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ELECTRICAL CONSTRUCTION AND MAINTENANCE

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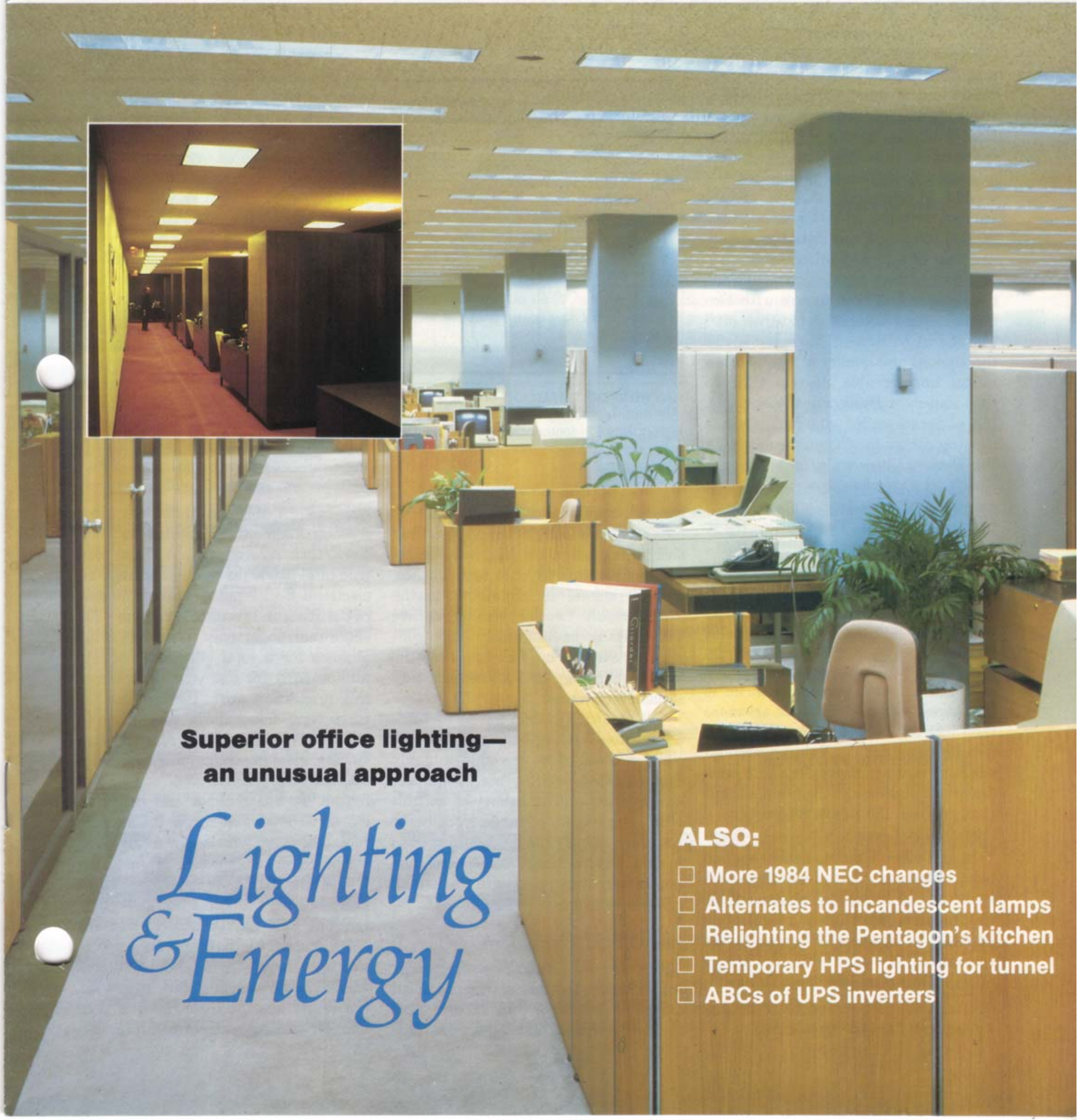

Superior office lighting—
an unusual approach

Lighting
& Energy

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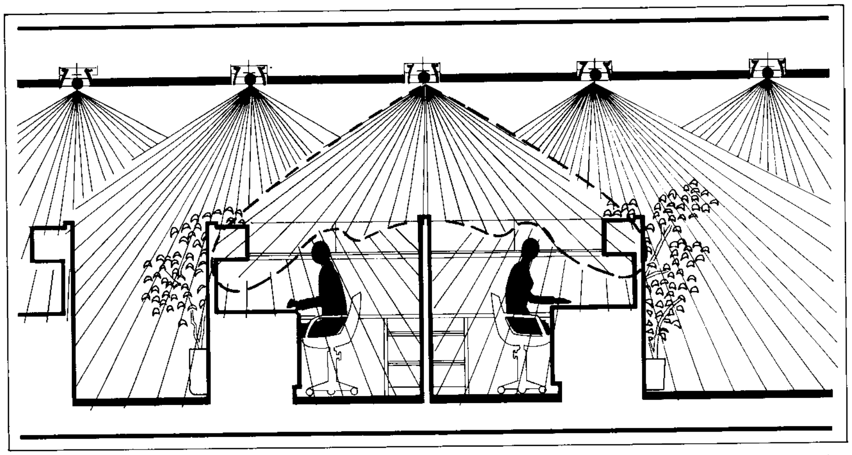
Wednesday, October 10, 2001 (2).jpg

Superior office lighting—an unusual approach

Integrating an advanced lighting system into the overall office environment produced far better lighting and slashed energy consumption from 2.5 W/sq ft to only 0.7 W/sq ft.



BATWING DISTRIBUTION of light output from each fixture concentrates the light at angles that minimize veiling reflections. Overlapping light from adjacent fixtures provides sufficient high-quality ESI footcandles for the required task lighting.

When energy costs began to get out of hand, Citicorp, the parent company of Citibank, set up an Energy Management and Conservation Department (EMAC), with a mandate to reduce energy costs throughout the worldwide organization. After EMAC finished with the HVAC systems, they tackled lighting. Their initial approach, like that of so many others, was, "a 2 × 4 fixture with four lamps? Take out two lamps. A 1 × 4 fixture with two lamps? Turn alternate fixtures off." The energy costs went down, but so did the amount and quality of light—often to an unacceptable degree. Citicorp then called in Designetics Associates, Inc. of Secaucus, NJ, who had done the lighting design for the public spaces in the 59-story Citicorp Center building, a New York City showplace noted for its unusual and attractive lighting. David Liametz and his Designetics team, working in conjunction with EMAC, studied the most advanced lighting systems and their application. He reached the conclusion that for maximum effectiveness the lighting system should not be considered alone, but as part of the overall environment—what Liametz calls the holistic approach. Holism is the theory that whole entities are more than just the sum of their parts, and a holistic approach to lighting emphasizes the functional and aesthetic relationship between each interdependent element and the whole to produce a superior total result.

In the office lighting design system being developed, that meant that each space had to be lighted effectively for its function, with easy modification possible as space and functions are rearranged. It meant taking advantage of daylight where available. It meant ease of maintenance and long life. It meant coordinating the hung-ceiling design, floor, window, and wall treatments, furniture layouts and finishes, and all colors, to contribute to the overall result. The goal was to improve the working environment while conserving energy, by incorporating the latest technology into an aesthetically satisfactory whole.

