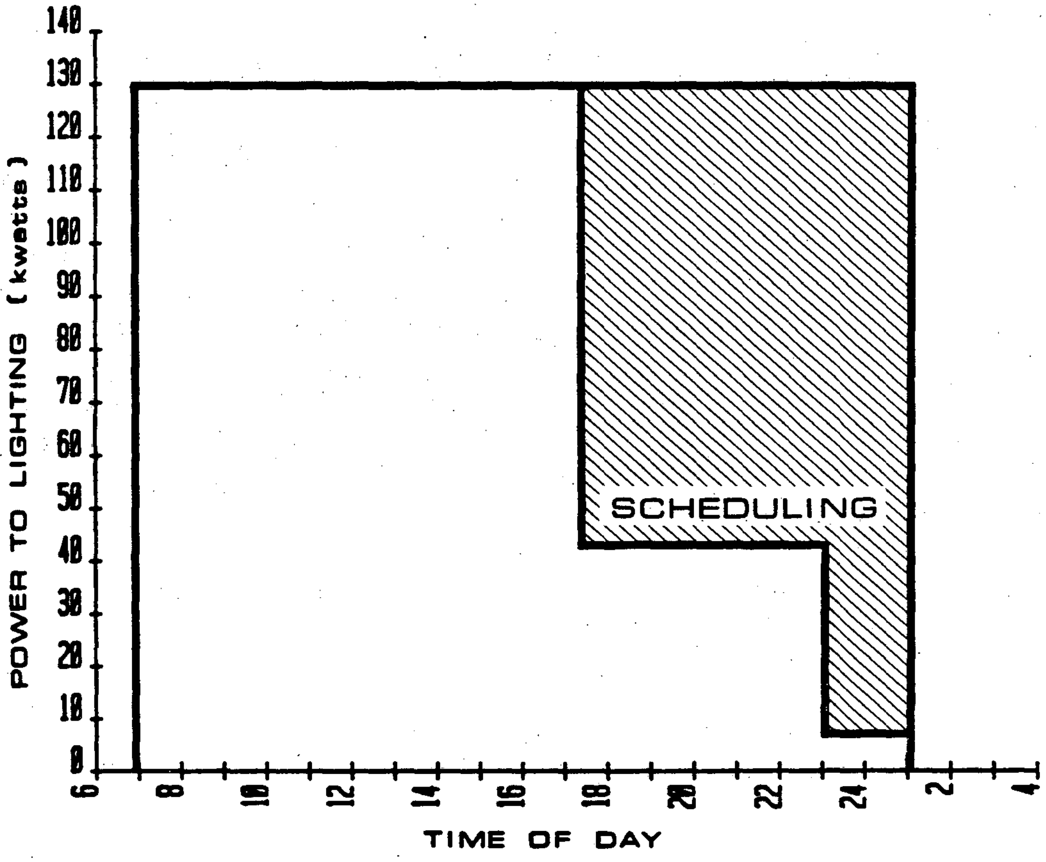


Figure 5. Effect of Scheduling on Energy Consumed for Lighting at 58th Floor of World Trade Center.

