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INTRODUCTION

Electric lighting consumes for 30% to 50% of electrical energy used in large commercial buildings, and has significant impact on cooling energy requirements. The integration of daylighting with electric lighting to provide ambient illumination and providing task lighting separately at each workstation is an attractive strategy for energy conservation. Energy savings come from proper control of the electric lighting system in response to available daylight. Building-level energy use measurements are generally insufficient to determine how well a building is operating. Detailed measurements of energy used by separate building components are needed to understand how a particular building system is operating.

This paper describes instrumentation used to monitor the electrical energy consumption and illumination levels in a recently completed 56,000-m^2 office structure in the San Francisco Bay Area. Interfacing of the temperature, electrical, and illumination measurements to the dataloggers is described. Data acquisition in this occupied building presents several challenges. Researchers needed to make measurements quickly, with minimal disturbance to occupants by equipment and wiring, in four quite different daylighting zones separated by large distances--all on a limited budget. We give a brief description of the building and the issues to be addressed by this monitoring project. We then describe the instrumentation installed in the building to measure both lighting levels and electric power consumption. Finally, we present and discuss typical results that can be obtained with this instrumentation.

THE BUILDING

The instrumentation of the building offers a valuable opportunity to examine performance data of a building having a number of innovative daylighting features. The building represents a major experiment in the use of daylighting by a large U.S. corporation to significantly reduce energy consumption and improve employee productivity. The building is a 56,000-m^2 (600,000-ft^2) office building housing over 3,000 technical personnel engaged in engineering tasks.

Daylighting-related criteria was a major consideration in the design of the building. The rectilinear mass of the building was elongated on an east-west axis, producing major fenestration surfaces facing roughly north and south. (The building faces about 20 degrees west of south.) Many building functions without a strong relationship to daylighting, such as computer facilities, conference rooms, rest rooms, copy rooms, etc., are grouped in explicit core zones. The cores were designed with opaque surfaces and placed on the east and west ends of the building to mitigate the adverse radiation impacts associated with these orientations.

Central Atrium

Realizing that even the most effective perimeter daylighting system could not project light more than about 12 m (40 ft) into the building, the architect designed an atrium to provide natural light to the building's large interior zones. The atrium became a major organizing feature of the building. The spaces adjacent to the atrium have natural light with a strong downward component. Light from the overhead atrium glazing ranges from strongly diffuse on the south side of the atrium to directional light through the translucent atrium glazing on the north side. On both sides of the atrium, light levels diminish as the distance from floor level to atrium roof increases and as the view angle between that floor and the roof becomes more acute. A section view of the building is shown in Figure 1.

Exterior-Zone Light Shelves

Because of the large, open plan, the daylighting strategy requires a substantial penetration of daylight from the exterior fenestration to the building's interior spaces. To increase the depth of this penetration the designers established a fairly radical floor-to-floor dimension of 5.5 m (18 ft). To prevent glare from the exterior glazing, large light shelves were placed along both north and south exterior walls. The light shelves are horizontal interior elements about 2.3 m (7.5 ft) above the floor, extending from the exterior glazing inward 4 m (13 feet), as shown in Figure 2.

The ceilings on each floor, built with standard modular materials, are sloped to effectively intercept and reflect illumination directed inward from the light shelves. Through the year the interior receives light from the region above the light shelf that has a strong horizontal component as it is reflected into the interior.

Spaces along the south exterior wall are exposed to high levels of natural light, with beam daylight during winter months. The south side of the building has an additional exterior light shelf reflector. To further prevent glare and winter solar gain, the glazing below the light shelf has a relatively low transmittance (17% on the south side and 43% on the north). The north is primarily exposed to diffuse sky vault radiation, and the distribution of interior light is characterized by this sideward diffuse light.

Electric Lighting System

Separate systems provide ambient and task illumination. Ambient illumination, the lighting circulation areas and casual tasks, is provided by indirect fluorescent ceiling fixtures and supplemented by available daylight. Task lighting is provided by fixtures built into individual workstations. These fixtures are under the individual's control and illuminate the work surface.

The electric lighting system was designed to produce and maintain an ambient illumination at about 350 lux (32 fc) supplemented by daylighting. The design lighting power density based on measured power and fixture distribution is about 10 W/m^2 (0.9 W/ft^2). Projected to the entire building this would give a design electric power consumption for ambient lighting of about 450 kW. The electric lighting system has two types of control: on/off and continuous dimming. The on/off control of each bank of fixtures is tied to a computer control system that sweeps the lights off at regular intervals during periods of low occupancy. Occupants can manually restore the lights during these periods.

The electric lighting system uses fluorescent fixtures with continuously dimming ballasts controlled by photocells. This permits the electric light to be reduced in direct proportion to the available daylight. The lighting system is specified to dim the lights from 100% to 15% of full light output. Measurements indicated that the actual minimum dimming level is about 22% of full light output with 27% at full power output. Photocells are used to sense the light entering the building. There is a photocell sensor for each row of fluorescent fixtures. All of the exterior-zone dimming system sensors are grouped underneath the light shelf. The atrium-zone dimming system sensors are on the ceiling about 3 m (10 ft) from the atrium edge. Open-loop control with sensors remote from the area of control is employed. In principle it is possible to adjust the gains on each control circuit to represent the daylighting contribution to the ambient illumination level at that row's position; however, this requires careful adjustment. The original specification called for downward-looking sensors to directly measure the illumination near each fixture to provide closed-loop feedback control.

The building design is strongly influenced by daylighting criteria. During much of the daytime, daylighting provides for nearly all of the ambient lighting needs throughout the entire area. The architect projected an 80% decrease in electric power consumption for ambient lighting during daytime hours. This project addresses the efficacy of the building's daylighting features.

INSTRUMENTATION

The instrumentation program was designed to collect data at four locations in the building with different daylighting characteristics. The south light shelf zone, the south atrium zone, the north atrium zone, and the north light shelf zone. The light shelf or exterior zones on the north and south sides use a horizontal array of illuminance sensors, as shown in Figure 2. There is very little difference from floor to floor on the external facades. For the purposes of this study the third floor represents as a typical floor. The atrium or interior zones are represented by vertical profiles along either side of the atrium and include sensor locations for a short distance into each floor, as shown in Figure 3. The measurement program plans to move the data acquisition equipment from one daylighting zone to the next.

The instrumentation of an existing facility poses some interesting technical challenges. Minimum disturbance of occupants and the orderly installation of sensor wiring are major practical criteria for this type of data acquisition effort. The instrumentation program had the following objectives:

1. Evaluate the dimming control system by recording power consumption and ambient light levels during the building's daytime working hours.
2. Establish illuminance profiles in the building interior for various sky conditions. Collect data showing the combined effects of daylight and electrical ambient lighting during the weekdays. Measure the daylight component when the building is unoccupied. Measurements were made across the width of the building from the exterior skin to the atrium.
3. Measure the light shelf luminance as an indicator of daylighting resource, including a profile of the light shelf's average luminance as seen from above.
4. Measure the air and surface temperatures in the space above the light shelf that relate to the thermal loads occurring in this space.

The instrumentation system was based on a series of four battery-powered, decentralized dataloggers. Four Campbell Scientific CR-21 dataloggers provided relatively short runs of analog sensor wiring and increased system flexibility in routing those wires. The CR-21 system features seven analog inputs with slope and intercept scaling and signal conditioning within user-selected input ranges. The devices use 12-bit analog-to-digital converters and stores several types of data (averages, minimums, maximums, standard deviations, etc.) at user-selected time intervals. The sensors were polled once a minute with averages stored on tape cassette every 15 minutes. Minima, maxima, and standard deviations were recorded on an hourly basis. For some detailed measurements, one-minute data was stored for brief periods.

The dataloggers were used to poll the following types of sensors:

Illuminance	LiCor 210S photometric sensors measured as a voltage source by the addition of a 1% 5,110-ohm resistor across the LiCor's leads.
Temperature	A CSI Model 101 thermistor calibrated to a standard input program in the Campbell Scientific's signal conditioning options.
Electrical Power	Ohio Semitronic Model PC5-59C AC watt transducers read as a DC output voltage by the dataloggers.