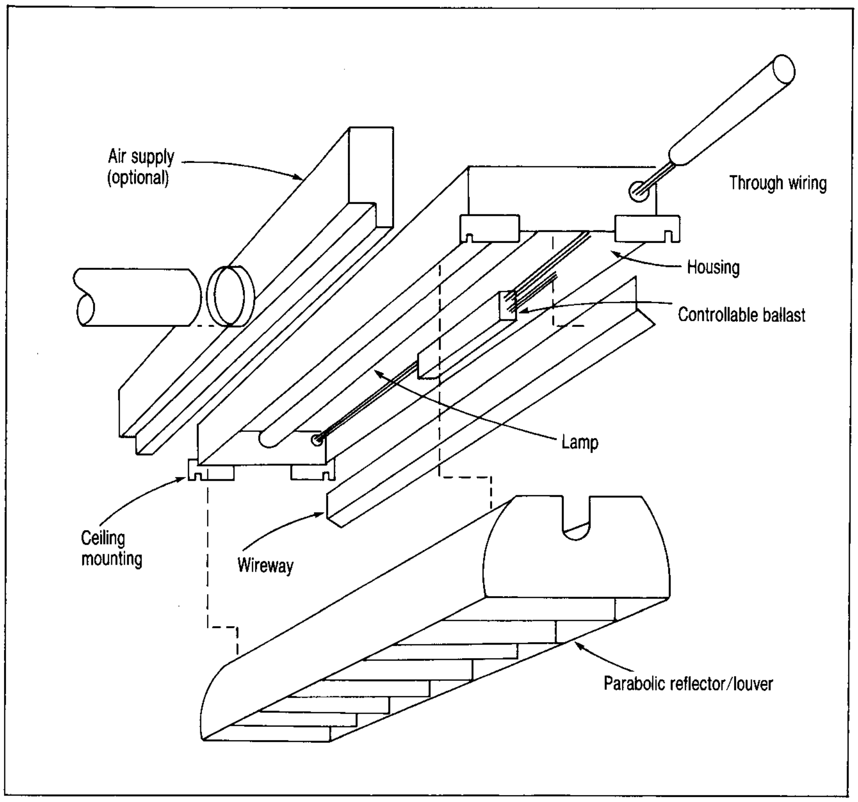
By ARTHUR FREUND, Senior Editor

The resulting system has as its basis an unusual lighting fixture with a specially selected lamp, driven by a highly sophisticated, solid-state, high-frequency ballast. The ballast is controllable over a wide range, locally or remotely, to vary the light output. This ballast, fixture, lamp, and control system is fully integrated with the overall office environment.

The Citibank approach

Not only did Citibank require energy conservation, but they also hoped to cut down the electrical construction costs of their frequent office space rearrangements. In 1980, at their 399 Park Avenue main office building in New York, their records showed actual bills paid of $176,000 for ceiling lighting and electrical work—not including the cost of partition and furniture changes—for space rearrangements. These are actual costs for a total office area of one million sq ft for one year. In some of this renovation work, the lighting fixtures were taken down carefully and reused. The actual cost of removing, storing, cleaning, relamping, and reinstalling these fixtures came to $119 per fixture. It was cheaper and better to rip them down and throw them away, replacing them with a new fixture.

The common approach of removing lamps or shutting off some fixtures for energy conservation did not work. Better, but still unsatisfactory, was the use of low-loss ballasts and lower-wattage energy-saving lamps; unless there was too much light to begin with, the result was too little light, of poor quality, causing visual discomfort. This



FIXTURE AND BALLAST, shown in exploded view, is critical to operation of the system. Fixture includes a return-air louver and can provide supply air if desired. Manufacturer can provide fast-connecting snap-in tubing for through-wiring between fixtures for minimizing labor costs.

was the brute-force method—reduce wattage and hope enough light remained to see by. The Designetics team decided to try something different—to completely renovate the space, with artistic goals and good design, implemented with the best lighting technology. Quality of light and environment and aesthetic effect came first, then energy saving. The usual 100 raw footcandles of maintained lighting as a standard was abandoned.

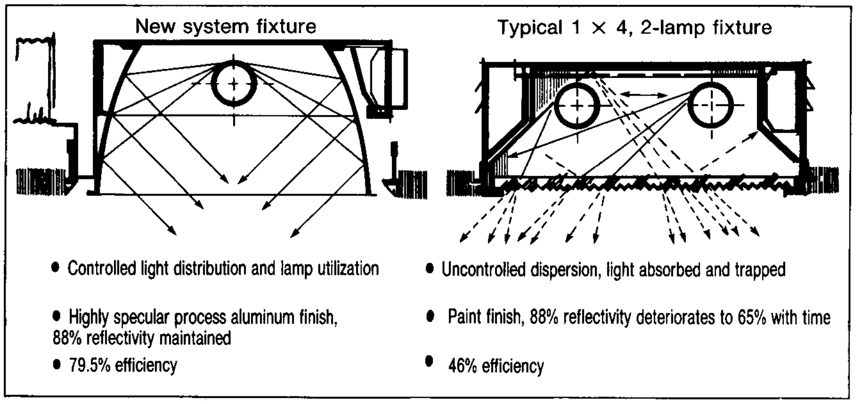
After many studies and experiments, the basic complete system was developed. A mockup of 2000 sq ft was installed on the 2nd floor of Citibank's 399 Park Avenue building, incorporating the modular ceiling, specific fixtures, lamps and ballasts, color schemes, furniture arrangement, and daylight and other control systems. The results were so convincing that a prototype installation of about 7000 sq ft was made on the 7th floor and carefully monitored for initial and operating costs. Analysis indicated a payback in less than two years from the electrical energy savings alone, completely repaying the cost of removing the old ceiling and lighting and installing the new hung ceiling and lighting and control system. This calculation did not include the additional savings in air conditioning as a result of the reduced heat (wattage), nor the savings in future rearrangements of the office space resulting from the modular and flexible ceiling and lighting system. The building was originally designed based on a lighting load of 3½ W/sq ft, typical for office buildings before the energy crunch, and the prototype lighting load was less than 1 W/sq ft. In new construction, the design would take into consideration the reduced heat output and lead to a smaller HVAC system. Also, the cost of later office rearrangements would drop dramatically.

The installation required internal coordination between the EMAC group and the interior design group. Previously, lighting was lighting and interior design (walls, window treatment, furniture) was interior design. This approach tied the two together, and cooperation between departments made it work. The resulting system was so successful that it is recommended by EMAC as a lighting guide standard for Citibank offices throughout the world. In addition, similar lighting programs have been produced by Designetics for McGraw-Hill and New Jersey Bell Telephone Co. facilities.

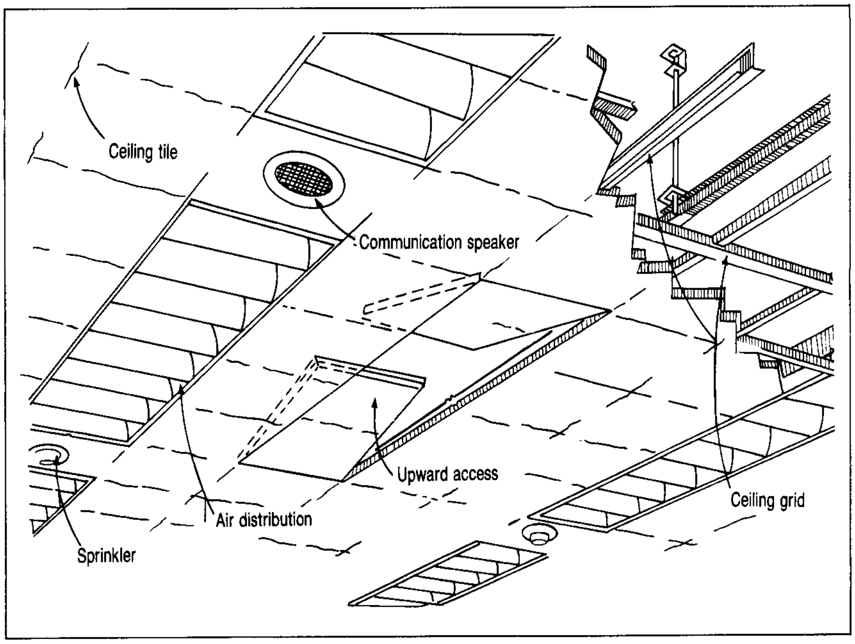
The fixture

It early became apparent that to obtain good office lighting with low energy consumption a parabolic reflector type of fixture, with "batwing" light output distribution, was necessary. Equivalent sphere illumination (ESI) is glare-free, visually effective light, measured in ESI footcandles, as opposed to "raw" footcandles. ESI lighting reduces veiling reflections (caused by light reflected at a bad angle from a work surface) that lower contrast and visual acuity and cause visual fatigue and discomfort. Parabolic-reflector fixtures have a light output pattern that effectively produces high ESI ratings when properly applied.