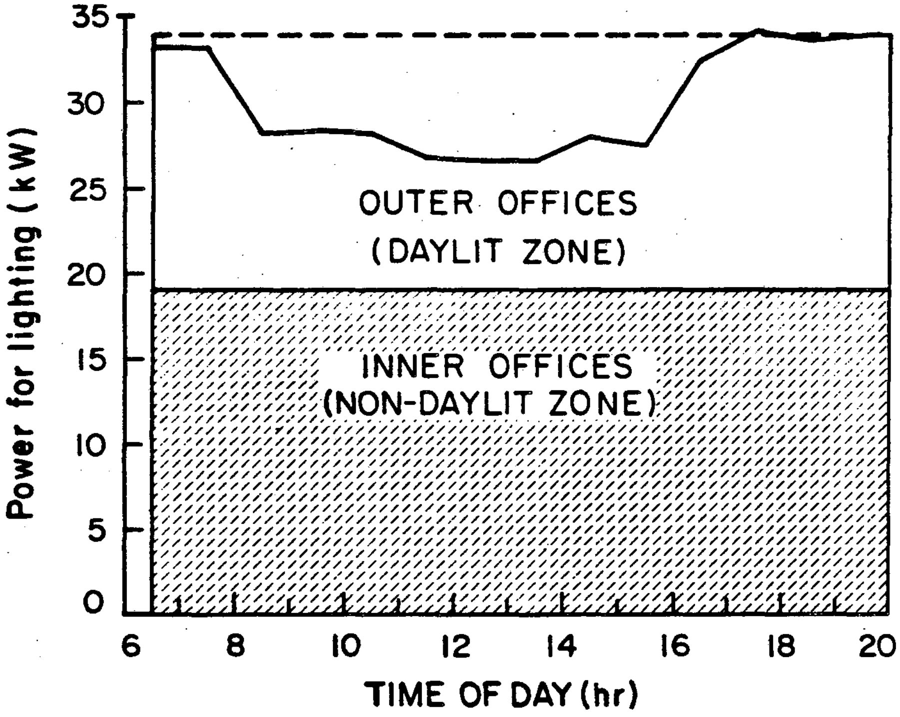


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Figure 6. Effect of Daylighting on Lighting Load at 30th Floor of PG&E Building.

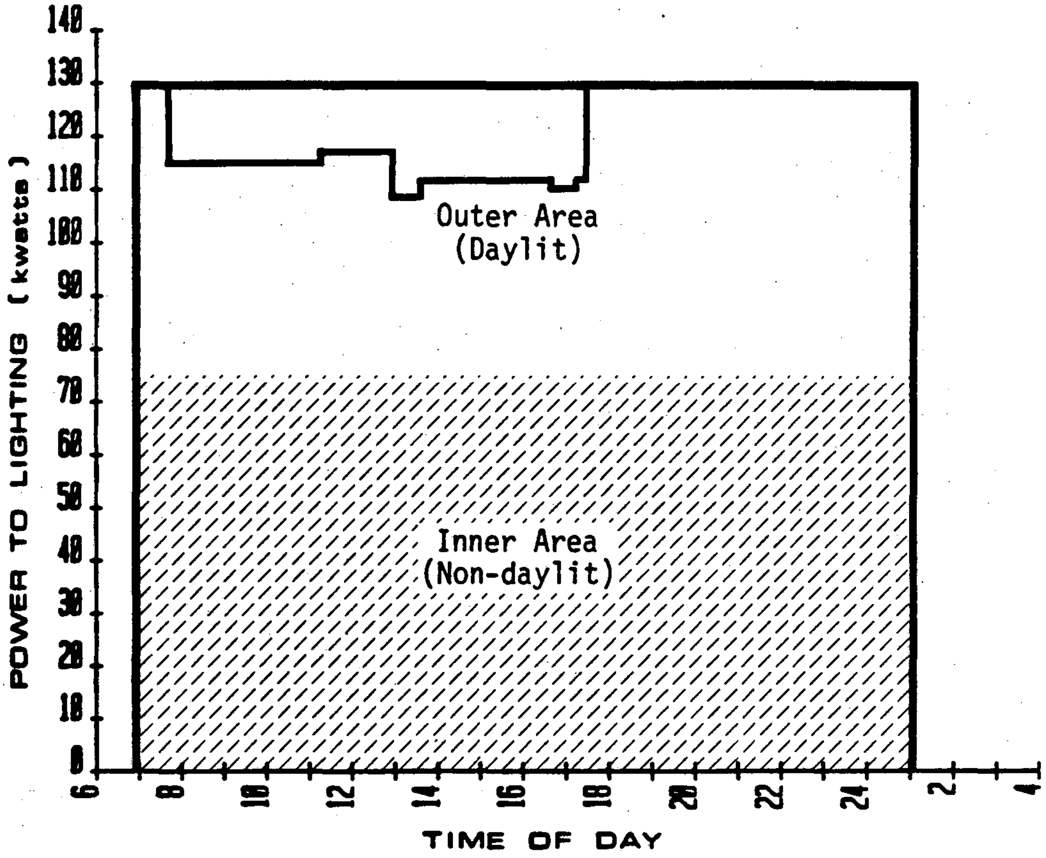

Figure 7. Effect of Daylighting on Lighting Load at 58th Floor of World Trade Center.