Illuminance sensors

Illuminance sensors develop a current output. Each sensor has a factory-provided calibration in the range of 20 μA/100 klux. To convert this current to a voltage, a 5,110-ohm resistor is placed across the LiCor output. The size of the resistor was chosen to give sufficient resolution at low light levels, but not exceed the range of the datalogger at the maximum illuminance levels. The datalogger had a resolution of 5 μV with a scale reading from -2 mV to 25 mV. For example, illuminance sensor L83 had a calibration of 16.7 μA/100 klux. With a 5,110-ohm resistor this gives an output of 85.38 mV/100 klux, or 1172 lux/mV. The maximum signal that the datalogger can measure corresponds to about 29,000 lux. The resolution is about 6 lux, compared to the target illuminance level for ambient lighting of 350 lux, and is adequate for this application.

The datalogger automatically computes the light output in lux by multiplying the sensor reading in mV by a scale factor and subtracting an offset. In addition there was a limitation on the largest number, 6999, that could be stored in the datalogger. With the calibration factor in lux for ease of data analysis, this set a limitation of 6999 lux, which is acceptable for the zone illuminance sensors. However, the sensor measuring the brightness of the light shelf looking downward from the light shelf ceiling measured up to 8,000 lux. The vertical sensors looking out the light shelf glazing recorded values up to 26,000 lux. Consequently, these higher values were recorded using two 5,110-ohm resistors in parallel and the scale factors divided by 100. The range of values, both electrical and numerical, must always be carefully considered in interfacing sensors to the data acquisition equipment.

Sensor locations for measurement of the south exterior zone were determined after site inspections including spot measurements with hand-held instruments. These survey measurements indicated little variation in light level along the east-west axis of the building. In addition, the south exterior zone exhibited little variation from floor to floor. Measurements made in the south side of the third floor were therefore considered representative of the south exterior zone. LiCor photo sensors were mounted at a height of 1.72 m (68 inches) above the floor as a measure of ambient illumination. This was at the top of the office partitions and eliminated the shadows cast by the partitions and the other office furniture. Thirteen LiCor photo sensors were placed several feet apart across the width of the open-plan office as shown in figures 2 and 3.

Datalogger No.1 was located on top of the south-side light shelf. From this location, short cabling runs connected the device to three illuminance sensors and four temperature sensors. The illuminance sensors were placed above the light shelf in locations selected to represent the amount of natural light available to the daylighting system. As shown in Figure 2, two of the LiCor sensors, L81 and L82, were placed in a vertical plane immediately behind the clear light shelf glazing. The two vertical sensors were separated by a horizontal flat black shield that caused the upper sensor to measure illuminance from the horizon line upward (the sky component). The lower vertical sensor measured illuminance from the horizon line downward (the reflected component), a view that included the exterior reflector mounted on the south side of the building. The remaining illuminance sensor, L80, was mounted on the sloped ceiling above the light shelf with a downward view of the light shelf's reflecting surface. This gave a measure of the lighting resource available from the light shelf. Similar measurements were made for the north exterior zone light shelf; however, the north side does not have the exterior reflecting surface.

Datalogger No.2 was connected to a series of LiCor illuminance sensors, L83 through L89, that stretched along a cross-section line from the south exterior wall to the south side's centerline corridor. These sensors, the datalogger, and their wiring were mounted on top of the open-plan office partitions. A similar deployment of Datalogger No.3 produced a partition height profile of illuminance from the centerline corridor to the south edge of the atrium, L90 through L96, as shown in Figure 3.

Electrical Power Transducers

The fourth datalogger, recording power consumed by the indirect electric lighting system, measured branch circuits supplying lighting fixtures across the width of the building's south side. Specific electrical lighting circuits were interfaced to the dataloggers using watt transducer as shown in Figure 4. Datalogger No.4 was located in the south side's third-floor electrical closet and was used to poll the eight watt transducers connected to the electrical lighting circuits 1, 3, 5, 7, 9, 11, 13, and 15. Because only seven sensor channels were available on the datalogger, the signal from the transducers' circuits 3 and 5, representing the double row of fluorescent tubes in the light fixture in the middle of the south atrium side, were combined in series. The datalogger and the watt transducers were mounted in a custom enclosure to eliminate any shock hazard for building staff. The rows of fixtures, designated A through F, and circuits monitored are shown in figures 2 and 3. The positions of the lighting sensors are also shown in the figures.

Temperature Sensors

Datalogger No.1 on top of the south-side light shelf also had four temperature sensors placed in representative points at the top, bottom, entry, and lower surfaces of the light shelf cavity. These are indicated as inverted triangles on Figure 2. These provide information regarding the thermal behavior of the light shelf.

Data Capture

The data collected by the Campbell Scientific CR-21 dataloggers were stored on a cassette tape recorder integral to the Campbell system. Our standard procedure for recovery of the data involved reading these cassette tapes in the field. A portable Compaq microcomputer was taken to the building and used with a Campbell C-20 cassette interface to download the Campbell data files to IBM floppy diskettes. The data tapes were then reconnected to the datalogger to store additional data.

The data collected by this procedure was transported from the building as a standard ASCII-format file in Campbell data format. From this form it was reduced using a series of microcomputer programs. The data reduction process, outlined in Figure 5, began with data in a standard Campbell data format that mixed different data types (averages, standard deviations, minimums, maximums, times of occurrence, etc.) in files containing up to two weeks' data from one of the Campbell dataloggers. A program written specifically for this project was used to reformat the data from the Campbell file format into individual files by day and data type. The data were then inspected using an editor and reassembled into contiguous multi-day blocks that were still separated by data type. An analysis of the data was conducted using data base and spreadsheet programs. REFLEX, a powerful data base management program from Analytica Corporation, is adept at providing rapid statistical summaries of the data while providing a series of filters for the isolation of data subsets. The data were also examined and plotted using the 123 spreadsheet program from Lotus Corporation.

Other Available Building Data

In addition to the data from our monitoring of the building, data from daily manual readings of main electrical power circuits and hourly and daily readings from the energy-management system to fill out the picture of building operation. Hourly energy-use data for both the total-building electricity usage and the submetered circuits for ambient lighting and fans were obtained and plotted. Estimates of the annual building electrical consumption were also obtained. The data were obtained on hardcopy printouts and manually entered into spread sheets for analysis and plotting. Because only a small sample of data was analyzed, the manual data manipulation was acceptable. However, for longer-term analysis, procedures should be developed to capture the data in a computer-readable form.

RESULTS

Illuminance measurements

As an example of the type of information that can be obtained from this limited instrumentation, several examples of performance analysis are given. The detailed performance of the building was examined using data measured on the south side of the third floor during a nine-day period beginning 20 May 1985 (day 140) and ending 28 May 1985 (day 148). This period includes a set of typical sunny business days and a pair of cloudy weekend days.

The illuminance in the south-side light shelf zone for a typical bright occupied day in May (day 140) is shown in Figure 6. The illuminance levels reported are the sum of daylight and electrical light components. The electrical lighting system has been measured at approximately 225 lux at full light output. Each curve represents the illumination at a different distance from the exterior of the building. Illuminance levels during occupied hours stay well above the 350-lux target level in the middle of the zone as indicated by sensors L84, L86 and L89. The lowest illuminance levels were measured by sensor L83 beneath the light shelf. The windows below the light shelf are of low-transmittance glass ($<17\%$) to reduce glare and to reduce heat gain during winter months. This area receives minimal contribution from daylighting.

The light levels on the third-floor south atrium zone on this same bright occupied day are shown in Figure 7. The illuminance at sensor L92 (12 ft from the atrium edge) and sensor L93 (19 ft from the atrium edge) peak near 1000 lux and 700 lux respectively. Sensor L91 (5 ft in from the atrium edge), with a view of the atrium roof, has illuminance levels exceeding 1600 lux. While these illuminance values include some electrical lighting, they also exceed the target illumination by a comfortable margin. The contribution of daylighting to ambient illumination over most of the floor area in both the atrium and light shelf zones stays well above the 350-lux target load. One would anticipate significant reduction in electrical lighting power consumption during these sunny days.