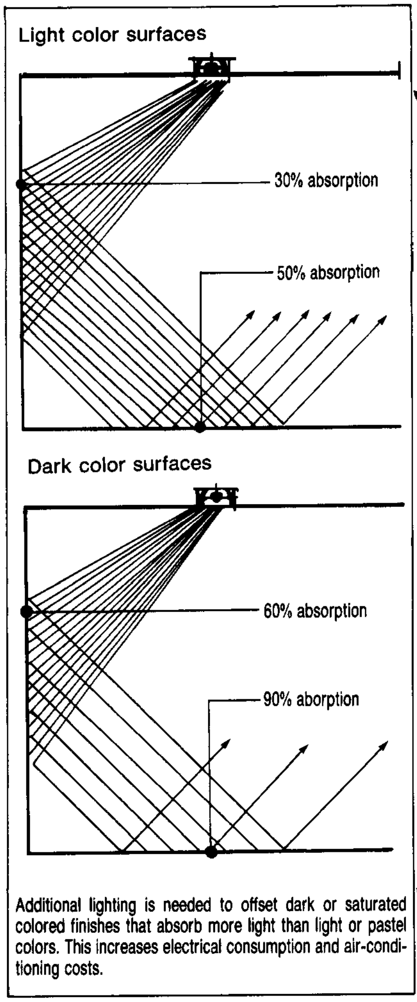
The selected fixture also had to have a high efficiency. Fixture efficiency is the measured total fixture output lumens as a percentage of the total lamp lumens produced. Typical 2 × 4 fixtures have an efficiency of 55 to 60% when new. However, the paint finish



PARABOLIC REFLECTOR FIXTURE is compared with standard fixture. Additional light control is provided in parabolic fixture by parabolic wedge-shaped louvers.



CEILING SYSTEM integrates hung ceiling, tiles, fixtures, and other services. The supports for the ceiling tile are hidden, resulting in an even ceiling appearance. For maintenance or access, the fixture can be removed without disturbing adjacent ceiling tiles.


Light color surfaces

Dark color surfaces

Additional lighting is needed to offset dark or saturated colored finishes that absorb more light than light or pastel colors. This increases electrical consumption and air-conditioning costs.

LIGHT ABSORPTION by dark-colored surfaces such as walls and carpeting can reduce lighting levels drastically. The use of light-colored surfaces and furniture is a significant factor in the low energy consumption for this lighting system.

ages, dropping in reflectivity from as high as 88% to about 65%. Dirt further reduces output, measured by the luminaire dirt depreciation (LDD) factor. At Citibank the original fixtures in the test areas measured an efficiency in place of about 46%. The fixture chosen for this system has an efficiency of 79.5% when first installed, and the unpainted, highly specular finish results in low LDD and high maintained efficiency. The open top and bottom, increasing air flow through the fixture, lessens the dirt deposit on the fixture and lamps, improving the LDD.

The highly specular, mirrorlike finish of the fixture is important. It results in less light diffusion and more precise light control than the semispecular, slightly matte finish usually standard in parabolic fixtures. This results in low fixture brightness (direct light) and less contrast with the ceiling surface. The ceiling itself appears less contrasty. If the finish were semispecular, all the fixtures would appear white and brighter. A ceiling with low overall brightness provides a visually comfortable and efficient environment.

The fixture measures 1 ft × 4 ft. In most cases, it is used with one lamp in a 5- × 5-ft module to cover 25 sq ft. However, the single lamp socket can be replaced directly by a two-lamp socket, and the same fixture can be used with two lamps to cover 50 sq ft or provide higher lighting levels where required. The two-lamp configuration results in little change to the desired light output pattern. The parabolic louvers and reflector provide refined light control to supply the batwing distribution necessary for good ESI lighting. Many ESI lighting installations require exact furniture placement. In this 5- × 5-ft modular arrangement, there is enough light overlap from fixture to fixture at normal office ceiling heights to make furniture placement noncritical, although the person at a workstation should preferably be facing along the lengthwise direction of the fixture. The 5 × 5 module lends itself to practical office partition rearrangement without changing the existing lighting and ceiling.

This fixture is listed by UL for through-wiring, permitting the lighting installation to be wired with a minimum of labor and materials. Provision for return air is inherent in the design, eliminating unsightly return-air louvers. It can, if desired, be used for supply air as well, using an available boot to connect to the air-supply system. The design operates the lamp at its optimum wall temperature to obtain the greatest lumen output. Although for a given space the initial cost of the fixtures is high compared to the common 2- × 4-ft, 4-lamp troffer on 8- × 8-ft centers, the overall effectiveness of the system in comfort, productivity, appearance, and especially reduced power consumption make it well worth the cost.

The lamp

The lighting system will perform as desired only when the fixture, lamp, and ballast are carefully matched. They must be coordinated for proper lamp wall temperature to produce maximum light output and efficiency. Originally, consideration was given to using some of the newer reduced-wattage lamps, in conjunction with low-loss, low-heat ballasts. These lamps are available in 34- and 28-W ratings, instead of the conventional 40 W. While these lamp-ballast combinations are highly efficient in terms of lumens per watt, their actual total light output is lower than that of conventional lamps and ballasts. They can be used in many retrofit applications because the original lighting was frequently overdesigned and the somewhat reduced light output is adequate. These efficient lamp-ballast systems are designed to operate best in the standard 2- × 4-ft, 4-lamp fixture. In the open parabolic fixture, air flow might cause the lamp wall temperature to be undesirably low, resulting in a considerable reduction in light output.

Color of the light was another important consideration, from both an aesthetic and visual-comfort point of view. Liametz feels that the standard cool-white (CW) fluorescent lamp, with a color temperature of 4000° K is too cool—not enough red light and too much blue. Conversely, he feels that the warm-white (WW) lamp, with a color temperature of 3000° K is too warm—too much red and not enough blue. He wanted a lamp with a color somewhere between CW and WW. This color output would also result in improved color rendition. Other factors desired in the lamp were efficiency, long life with low lamp lumen depreciation (LLD) with age, sufficient lumen output, and reasonable cost.

The final choice was a new triphosphor, high-efficiency lamp that meets all these criteria. The three-phosphor coating produces a color of 3500° K—just halfway between WW and CW lamps. This is the color desired aesthetically, and it provides excellent color rendition, making objects appear close to their true colors. The color rendering index (CRI) is 73, as opposed to a CRI of 52 for WW and 62 for CW lamps. In addition, the rated total light output is 3350 lumens for the selected lamp, compared with about 3150 lumens for both WW and CW lamps. The lamp has a high maintained lumen output over its life, helped by the fact that the cathodes are internally shielded.

The combination of high efficiency, high light output, long life with low LLD, excellent color, and reasonable cost (a moderate premium over standard CW or WW lamps) makes the chosen triphosphor lamp eminently suitable for this application.

The ballast

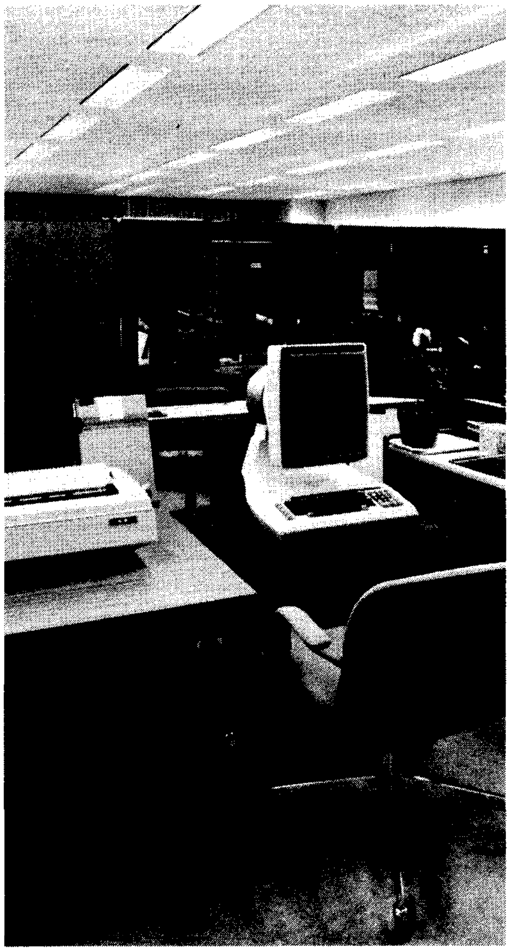
The heart of the entire lighting system is the controllable electronic solid-state high-frequency ballast. The many capabilities of this type of ballast make the lighting system responsive to the environment and the lighting requirements of each area, permitting the flexible control that results in the extremely low energy consumption of this system. The ballast was chosen first and the fixture and lamp selected to take maximum advantage of its characteristics.