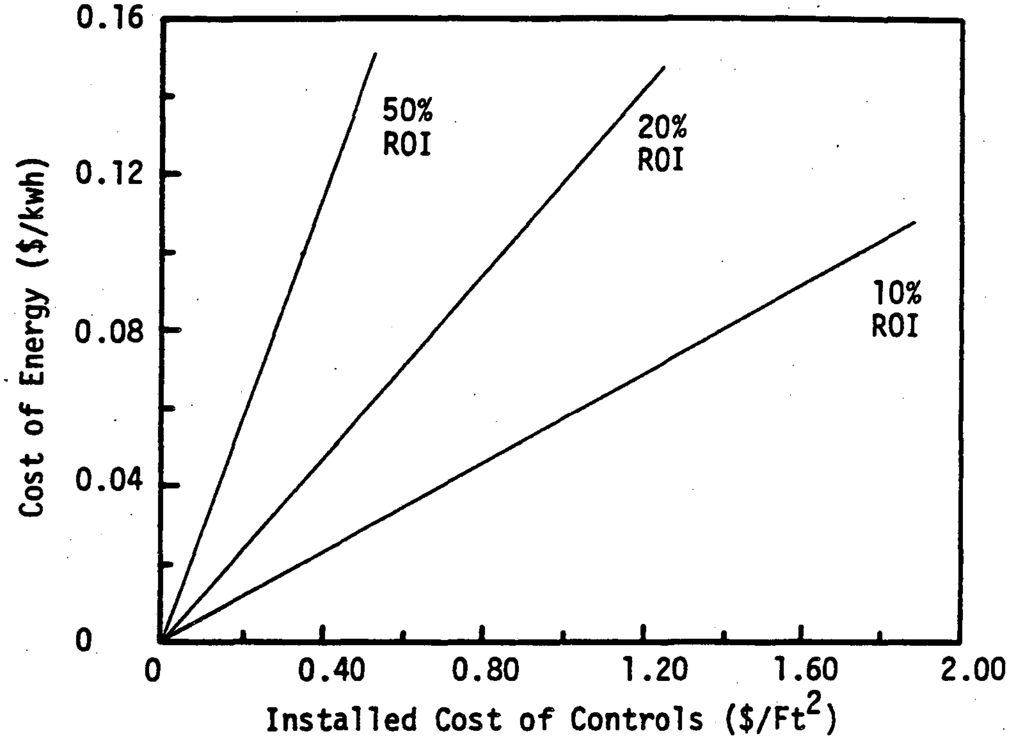

Figure 8. Cost-Effectiveness of Scheduling.

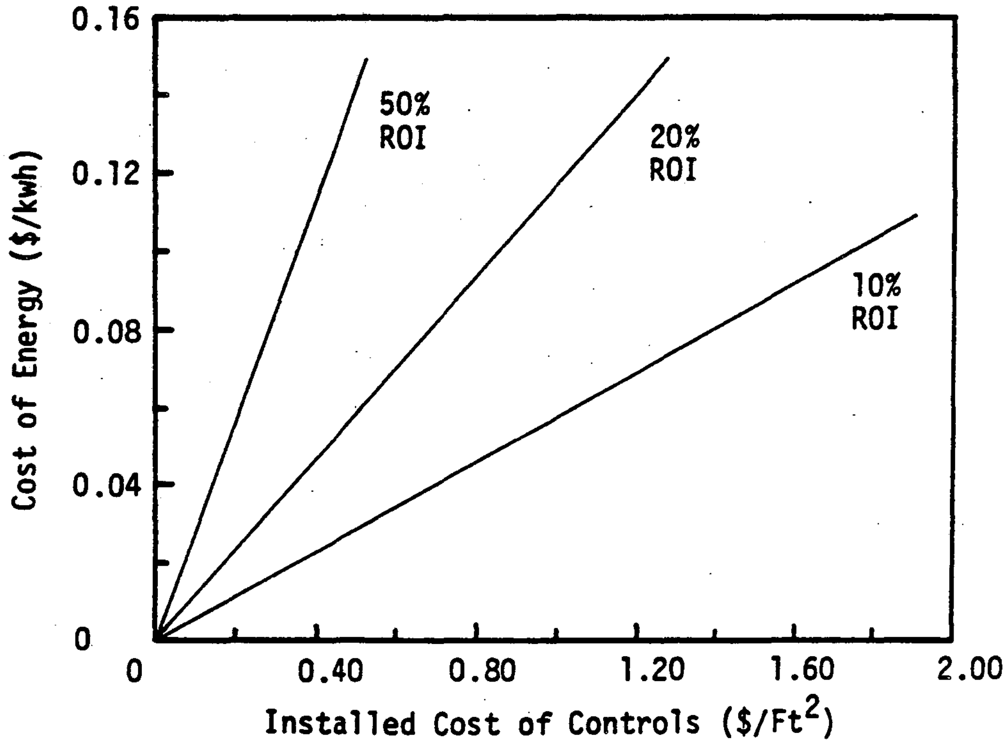

Figure 9. Cost-Effectiveness of Daylighting (Switching).