Figure 8 shows the ambient illumination levels on the south side of the third floor on a cloudy day. These data were collected on an unoccupied day with the electrical lights off. While the daylight levels are much lower than on a sunny day, a large portion of the floor exceeds 350 lux during a large part of the day. In fact, nearly the entire floor is illuminated most of the day at a level of 150 lux. Thus, even on a cloudy day one would expect the electrical lights to be dimmed by a significant amount.

Light Shelf Illuminance

Three illuminance sensors were deployed on the south light shelf to measure the illuminance resource, as shown previously in Figure 2. L80 is at the light shelf ceiling looking downward, and provides a measure of the brightness of the light shelf. L81 and L82 look outward through the exterior glazing. L81 is an illuminance sensor pointing outward. L82 is masked so that it receives illumination from the horizon plane upward. L82 is an illuminance sensor mounted adjacent to L81 and pointing outward, which is masked to receive illumination from the horizon plane downward, a view that includes the south-side exterior reflector.

The brightness of the light shelf as measured by the downward-looking sensor L80 has a good correlation with the daylight in the space. Figure 9 shows the relationship between interior illuminance just beyond the light shelf as measured by sensor L84, and ceiling brightness at the light shelf as measured by L80 for nine days in May. The data set includes unoccupied weekend hours and shows two curves separated by 250 to 300 lux, depending on whether the electric lighting system is on or off. The figure shows that for this time of year the illuminance exceeds the target value of 350 lux if the light shelf brightness is greater than about 1750 to 2000 lux. Figure 10 shows the correlation between interior illuminance 33 ft from the window as measured by sensor L89, and ceiling brightness at the light shelf as measured by L80. Again, the illuminance in the space is dependent on the brightness of the light shelf, though as one would expect, the illuminance level 10 m (33 ft) from the window is not as great as that near the light shelf. The two distributions of data points represent the electric lights being on or off. The figure shows that the illuminance exceeds the target value of 350 lux if the light shelf brightness is greater than about 4000 lux.

For this specific time of year, there is good correlation between the brightness of the light shelf and the illuminance in the space, as measured by sensors L84 through L89, even over the daily variation in sun angle incident at the light shelf. We hope to examine this correlation at other times of the year, particularly for low sun angles in the winter months.

Power Measurements

Watt transducers have been installed to measure the electrical power consumption on both the north and south sides of the building. Figure 11 shows the electric lighting power consumption of lighting circuits 9, 11, and 13 on the south light shelf zone on a clear sunny day in May. These circuits correspond to the two rows of fixtures, D and E, that are 36 ft and 12 ft from the window. Each circuit has several sections that can be switched on and off independently. After 6 PM all the lights, with the exception of emergency access lights, are swept off about once an hour and can be turned on manually if employees are working late. This contributes to lighting energy savings. The power consumption curves show that the circuits are automatically turned on at 6 AM, part are turned off at 6 PM and 8 PM, and all are turned off at 10 PM.

During the day all circuits exhibit some dimming. Circuit 13, close to the window, dims by as much as 35% (2.8 kW to 1.8 kW) at noon. The other two circuits are dimmed, at most, by 18% (2.2 kW to 1.8 kW). The dimmers on circuits 13, 11, and 9 are controlled by photocells that sense the relatively dark space beneath the light shelf and look through the tinted view glazing. Measurement of the illuminance levels in the space clearly indicate that daylighting is sufficient to reduce the electric lighting power demand to a minimum. Measurements of the dimming system demonstrated that the power demand of the electric lights can be reduced to 27% of full power. At this power level the illumination level becomes about 22% of full light output. The potential lighting energy savings are not being achieved.

A scatter plot of the lighting levels recorded by sensor L84 and the electric power consumption of lighting circuit 13, adjacent to that sensor, is instructive (Figure 12). With the lights on and no daylighting, the illuminance levels are at the target of 350 lux and the electric power consumption is at maximum, 2.8 kW. As the illuminance level increases to 1400 lux, the lighting power level drops to about 1.8 kW, indicating some dimming. However, this is four times the target illumination level, indicating poor response of the dimming system. There is also a group of points at about 1.8 kW at low levels of illuminance, indicating that the lights in the vicinity of the sensor have been turned off, but that others on the same circuit are on.

When the lighting level in the space, as measured by sensor L93 is plotted against the combined electric power consumption of circuits 3 and 5, as is shown in Figure 13, the dimming shows up clearly. Circuits 3 and 5 control fixture B, which is 30 feet from the atrium in the location that is least likely to dim. The lighting circuits adjacent to the atrium are controlled by photo sensors that are mounted in the ceiling near the atrium. This is the type of control that would be expected from a well-operating control circuit. The illuminance level is held near 350 lux. When there is no daylighting, the electric power to the lighting circuit is a maximum at about 2.9 kW, maintaining an illuminance level of about 250 lux. As the available daylighting increases the brightness of the space, the electric power gradually decreases to the minimum power consumption of the fixture, a load of about 27 % of full output. Daylighting above that value would then increase the illuminance level further, as indicated by the distribution of points at about 0.75 kW.

Figures 12 and 13 demonstrate two responses of a dimming circuit to the available daylighting. Figure 12 demonstrates poor response while Figure 13 demonstrates good response. On surveying the dimming circuits on the third and fourth floors of the building we also found some circuits with no response. The instrumentation of the daylight sensor combined with the watt transducers has given us valuable information about the operation of the intergrated daylighting and electric lighting system. The data collected have allowed us to evaluate the operation of the daylighting system in the south light shelf zone. Similar analysis can be performed for the atrium zones and the north side of the building. The daylighting system provides light for large areas and long periods of time over the south light shelf zone analyzed in this example. The dimming system is clearly not responding in most cases to the presence of daylight. The strong correlation between the illuminance at the top of the light shelf and the illuminance in the space suggests that this may be a more effective position for the photo sensors that control the dimming of the exterior light shelf zone electric lights.

Total Building Performance

Potential annual energy savings can be estimated by considering the total building electrical energy use, as well as the fraction of energy used in electric lighting. The total electrical demand is shown in Figure 14, and is based on summing the hourly demand of the various major meters: 1A, 1B, 2A, 3A, and 4A. These readings were accumulated and stored hourly by the energy-management system and printed out daily. Comparison of daily manual readings of the main utility circuits shows good agreement. Peak building electrical consumption is about 1,600 kW with a continuous load of about 700 kW. The total building load is quite consistent from day to day. As a gross building area of 56,000 m^2 (600,000 ft^2), the building peak electric power consumption is about 29 W/m^2 (2.7 W/ft^2). The continuous building load is about 12.5 W/m^2 (1.2 W/ft^2), which probably represents computers, fans, and other equipment left on 24 hours a day.

Based on 325 days of manual readings of the main utility circuits (1A, 1B, 2A, 3A, 4A) the annual building electrical energy consumption is estimated to be about 8,660,000 kW-hr/yr. The total energy use consists of baseload at about 700 kW for 8760 hours a year plus an additional 900 kW of demand for about 54 hours a week. This gives an electrical energy use of about 14.4 kW-hr/ft^2-yr (49 kBtu/ft^2-yr). This does not account for chilled water usage for cooling.

The major ambient lighting load is on a submetered circuit (LK8) of meter 2A and was measured during December 1984. The task lighting is on a separate circuit. The peak electrical lighting load based on circuit LK8 is about 410 kW with a significant dip to about 330 kW around noon on Wednesday, Thursday, and Friday of the first week. Only the lighting circuit shows this noon-time dip of about 20%. The nighttime electric lighting load on this circuit is about 70 kW, which probably represents emergency lights. There is also a much smaller lighting load that is a submetered circuit, LC2, of meter 1A. Meter 1A has a daily peak of about 80 kW and a night-time minimum of about 25 kW, so that this circuit has minimal contribution to the overall building lighting load.