The solid-state ballast has been near at hand for several years. Early models were too unreliable or too costly or developed other problems. One manufacturer recently went out of the business when a purchased electronic component of his ballasts developed frequent failures with age, causing extremely high warranty replacement costs. (He is suing the supplier of the component.) The solid-state ballast selected for this system has a good experience record, is listed by Underwriters Laboratories (UL), and meets Federal Communication Commission (FCC) requirements for radio-frequency and electromagnetic interference. No NEMA, ANSI or CBM standard yet exists for electronic ballasts.

There are fundamental differences between the two types of ballasts. The standard ballast uses a magnetic iron core and coil to produce and control the necessary voltage and current, and operates the lamp at 60 Hz. The solid-state ballast uses an electronic circuit to generate and control the required voltages, converting the 60-Hz input to a high-frequency output to operate the lamp at about 27,000 Hz. Solid-state ballasts have many advantages over conventional ballasts. Although they cost more, the cost differential is narrowing. As the price of electronic devices continues to come down and the performance and reliability continues to rise, today's conventional ballast will be obsolete sometime in the near future. This happened with circuit-breaker trip units; solid-state trips have replaced all dual-magnetic types and are today replacing most of the larger thermal-magnetic units. The era of the electronic ballast is rapidly approaching.

One of the most important advantages of the electronic ballast is that it can easily be controlled to dim fluorescent (and HID) lamps. Full-range dimming from 100% down to 10% of rated light output or less is simple and inexpensive with the electronic circuitry; it is difficult and costly with magnetic ballasts and does not work too well at low light levels. Dimming is critical to the operation of this lighting system.

The electronic ballast has low losses—only about 40% of the losses of the conventional ballast. This results in low heat, low operating temperature, and long life. Manufacturers expect average life to be at least as long as conventional ballasts, and possibly considerably longer. The manufacturer of the ballast used in the Citibank system has a standard two-year warranty, with warranty up to 10 years available for a small premium. The high operating frequency, above the human audible range, and the absence of iron cores and coils results in very low, almost inaudible noise output compared with the low but audible 120-Hz hum of conventional ballasts. Also, the high frequency eliminates any visible flicker, even when dimmed to 10% of full output. Standard ballasts produce 120-Hz flicker that is subliminally notice-



TYPICAL OFFICE AREA shows pleasant lighting effect. Note the low brightness of most ceiling fixtures. The actual appearance is of even less fixture brightness, which is exaggerated by the camera. Note the open office plan and the light colors used, as well as the absence of harsh shadows.

able and more noticeable when dimmed. When cathode-ray-tube (CRT) screens are viewed in ordinary fluorescent light, both the CRT display and the light flicker at power-line frequency, but rarely exactly in phase. This out-of-phase flickering, called the strobe effect, has been shown to produce eyestrain, discomfort, and fatigue. The high-frequency ballast eliminates this problem completely. Third-harmonic distortion in conventional ballasts is about 40% to 45%. The solid-state ballast used in this system has considerably less than half that—about 15% third-harmonic distortion.

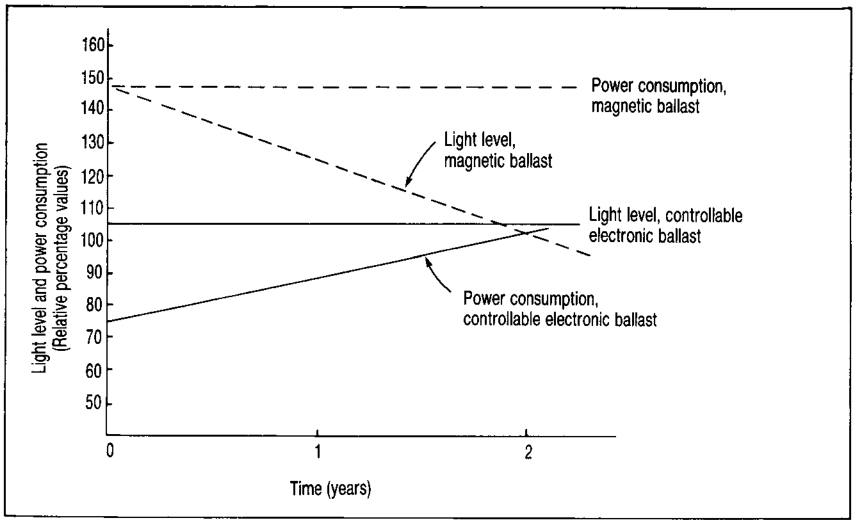
The electronic ballast is designed to operate the lamps at optimum bulb temperature in a cool fixture, such as the parabolic open fixture used in the Citibank system. In fact, the ballast initially drives the lamp to 106% of rated lumen output, as opposed to 92 to 98% for a conventional ballast, as a result of high frequency and optimum bulb temperature. That is, the ballast factor is 106%, compared with magnetic ballast factors of 92% to 98%. As the lamp is dimmed, the lamp heaters are driven harder to maintain proper filament temperature and to improve lamp life.

The electronic ballast has a high power factor, greater than 90%, as do the better magnetic ballasts. It produces a far more steady light output for input voltage variations. For voltages 10% below normal, light output drops only 0.3%, as compared with a 4.5% drop using a conventional ballast. For voltages 10% above normal, light output increases only 0.2%, as compared with a 3.1% increase for a conventional ballast. The temperature regulation is also excellent. When used for dimming, the electronic ballast maintains a high efficiency, measured in lumens per watt, down to about 50% of full output of the lamp. Below 50%, the efficiency drops, but the actual wattage is also low so the lower efficiency means little.

The control system

The electronic circuitry permits lamp dimming from the ballast itself (each ballast has a built-in control potentiometer), or from a remote controller such as a lighting programmer or photocell. This is the capability that is used to produce a lighting system of great effectiveness and low energy consumption. If the ballast is the heart of the system, the controls are the brains.

Fig. 1. Effect of ballast on light output and power consumption



The lighting levels are set by three different control systems—photocells, programmable controllers, and building-management system controllers.

The task lighting levels that have been found entirely adequate and comfortable are 50 footcandles (fc) for office areas and 14 fc for lobbies, aisles, corridors, storage areas, and reception areas. (A 20-fc level was initially used in these areas but was found to be unnecessarily high). For maintenance and cleaning, 10 fc was found satisfactory (20 fc was also initially used here, and later reduced). While these levels may seem low, the high ESI rating and evenness of illumination, with little glare and veiling reflection, have resulted in great visual comfort and employee satisfaction.

The ability to adjust individual fixtures, either at the ballast or through the programmable controllers, is especially useful where a word processor or computer terminal has a CRT display. Because of the parabolic fixture design and cut-off angle, the reflection of the ceiling in the CRT will not usually show direct brightness or glare from more than one fixture. This fixture can be dimmed to reduce the glare. The Eastman Kodak Company found that when they eliminated CRT glare, productivity went up 12% at the CRT workstations.

Photocells are used to maintain a given light level as required by the task. They can control a single ballast or a group of ballasts, depending on the size of the zone. They will compensate for daylight by dimming to maintain constant total light, reducing power consumption and automatically correcting for variation with season, weather, and time of day. Photocells also compensate for fixture and lamp lumen depreciation (LDD and LLD) by increasing light output as the system ages, to keep task lighting constant. Initial power consumption is low, and increases with time. Conventional systems have constant higher power consumption, with excessive light in the beginning that decreases with time to the desired level or lower (see Fig. 1). The photocells operate through the programmable controller.