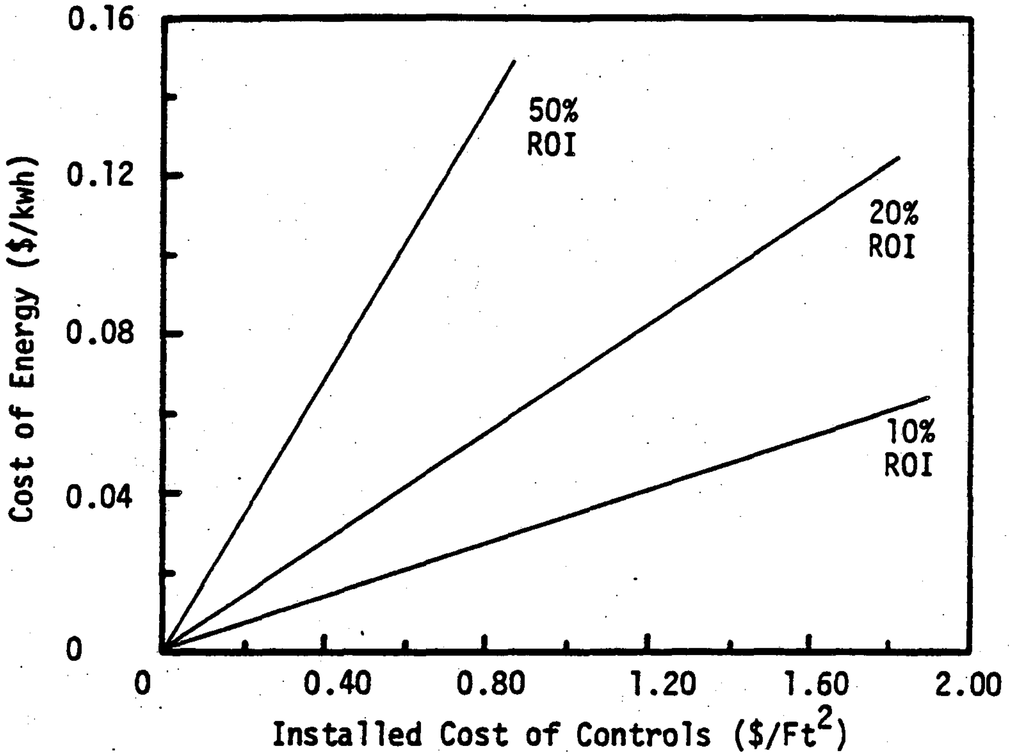

Figure 10. Cost-Effectiveness of Daylighting (Dimming).