On a weekly basis the LK8 lighting circuit is about 39% of the energy use on circuit 2A. On an annual basis this would correspond to 1,873,000 kW-hr/yr for lighting circuit LK8. The LC2 lighting circuit is about 33% of the energy use on circuit 1A, about 137,000 kW-hr/yr for lighting circuit LC2. The total ambient lighting circuit energy consumption is then estimated to be about 2,010,000 kW-hr/yr, or 3.5 kW-hr/ft^2-yr (12 kBtu/ft^2-yr). Thus, it is estimated that the ambient lighting represents about 23% of the total building electrical energy consumption of 8,660,000 kW-hr.

Measurements of the ambient electrical lighting system on the third floor showed an estimated installed power density of about 0.9 W/ft^2. This power density, if projected to the entire building, gives an estimated installed peak power of about 450 kW. This estimate agrees roughly with that measured for the whole building, i.e., the combined maxima of the main lighting circuits, LK8 and LC2 (490 kW). The minimum power level is about 95 kW. A minimum power level of 95 kW for 8760 hours/year gives 832,000 kW-hr/yr. An additional power level of 395 kW (490 -95) for 12 hours/day for 6 days a week, for 52 weeks per year gives 1,480,000 kW-hr/yr for a total of 2,300,000 kW-hr/yr, which is slightly larger than our annual estimate. If there were dimming of the lights to 80 % of full power, this would reduce the total power to our observed estimate.

Our present estimate of dimming on the south side is to about 84% of full power, while the potential is 50 to 60% of full power. The present electrical use for lighting is on the order of 2,010,000 kW-hr/yr. Increasing the dimming to 60% over the entire system would reduce the electric lighting consumption by an additional 300,000 kW-hr/yr. This would give an additional savings at current on-peak utility rates of $0.10/kw-hr of $30,000 per year. Thus corrective measures suggested from the detailed monitoring can have substantial economic benefit.

CONCLUSIONS

The instrumentation of the building with illuminance sensors combined with watt transducers has given us valuable information about the operation of the integrated daylighting and electric lighting system. Portable data acquisition equipment provides an effective method of monitoring and evaluating integrated daylighting and electric lighting systems in selected zones of a large commercial building. Careful survey of the building is necessary to insure that measurements are representative.

Use of watt transducers on electric lighting circuits together with illuminance sensors allows both the evaluation of the dimming system and estimation of the available daylighting. The daylighting system provides light for large areas and long periods of time in the south light shelf zone analyzed in this example. The dimming system is clearly not responding adequately in most cases to the presence of daylight.

The installed instrumentation can be used to evaluate the range of dimming that is possible. The lighting control system is capable of reducing the light level to 22% of full light output, and the power to 27% of full power. Proper integration of the electric light dimming system is essential for the realization of projected savings in electric power consumption.

Good correlations can be made between the brightness of the light shelf and the illumination levels that will be achieved in the space. These measurements indicate that it is possible to predict the available daylighting based on relatively few measurements and suggests a good location for lighting and control sensors.

Useful data can be obtained from the energy-management system that give a context to the limited survey measurements and allow estimates of whole-building impacts. Whole-building energy use measurements do not permit one to assess the energy performance of a building. Submetering of electricity usage and other measurements are required.

More detailed measurements, such as those described here, not only identify components that do not meet expected performance, but many times will suggest solutions that can permit the particular building component to better achieve its optimum performance.

ACKNOWLEDGEMENTS

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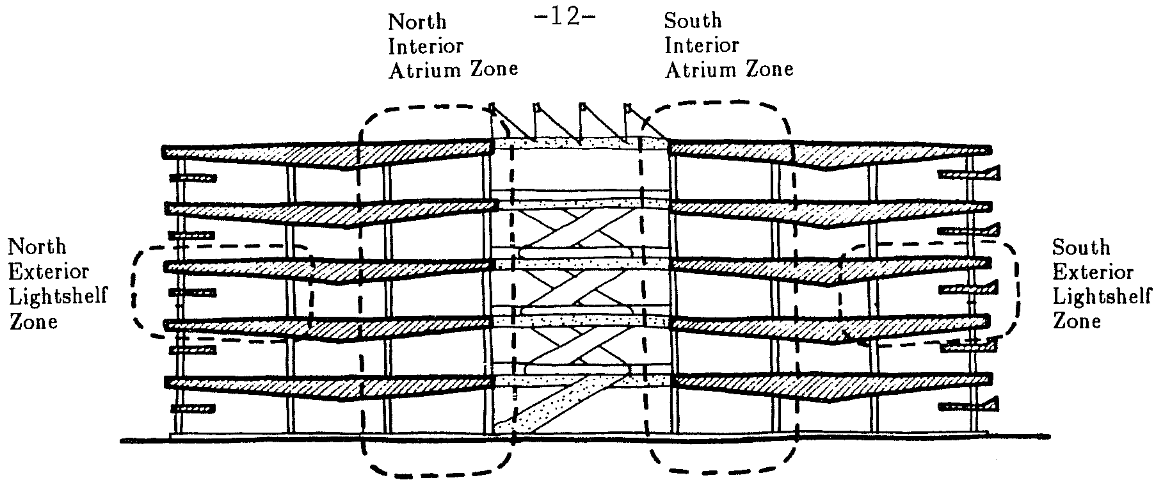

Figure 1. Section through the building showing the four daylighting zones under study: the south exterior light shelf, south interior atrium, north interior atrium, and north exterior light shelf zones.

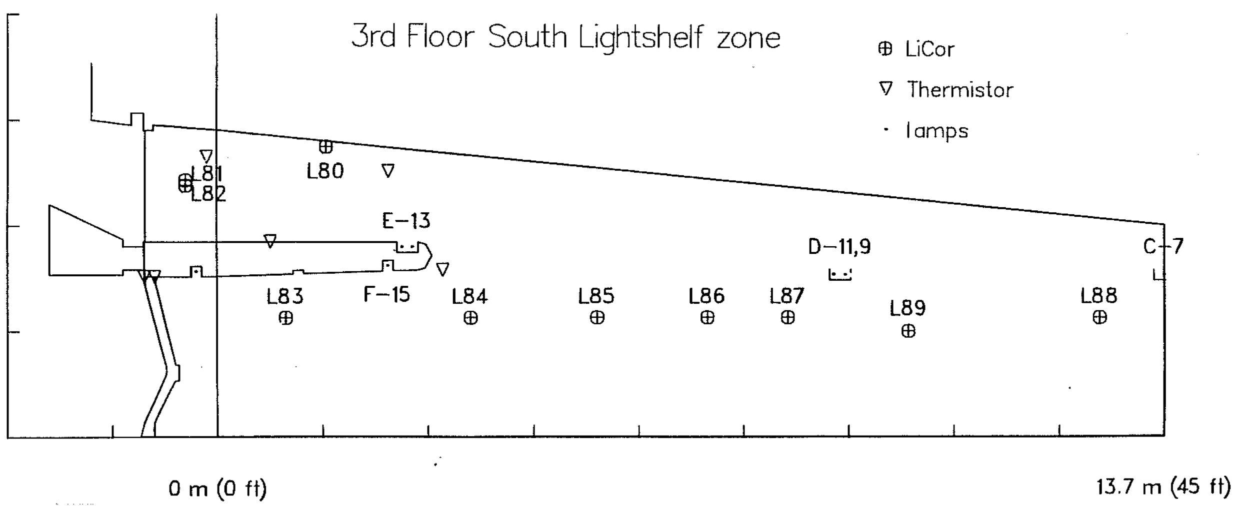

Figure 2. Section of the south exterior light shelf zone (third floor) showing the positions of illumination sensors, temperature sensors, light fixtures (C, D, E, and F), and electric lighting circuits (7, 9, 11, 13, and 15).