Programmable controllers are used, one on each floor, to provide overall control. Each controller has a microprocessor base with software control and can be set to control the lighting on its floor for a full year with, of course, manual override for any zone at any time. These controllers, with their power supplies and terminal cabinets, make up the light monitoring and control system (LMCS). Many variations are possible, and the units can be customized as desired. Input can be from a local or remote keyboard; a CRT display can also be local or remote. A modem with a standard RS-232 interface can be used for external input, monitoring, or reprogramming by telephone or other communication. Each controller has 32 photocell inputs, 32 ballast control channels, 16 digital inputs, 16 digital output channels, and 24 ON-OFF type input/output points. Each ballast control channel is capable of dimming smoothly up to 50 ballasts.

The controller can take data, log it, and transmit it as desired, on up to 16 internal or external parameters. Each zone can be operated individually in the automatic or manual mode. The software will permit any photocell to control any zone or zones, and the rate of dimming can be varied to avoid sudden changes in lighting intensity. A built-in clock with battery backup can be used to time events in complex sequences through the microprocessor. Minimum and maximum light levels in each zone can be set. Internal calibration means, self-checking, and status monitoring of each zone are provided, along with many other standard or optional features.

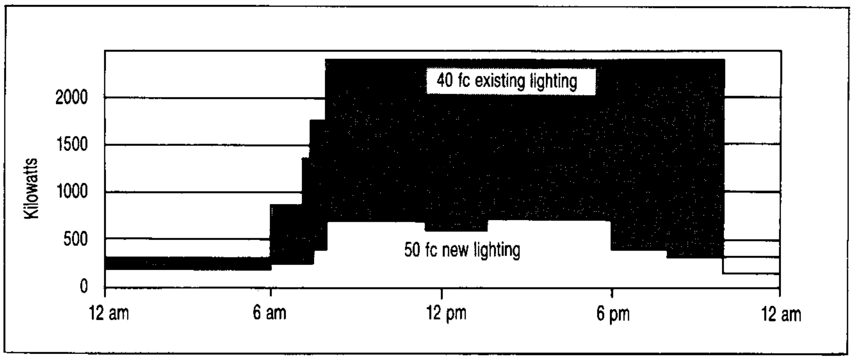
Where a building management system or other large, computerized system is installed, it can be used to signal the individual units of the LMCS. This is especially effective if demand control is used for peak shaving to reduce the electric utility demand charges. It has been found that a demand controller can reduce the light output up to 20% for brief periods with the variation being almost imperceptible if done slowly, rather than suddenly.

At Citibank, control wiring from the photocell sensors to the LMCS units and back to the dimmed ballasts used twisted-pair wiring. This shielded wire, insulated with low-smoke, low-flame material and so classified by UL, often (incorrectly) called "plenum" wiring, is permitted by the NEC and NY City code to be run in hung ceilings without conduit or other raceway. Each pair of wires could control up to 50 ballasts. A later installation, being done for McGraw-Hill in Colorado Springs, CO, takes advantage of a recent improvement—carrier-current power-line communications (PLC). This eliminates the need for control wiring, sending the control signals in digitally coded form over the power wiring. The manufacturer is developing this equipment gradually, integrating it with the LMCS controllers. One PLC module transmits photocell data to the LMCS; another PLC module controls the ballasts. Initially, there will be 32 ballast-control channels, with future capability of 1028 channels (addresses controlled) on one frequency. It will take no more than ½ sec to address any channel. Up to 11 frequencies are available. As initially installed, the PLC units are separate from the ballasts. Later, it is expected that the circuitry will be built right into the ballast unit.

Overall, this control system provides a flexible, easily adjusted lighting scheme that can be varied for the most-comfortable and economical lighting and changed as tasks change, such as for cleaning and maintenance, and as office space is altered. The control system can be designed to meet the needs of any user or installation.

The environment

For maximum effectiveness, visual comfort, and aesthetic satisfaction, this entire system must be integrated with the environment. The use of daylight means that windows should be large but of heat-resisting, solar-screen glass. The office spaces should be an open plan, taking advantage of the daylight contribution up to 30 ft from windows. Daylight varies, of course, with height, orientation, surrounding buildings, and other influences but, properly utilized, can be significant in reducing energy consumption. Walls, carpeting, and ceiling colors should be light, as should furniture finishes for minimum light absorption. Dark colors should be used for accent only, along with plants and works of art.



The results

The Citibank installation more than met expectations. The primary objective, lower electrical energy costs, was exceeded. The design goal was 1 W per sq ft; actual measured consumption in the prototype area was less than 0.7 W per sq ft. If the entire Citibank building at 399 Park Ave were converted to this system, the actual measured lighting demand load of 2400 kW would drop to below 700 kW. In the initial 2000-sq-ft test area, which is the building office, the space has been rearranged more than 10 times, including converting some storage space to a drafting area. No fixtures had to be moved and no ceiling work done for these changes. All that was necessary was resetting of the light levels. Similar results were obtained in the 7000-sq-ft prototype area, in the personnel department. An employee store was moved to a different part of the area, the original space became office space, and other changes were made—all without ceiling or fixture work, merely reprogramming controls. The costs of space rearrangements dropped drastically.

Actual readings in these areas were 40 fc with the original lighting and 50 fc with the new system. The areas were more attractive, there was less CRT reflected glare and strobe effect, and less heat was developed, reducing the air-conditioning load. This improved environment meant better comfort and productivity, with a 70% reduction in energy consumption. Additional benefits are reduced maintenance costs for lamp and ballast replacement and lower construction costs for space renovation.

In the McGraw-Hill building in Colorado Springs, which will use the PLC ballasts, the air-conditioning load was reduced by between 10 and 20 tons based on the reduced heat from the lighting. The connected lighting load is only 1.2 W per sq ft, and the anticipated actual operating load is expected to be less than 1 W/sq ft—probably close to the Citibank 0.7 W/sq ft.

The holistic approach taken by the Designetics team has set a standard that optimizes both low cost and beauty, with neither sacrificed for the sake of the other. **EC&M**

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The Integration of Microcomputers and Controllable Output Ballasts—A New Dimension in Lighting Control

WILLIAM R. ALLING, ASSOCIATE MEMBER, IEEE

Abstract—**With the introduction of controllable output solid-state ballasts for lighting, it was desirable to utilize small computers to take full advantage of these devices in the built environment. Lighting use accounts for over 50 percent of the energy consumption in most high rise office buildings and therefore represents a significant opportunity for energy and power reduction through the application of efficient hardware and effective control strategies. In one such application in a New York City high rise office building, energy demand for lighting dropped from 2.3 W/ft^2 to an average 0.7 W/ft^2, while the lighting levels increased. Peak power demand was reduced to 1.1 W utilizing the hardware and strategies discussed. The increased component costs for these systems pay for themselves in reduced energy costs in well under three years and in most cases under two years. Additionally, these systems provide a better, more human-oriented working environment which is thought to be more productive.**

I. INTRODUCTION

THE ENERGY BUDGET for lighting a typical high rise office building can exceed 50 percent of the total electrical demand and costs. This is a significant opportunity to use microcomputers and controllable output ballasts as a system to reduce the electrical energy and power consumption in the built environment. The system approach delivers only the amount of light required for the task when and where it is needed and uses the minimum amount of energy necessary to achieve those lighting levels.

In the past, microcomputers have been used to switch lighting levels with good energy saving results. However, with the advent of solid-state controllable output ballasts controlled by a microcomputer, a new dimension is added which achieves an extraordinary level of performance by combining the inherent advantages of both. The electrical energy savings gained by adopting the systems approach has been well reported [1], [2]. There are four control strategies involved, namely, scheduling, tuning, lumen depreciation, and daylighting, which can have the following energy savings potential: 26, 12, 14, and 15 percent, respectively. A fifth strategy called load shedding is also discussed. This is in addition to the basic component [3] savings due to the use of more efficient basic elements in the underlying system, i.e., solid-state ballasts, efficient lamps, fixtures, etc.