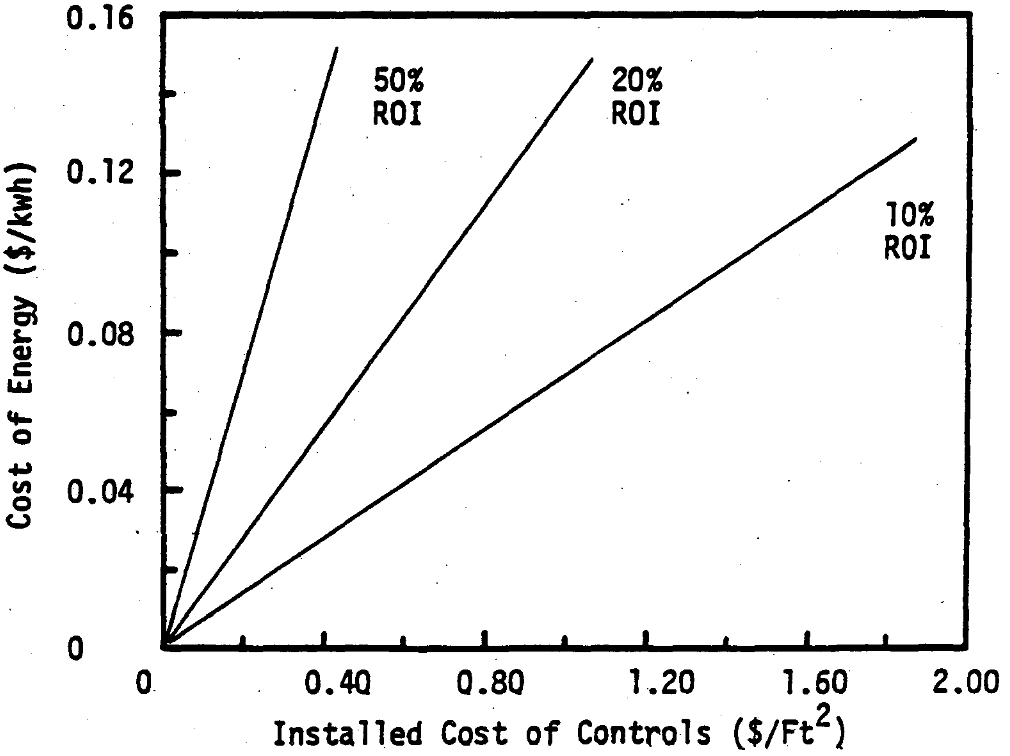

Figure 11. Cost-Effectiveness of Tuning.

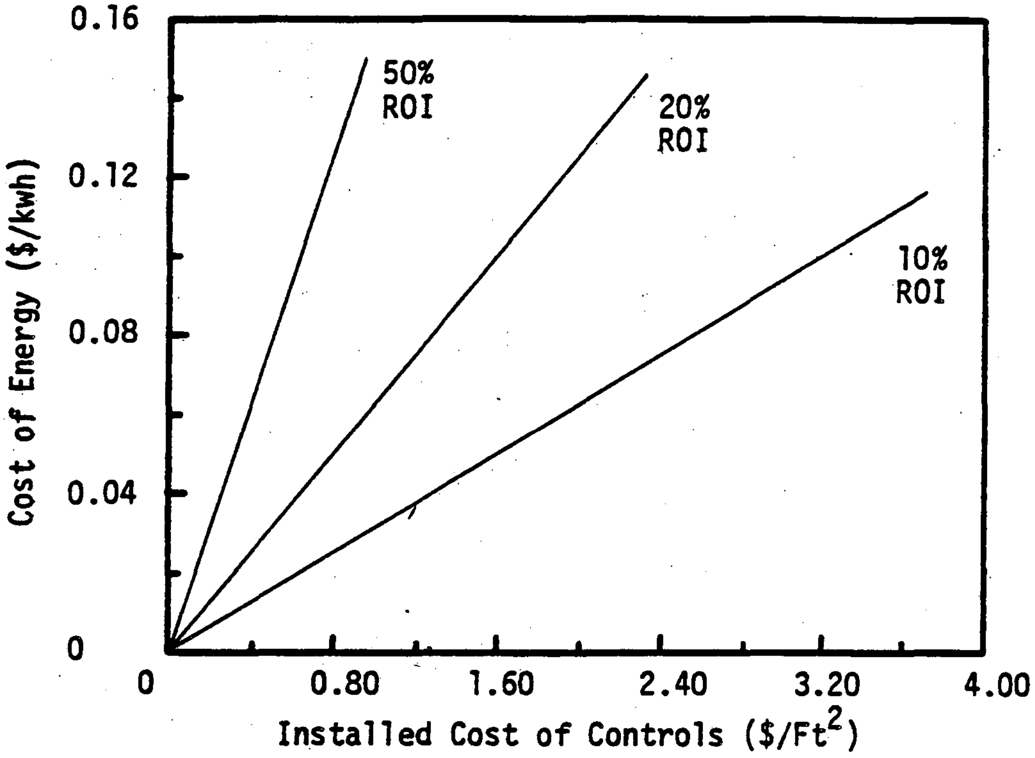

Figure 12. Cost-Effectiveness of Scheduling and Daylighting (Switching).