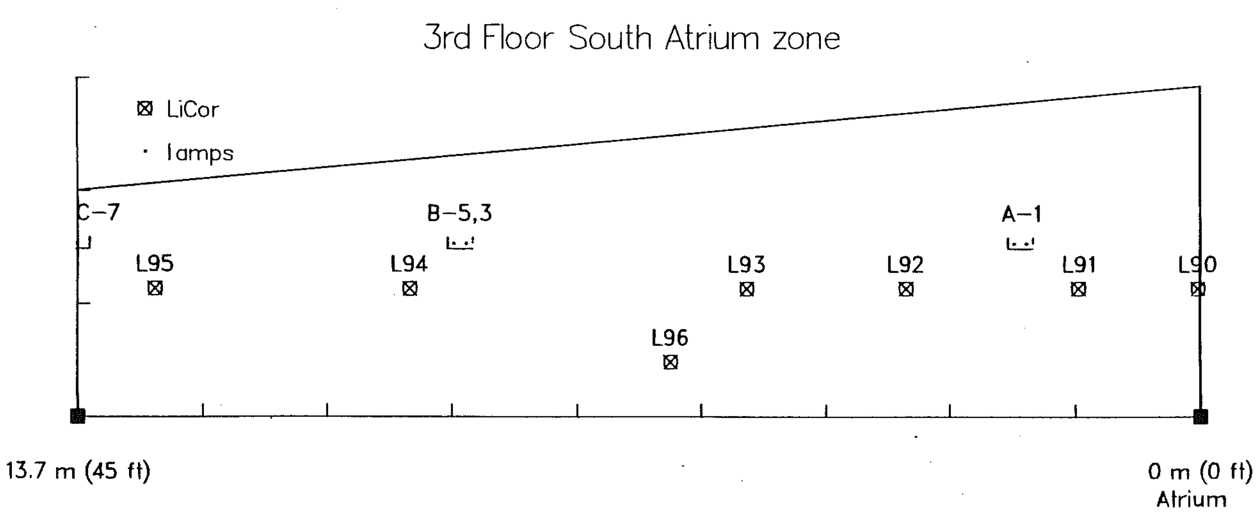

Figure 3. Section of the south interior atrium zone (third floor) showing the positions of illumination sensors, light fixtures (A, B, and C), and electric lighting circuits (1, 3, 5, and 7).

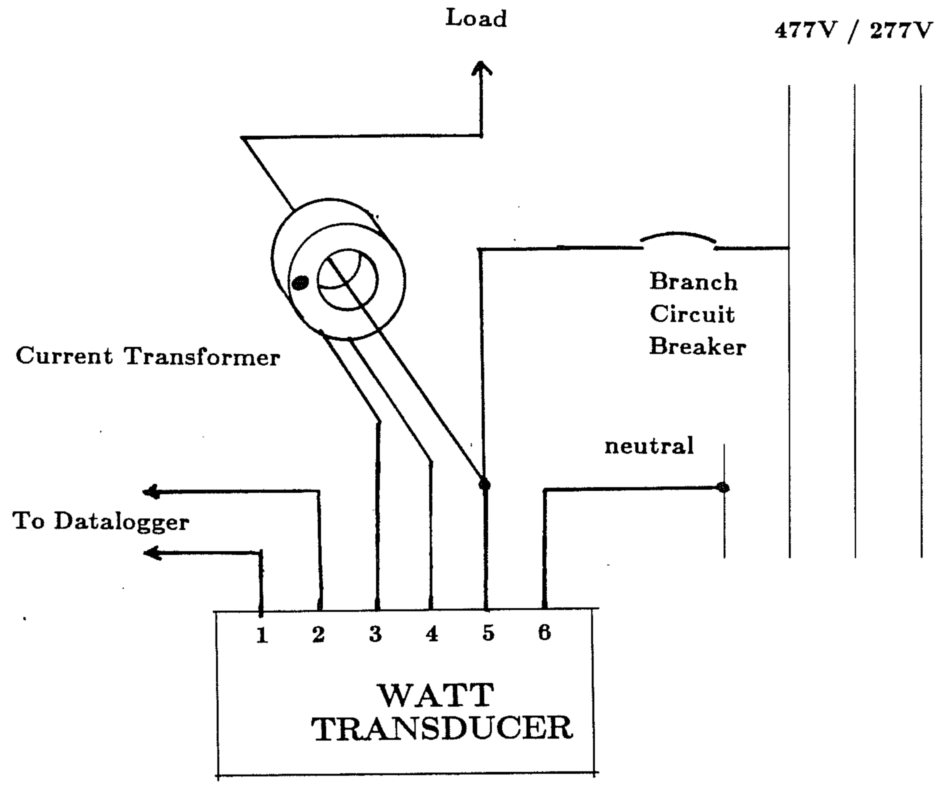

Figure 4. Watt transducers are connected to each of the lighting circuits in the area under study.

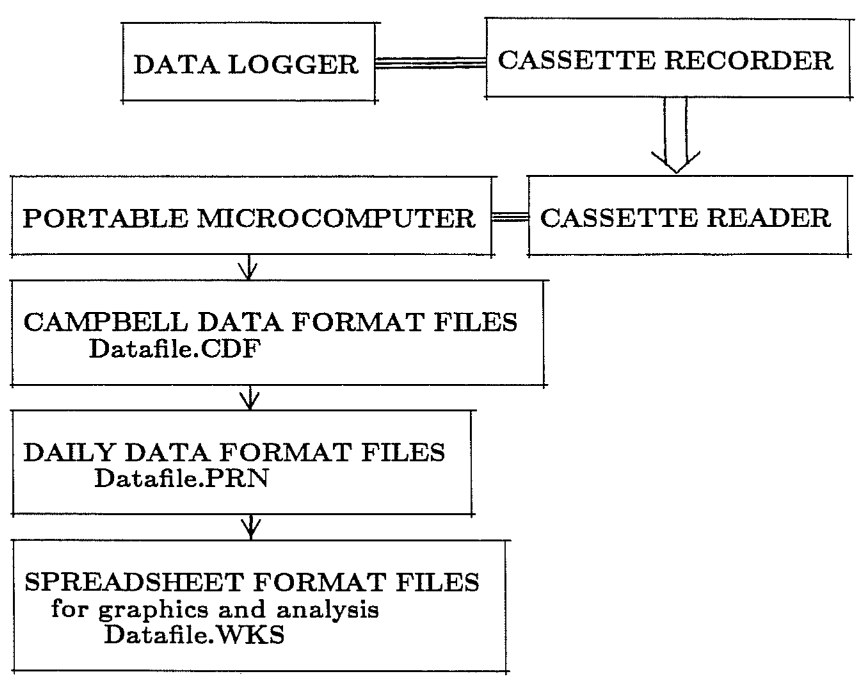

Figure 5. Data Reduction Procedure. The data from cassette tapes is converted to Campbell-format data files. These files are separated by day and data type and converted to data base and spreadsheet files.