The systems approach utilizes all of the control strategies, to whatever extent each is available to maximize the energy and power savings without reducing light levels. Using this approach, we find that the average energy reduction is 71 percent when compared against the installed base, 65 percent when compared with current regulatory requirements, and 55 percent compared with the best current design practices.

II. THE SYSTEM

The lighting control system shown in Fig. 1 consists of lighting fixtures which contain the controllable output ballasts; lamps, and control interface equipment; photosensors located within the task areas; low-voltage on–off and override switches placed appropriately within the space to be controlled; relay contactor interface equipment for turning off and on lighting circuit branch power; a microcomputer; a CRT display; and a modem interface. The system described can control 32 ballast zones with up to 50 ballasts per zone in a hard wire configuration and is expandable in 16 or 32 zone increments. The system also contains 32 photosensor channels (also expandable) to monitor light levels throughout the zones. Photosensor information is used by the microcomputer to control zone lighting levels in accordance with operator input instructions. Light levels in the zone can be controlled from 100 percent (full on) to 0 percent (full off) in 256 increments.

The microcomputer is self-contained. No operator intervention is required after the initial setup. It will automatically maintain the operator instructed light levels, turn-on/turn-off times, and various other functions described later in this paper. System parameters are saved in battery backed up memory so that after a power failure the microcomputer will come back on line and continue with the lighting control without further operator input. The system also contains an eight-day battery backed up clock.

The CRT terminal is used to "talk" to the microcomputer. This can be accomplished either locally or through a modem interface. The terminal is a general-purpose CRT and is used during initial installation and afterward to change any of the permitted operating parameters.

Switch input channels and contactor control output channels are expandable in 16 channel increments and are digital in nature. Switch inputs convey information to the microcomputer such as a demand for more light in a zone or to instruct the system to shut down certain branch lighting power circuits. Contactor control outputs are also used to trip subbranch power circuits in response to switch inputs appropriately delimited or in response to time-clock intelligence or both.

The system gathers light sensor information from the photosensors and then issues control commands to the appropriate ballast zones in accordance with preconceived and programmed control strategies. In the daylight zones, the

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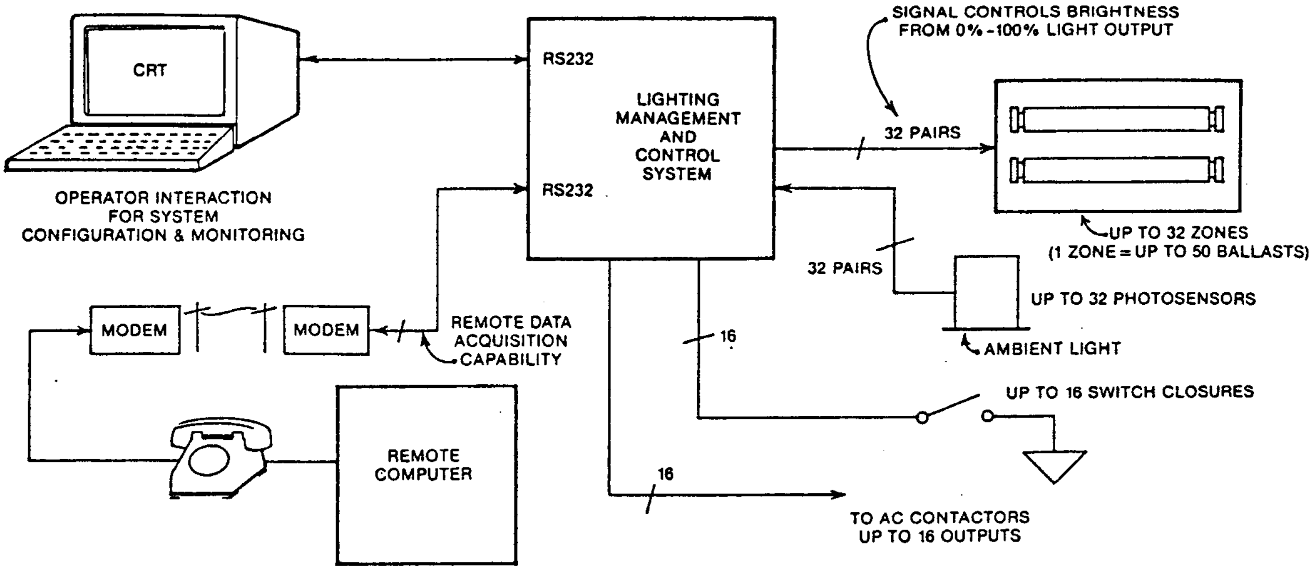


Fig. 1. Lighting management and control system.

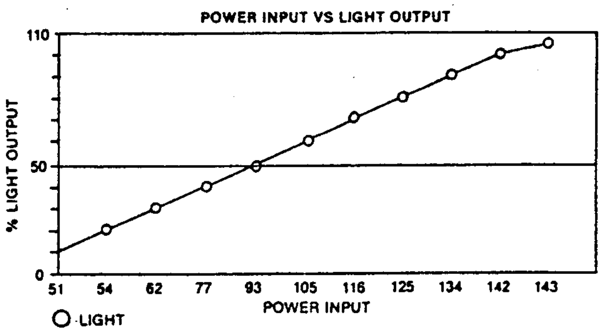


Fig. 2. Ballast dimming curve.

system strives to maintain the user-defined light level by raising or lowering fixture electric light output in response to varying daylight contributions. In the interior areas some zones might be corridor or low task zones which require different light levels than the high task areas. The lighting levels can be raised or lowered as a function of the time of day, week, or year. During lunch and cleaning periods, the lighting requirements are different than for the occupied periods, and the system will respond automatically to these changing requirements.

At the heart of the system is the controllable output ballast. This type of ballast is also referred to as a dimming ballast.

III. THE CONTROLLABLE OUTPUT BALLAST

The function of all balasts is to start and operate reliably the lamps they are intended to operate. The controllable output ballast must also operate the lamps at various light output levels.

One should be aware that the amount of light out of a lamp is directly proportional to the amount of power flowing through that lamp. If a straight line relationship between light and power is assumed, then at 50-percent light output only 50 percent of the power is consumed. If the designed light level in a zone is 50 fc and the particular lighting design has an initial 100-fc level, then it is appropriate to dim out the excess light and save the difference in energy flow.

The relationship between ballast input watts and light output is usually not linear. This is due to the fact that some residual power is required to operate the ballast, ballast losses, and the requirement to increase lamp filament power in rapid-start lamps as lamp arc watts are reduced to preserve lamp life. Fig. 2 shows the relationship between ballast input watts and lamp light output for a three-lamp solid-state high-frequency controllable output ballast using standard F40T12 rapid-start fluorescent lamps.

While a discussion of appropriate ballast parameters is beyond the scope of this paper, the reader may wish to check [3]-[5] for further information. It is sufficient to mention here that there are literally tens of ways to design ballasts and not all of them will give the desired results.

Communications between the microcomputer and the ballast can take many forms. In a hard-wired system each ballast zone has the same control wire or wires connected to all ballasts within the zone and one home run from the ballast zone to the microcomputer. A zone is defined as a logical grouping of ballasts/fixtures that is controlled in the same way.

The communications format can be a low-voltage pulse-modulated signal, FSK, or any other format that can convey appropriate dimming level information to the ballast(s). If low-voltage signals are utilized, some method usually is provided to isolate the control signal from the high-voltage fixture cavity. Note that in some areas of the country local codes require that control wiring be placed in conduit even if isolation is provided.