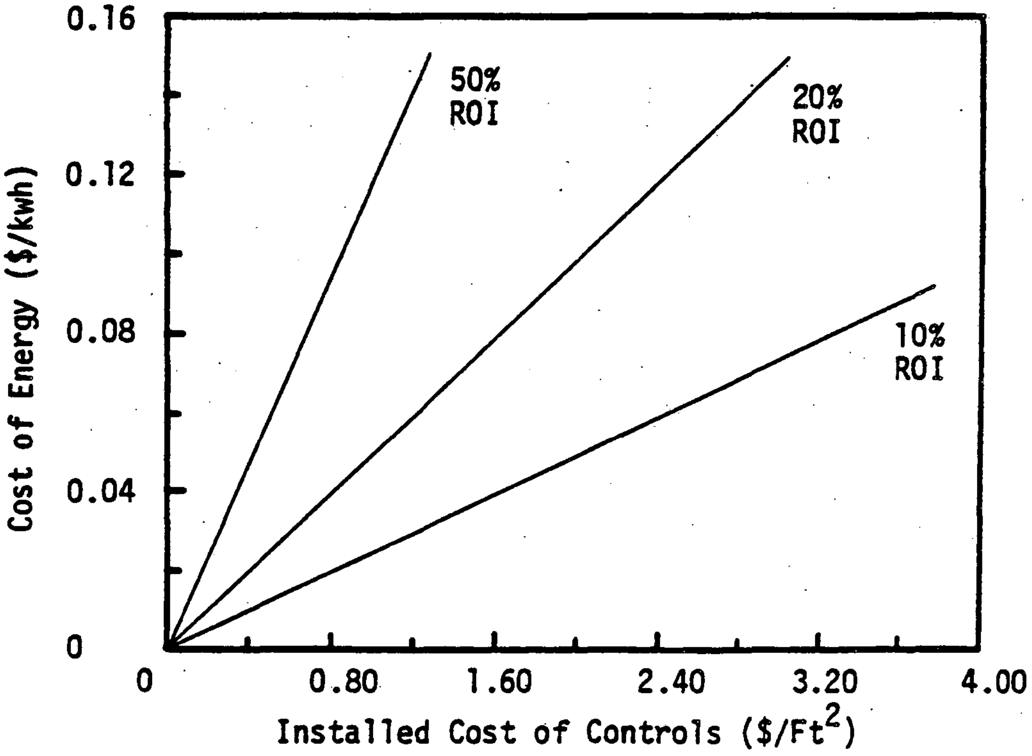

Figure 13. Cost-Effectiveness of Scheduling and Daylighting (Dimming).

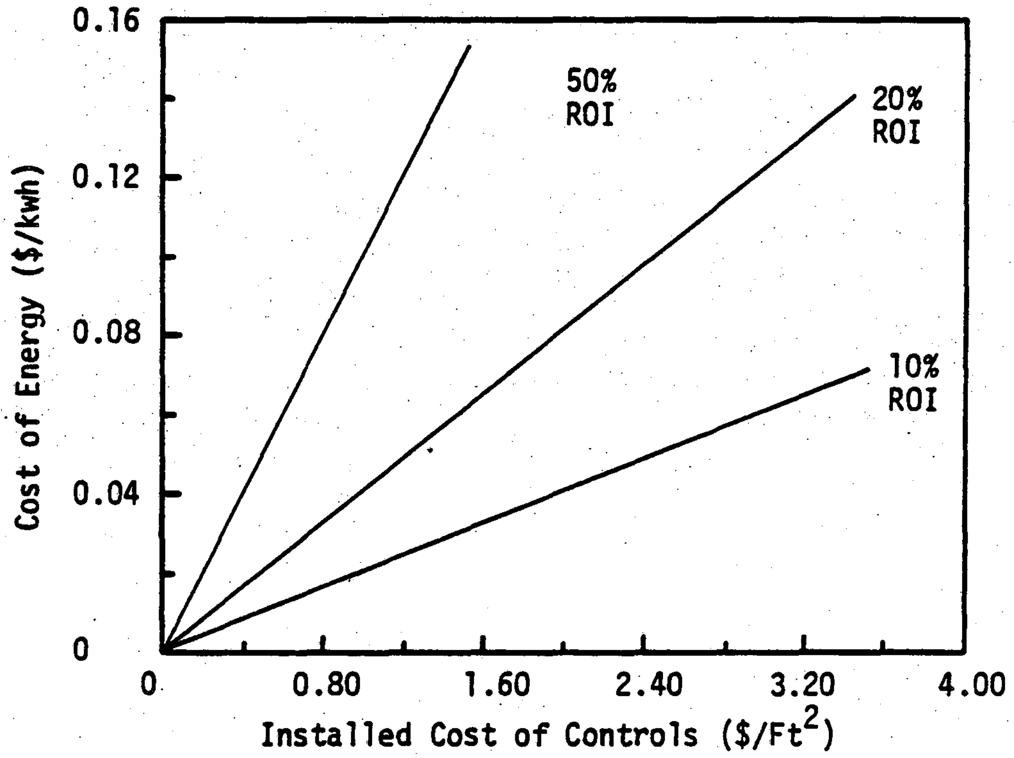

Figure 14. Cost-Effectiveness of Scheduling, Daylighting, and Tuning (Dimming).

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