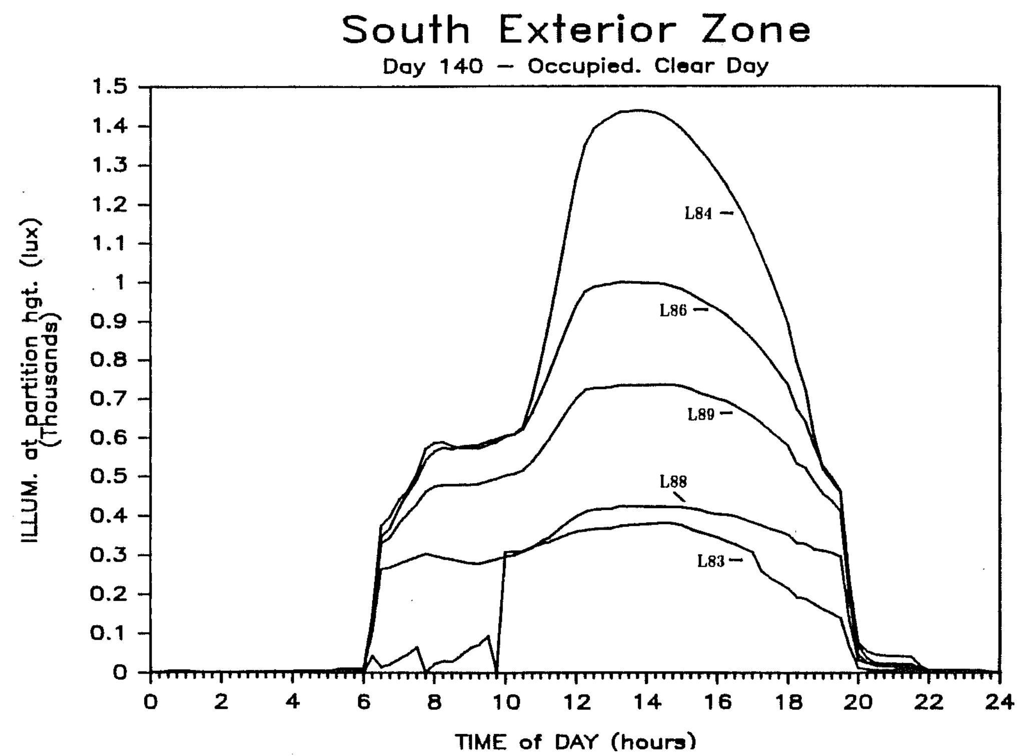

Figure 6. Illuminance south exterior light shelf zone for Day 140 as measured by illuminance sensors: L83 under light shelf; L84 in 15 ft; L86 in 25 ft; L89 in 33 ft; and L88 in 42 ft.

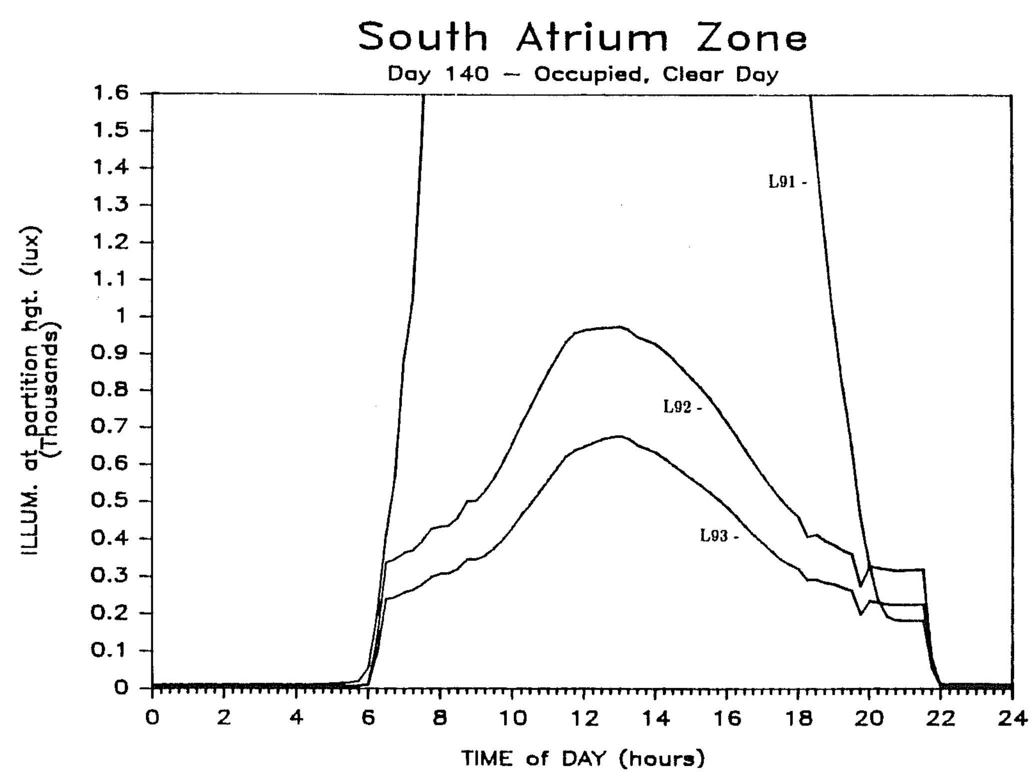

Figure 7. Illuminance south interior atrium zone for Day 140 as measured by illuminance sensors: L91 in 5 ft from atrium; L92 in 12 ft; and L93 in 18 ft.

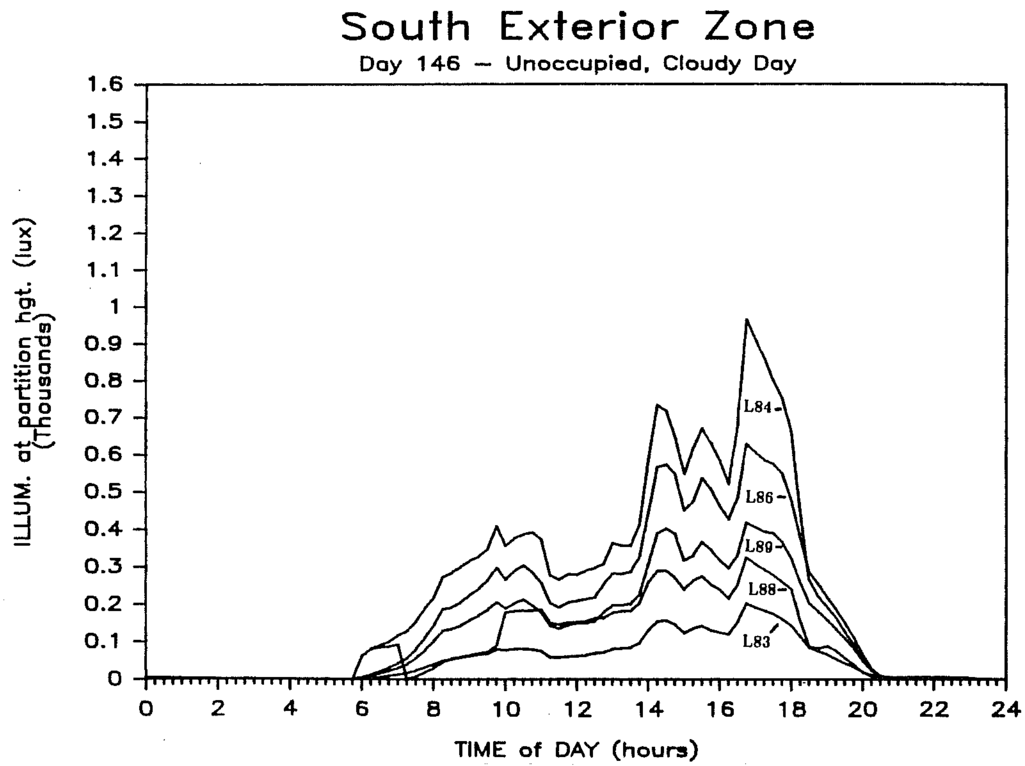

Figure 8. Illuminance south exterior light shelf zone for Day 146 as measured by illuminance sensors: L83 under light shelf; L84 in 15 ft; L86 in 25 ft; L89 in 33 ft; and L88 in 42 ft.