A second approach is to use power line communications (PLC) to convey level information to the ballast. With this method a small signal in the 100–150 kHz range is placed on the main ac lighting branch circuits. The carrier signal containing the appropriate level information is decoded by each ballast directly from the mains. This has the advantage of eliminating the control wiring, thereby reducing the economic penalty associated therewith. If two-way power line communication is utilized, photocell, switch, and occupancy detection

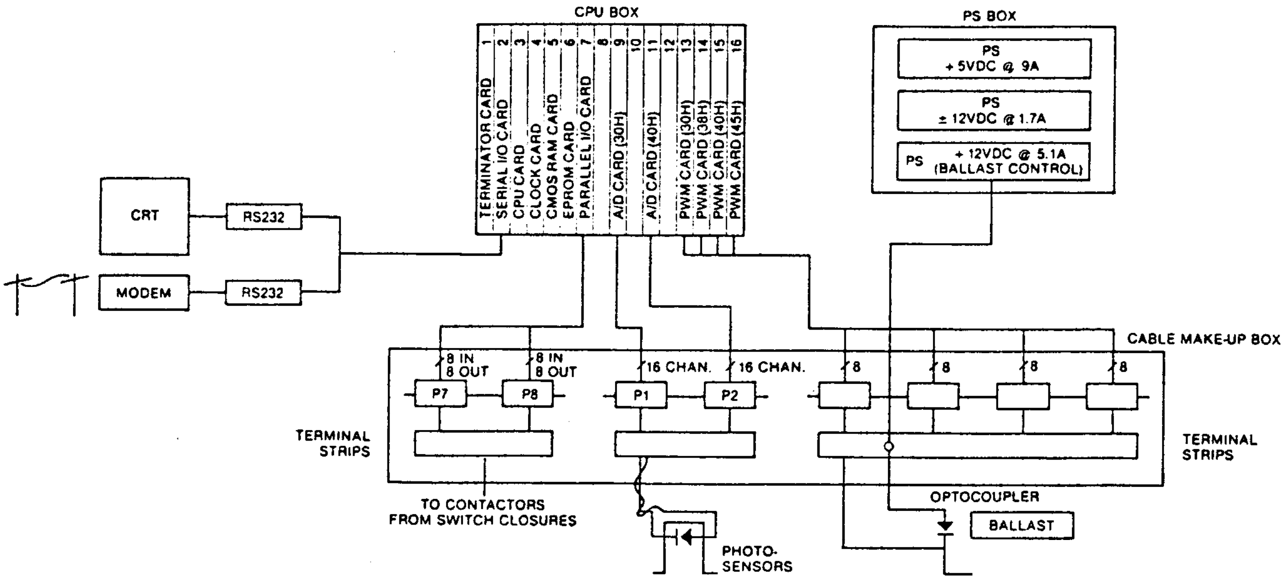


Fig. 3. System block diagram.

can be conveyed over the power lines, further reducing overall installed cost. With the PLC approach the number of ballasts per zone can be increased significantly.

IV. THE CONTROL SYSTEM

The microcomputer consists of a small housing for the computer; a power supply enclosure, and a cable makeup box. All field wiring is routed into and out of the cable makeup box.

Fig. 3 is a block diagram of the microcomputer. The hardware uses an STD bus standard, Z80 based microprocessor, 16K of battery backed up RAM and 32K of EPROM for program instruction storage. It has two serial I/O ports and a battery backed up time of day clock. Special circuitry is used to interface with the photosensors and the ballast. In the example shown, a pulsewidth modulated technique is used.

The photosensors are 2 × 2-cm silicon solar cells connected directly to the micocomputer input amplifier circuitry. The cells have a corrected response that approximates the human eye. The type of photocell selected is not particularly critical but must have a range of operation suitable for the application. Photocells are usually mounted in the ceiling looking down at the task area with an appropriate viewing zone. The photosensor selected must have good repeatability characteristics. Calibration of the sensor is accomplished in the microcomputer.

Ballast control signals consists of a low-voltage (under 36 V) pulse modulated signal with a 5-kHz mark space ratio. The system is configured so that, when no pulse is present, the ballasts interpret this to mean that the lumen output of the lamps should be at maximum. As the pulsewidth is widened the ballast dims lamp output in direct ratio to the pulsewidth. That is, 70-percent pulsewidth equals 70 percent of maximum light output, 22.5-percent pulsewidth equals 22.5-percent light output, and so on. Control is accomplished on a percentage of maximum basis.

An important requirement is that the control system be fail-safe. The absence of a control signal should be interpreted by the ballast to mean 100-percent light output.

Each controllable output ballast has a manual dimming potentiometer. This adjustment is used to set the maximum absolute light output of the lamps and is useful to compensate for various irregularities encountered in every installation. Having a local adjustment within a zone of ballasts allows the lighting designer considerable flexibility to compensate for individual worker needs as well as to create special lighting effects. In noncontrolled areas such as bathrooms and stairwells this adjustment is used to set operating light levels and is consistent with the overall philosophy of a controlled system.

The system real-time clock is an eight-day battery backed up clock. Four programmable day types are provided to control master scheduling. Day type 1 is used for usual work days; day type 2 for Saturdays; day type 3 for Sundays and holidays; and the fourth type is for special days. A perpetual date clock can also be provided.

A standards RS-232 modem interface is provided. With the modem the system can be reprogrammed from any telephone. This is extremely important in terms of checking system status, remote trouble shooting, and data analysis using larger capacity computers.

Switch inputs and contactor output signals are on–off type low logic voltage signals. Switches are used as a manual override for automatic programmed operation by the microcomputer. Contactor outputs are low-voltage trigger pulses that latch or unlatch the branch circuit lighting contactors.

V. THE CONTROL STRATEGY

Five control strategies are implemented by the microcomputer. They are tuning, scheduling, lumen depreciation, daylighting, and load shaving. It is important to note that solid-state high-frequency controllable output ballasts have an inherent 25 percent + advantage when it comes to energy savings [3]. Using these control strategies increases the energy

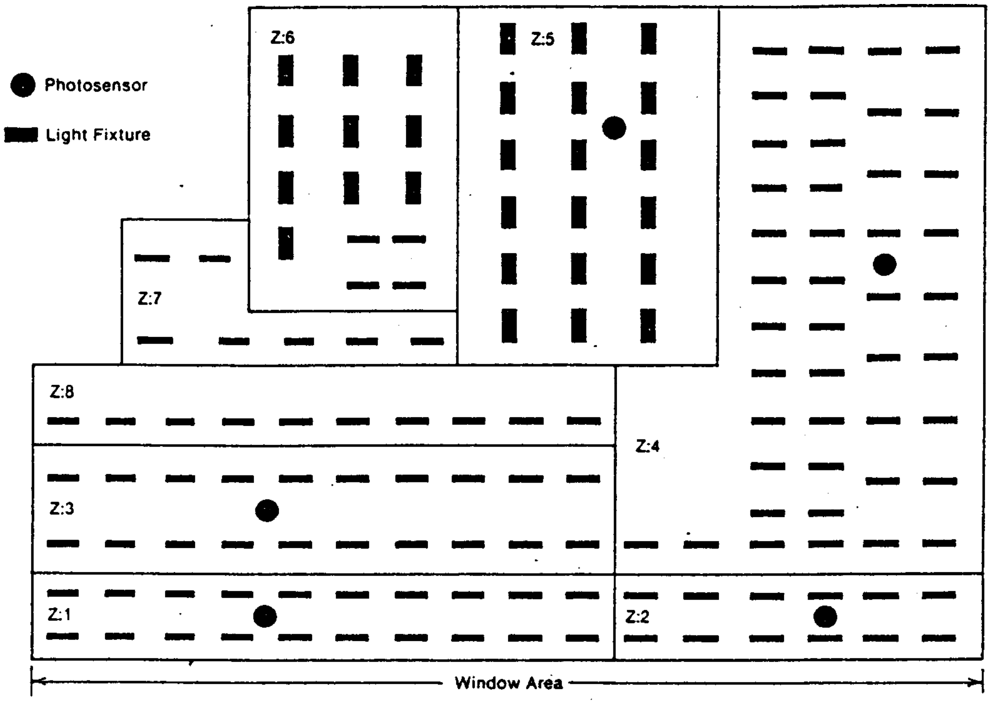


Fig. 4. Zone lighting layout. Typical 1-ft by 4-ft fixture layout usually on 5-ft centers. Most fixtures are single-lamp slave-master combinations with some two-lamp fixtures interspersed as appropriate.

saved by an average 30–46 percent, depending on the installation being compared with.