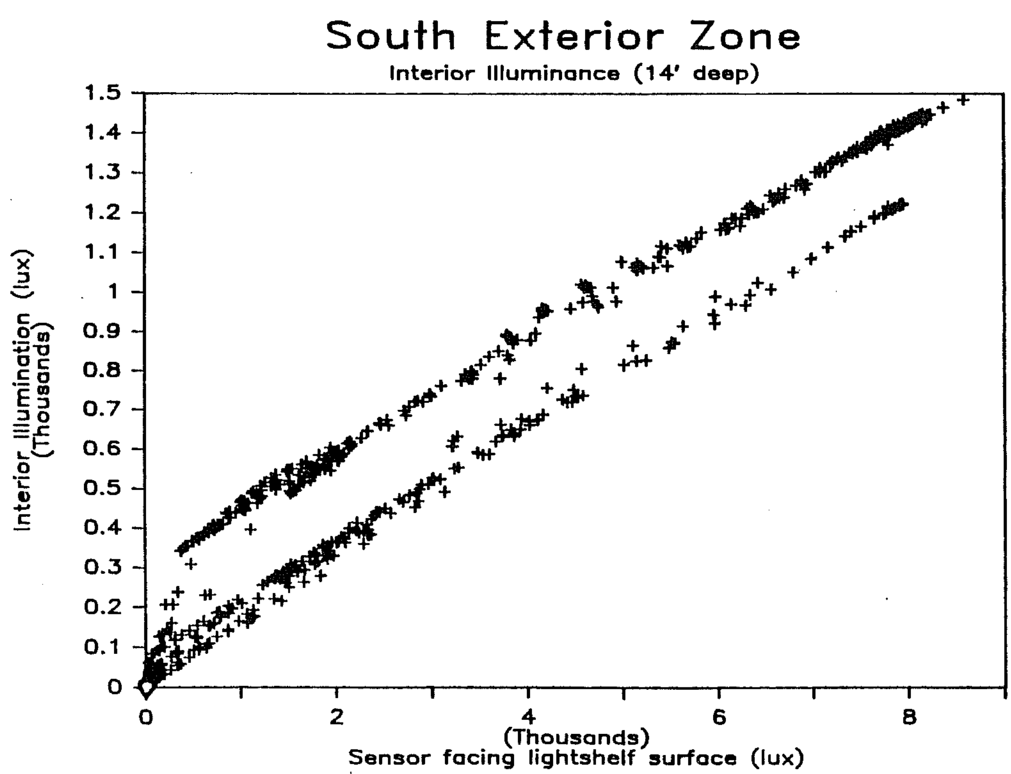

Figure 9. Interior illuminance, L84, just beyond the light shelf 15 ft from the windows, vs. light shelf luminance, L80.

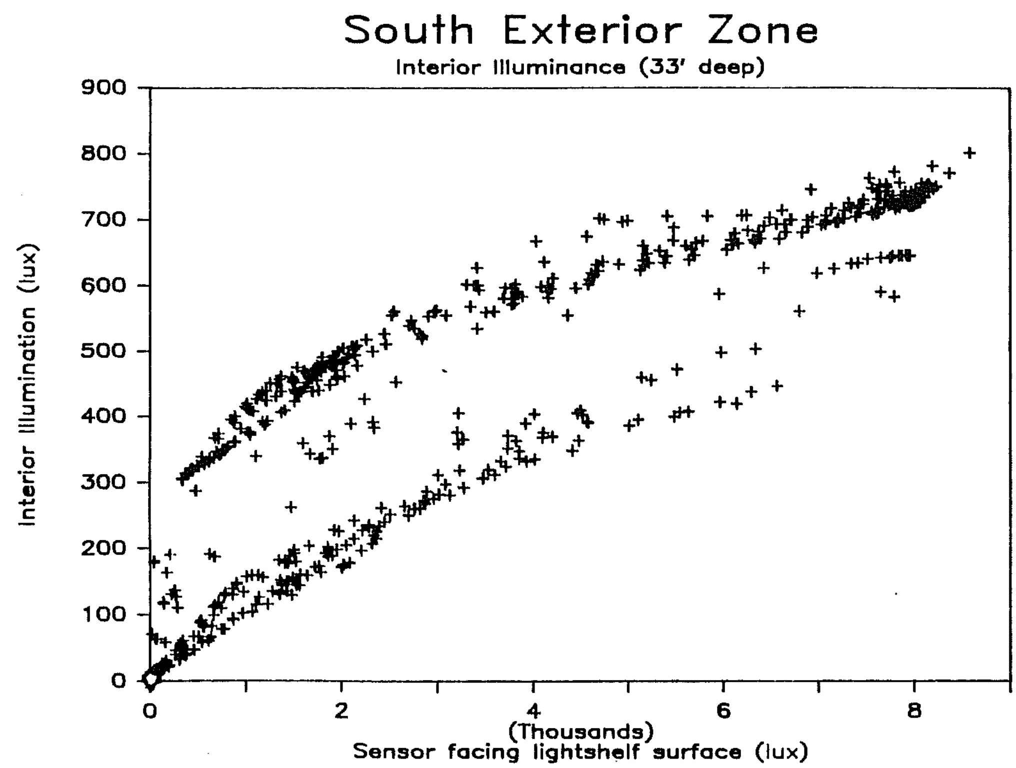

Figure 10. Interior illuminance, L89, 33 ft from the windows, vs. light shelf luminance, L80.

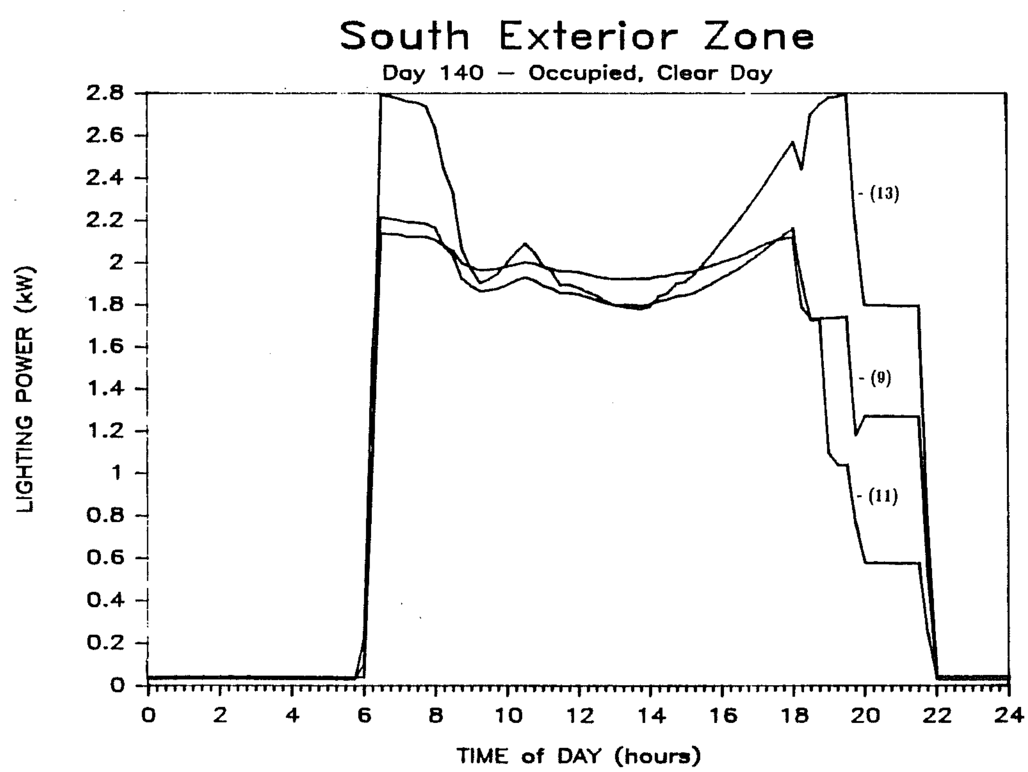

Figure 11. Watt transducers - south exterior light shelf zone for Day 140 showing circuit 13 in fixture E and circuits 9 and 11 in fixture D.

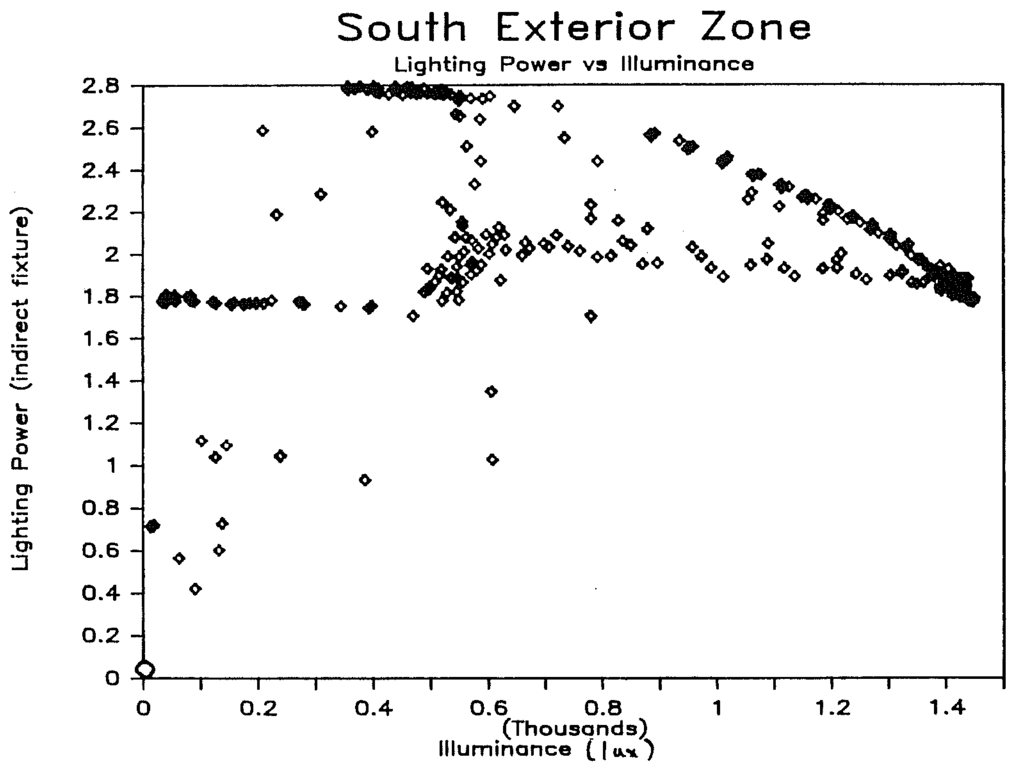

Figure 12. Illuminance, L84, 15 ft from the window, vs. lighting power 13 in circuit 13, showing some dimming.

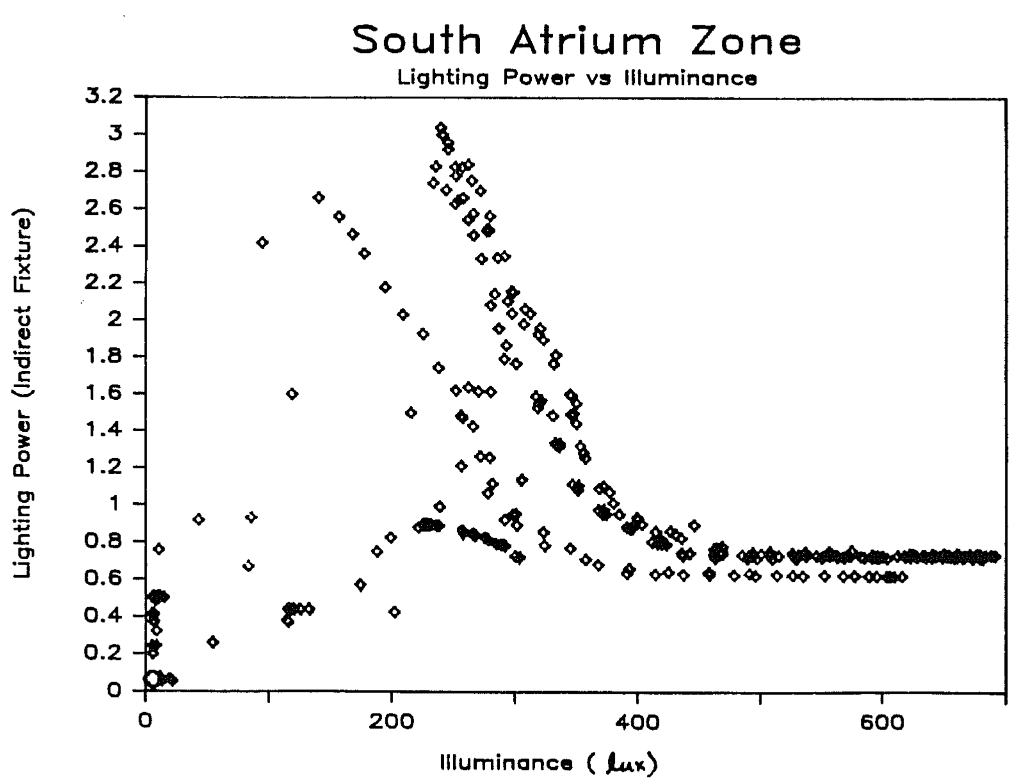

Figure 13. Illuminance, L93, 18 ft from the atrium, vs. lighting power in circuits 3 and 5, showing proper dimming operation.

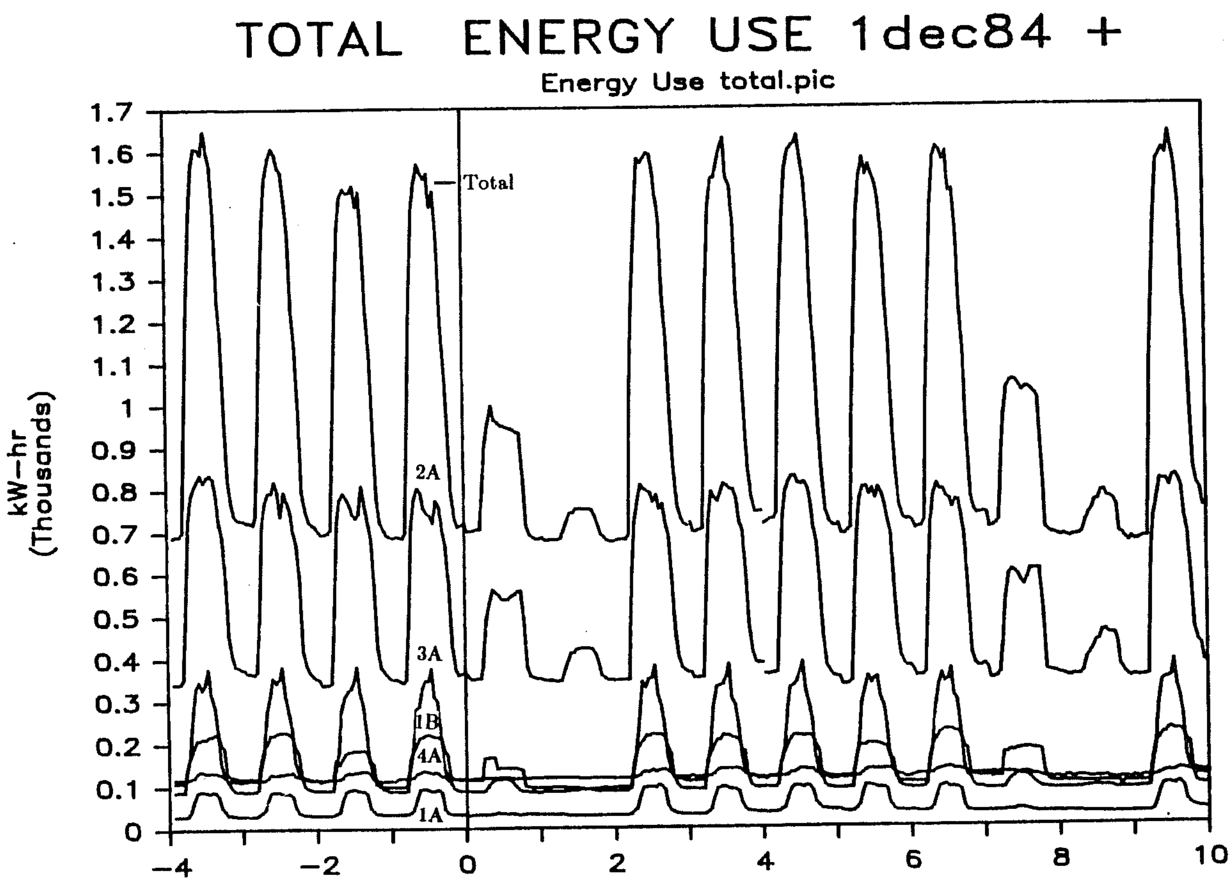

Figure 14. Hourly electrical energy use for the total building and main meters (1A, 1B, 2A, 3A, and 4A) for the period 3 December 1984 through 10 December 1984.