Tuning

Simply stated, tuning is the ability to dim out excess lighting levels when they are not needed. The amount of energy used to generate light levels above those that are needed is saved. Fig. 4 and Table I show one example of current lighting design practice. The fixtures are 1 ft by 4 ft on 5-ft centers yielding 25 ft^2 per fixture. A high-lumen F40T12RS lamp will produce about 3600 lumens with a ballast of the type described. The actual footcandles measured were between 105 and 110 without furniture and with standard reflectances. With furniture, this figure dropped to 85 fc average. The specified footcandle level for this space is 50 fc for occupied normal task work.

The amount of energy required to deliver 50 fc can be easily calculated. Assuming that the relationship between light and power is linear, 50/85 or 59 percent of the maximum energy will be required to attain 50 fc. This is a simple method and ignores the effects of lumen depreciation, residual ballast losses, and other factors which will be discussed later. Tuning is therefore correlating the amount of light required and energy required to the specific task requirements.

Tuning is also combined with scheduling. At 6:00 P.M. when most of the occupants of a building have left for the day the task requirement may be only 20 fc for the maintenance crew. From the simple calculation given earlier, we know that only 24 percent of the maximum ballast input energy need be used to generate adequate lighting for the "task" of cleaning and then only during the hours the cleaning crew is at work.

TABLE I
ZONE FUNCTIONS WITH TARGET LIGHT LEVELS (L^{tar})

ZONE NUMBER	SQUARE FOOTAGE	TYPE	L^{tar} HIGH/LOW
1	660	Daylight	50/20
2	420	Daylight	50/20
3	924	Interior	60/20
4	2,124	Interior	50/20
5	1,200	Interior	40/20
6	840	Interior	35/20
7	420	Interior	35/20
8	528	Corridor	20/10

A better and more accurate method for calculating savings which correlates specific ballast input wattage reduction due to tuning is as follows:

$$\frac{\left(\dfrac{P^{max}-P^{min}}{L^{max}-L^{min}}\right)\times(L^{tar}-L^{min})+P^{min}}{P^{max}}=\mathrm{BP}$$

where

L^{tar} designed lighting level,
L^{max} maximum lamp light output,
L^{min} minimum lamp light output,
P^{max} maximum ballast power in watts,
P^{min} minimum ballast power in watts,
BP percentage of maximum ballast input wattage,

and the following assumptions are made:

ballast input watts $= 94$
$L^{tar}=50$ fc
$L^{max}=85$ fc
$P^{max}=94$ W
$L^{min}=8.5$ fc
$P^{min}=18$ W

$$\frac{\dfrac{94-18}{85-8.5}\times(50-8.5)+18}{94}=\mathrm{BP}$$

$$\frac{(0.99)(41.5)+18}{94}=63.0 \text{ percent.}$$

With this method residual ballast power, ballast losses, and increased filament power with dimming are taken into consideration. The method is precise enough for most needs. Note that 59 percent of the maximum ballast input watts were required in the previous example when the light level was dimmed from 85 to 50 fc. When all factors except lumen depreciation are taken into consideration, this becomes 63.0 percent under this more rigorous approach.

Scheduling

Scheduling means having the microcomputer adjust the lighting levels in response to varying tasks as a function of time of day. It is "tuning" the lighting to various tasks which occur at different times of day. A typical building schedule might be as shown in Table II.

TABLE II
TYPICAL BUILDING SCHEDULE

TIME OF DAY	FUNCTION	LIGHTING REQUIRED HIGH TASK	LIGHTING REQUIRED LOW TASK
0700-1200	OCCUPIED	50 FC	20 FC
1200-1300	LUNCH	25 FC	20 FC
1300-1800	OCCUPIED	50 FC	20 FC
1800-2100	CLEANING	20 FC	15 FC
2100-2400	SECURITY	10 FC	5 FC
2400-0700	NO TASK	OFF	OFF

The microcomputer automatically takes all of the building task requirements into account and maintains the light level(s) specified at the minimum energy level.

Lumen Depreciation

Lumen depreciation refers to the rate at which a gas discharge lamp light output degrades with use. The rate at which a lamp degrades is a function of ballast characteristics, the particular lamp type, the particular process of manufacturing the lamp, and other parameters. A standard fluorescent F40T12 lamp will produce anywhere from ten percent less light at the end of life to up to 40 percent less light.

Two things are important when considering lumen depreciation. The first is that the lower the lamp energy level, the lower the lumen depreciation rate. The second is that, with a controllable output ballast system, it is possible to compensate for lumen depreciation and save some electrical energy in the process.

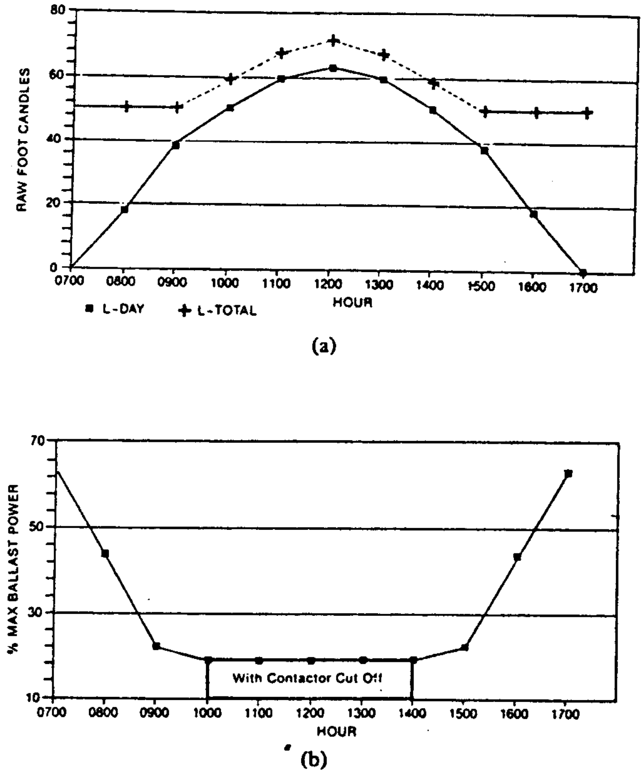
The harder a lamp is driven, the greater the lumen depreciation rate. It therefore follows that if a lamp is not driven hard over most of its life then the rate at which the light output degrades will be less. With tuning and scheduling we find that the lamps in our typical installation are operated at average power levels half of what they would experience with standard commercial ballasts.

With a controllable output ballast and control system, the effects of lumen depreciation are eliminated by increasing the power to the lamps as they age. On average, 1.5-2.5 percent power is added back into the system for each 3000 h of operation with lightly loaded lamps and slightly more with heavily loaded lamps [3]. The overall savings in energy using this technique is at least one half the lumen depreciation rate.

Daylighting

In zones where natural light is available, the system automatically takes advantage of this resource and incorporates it into the space. Considerable energy and cost savings are possible particularly in terms of peak loading. The electric lighting in daylight zones is used as fill-in lighting to provide even illumination across the space.

Care must be exercised when harvesting daylight in that too much daylight can be counterproductive in terms of visual comfort and productivity. The amount of usable daylight is dependent on the window and skylight types and sizes, window and skylight treatments (drapes, blinds, glazing, etc.), building design, interior design, and furnishings.



(a)

(b)

Fig. 5. Daylighting calculations. (a) Daylight illumination [6] 10 ft from window, north zone, average January day, New York City. (b) Ballast power level required to maintain 50 fc in (a).

The procedure for calculating daylight contribution to a zone and the effect on ballast input watts, as shown in Fig. 5 and Table III is as follows.

1) Determine the daylight contribution in each zone for each hour of the day (L^{day}).
2) Determine the amount of electric lighting L^{elec} required to maintain designed lighting level L^{tar}, i.e., $L^{tar} - L^{day} = L^{elec}$).
3) Using the example given under the discussion of tuning, calculate BP, but use L^{elec} in place of L^{tar}.
4) For practical purposes, find the average BP for the entire day. In the example shown this is 32.6 percent without contactor cutoff and 23.5 percent with.

TABLE III
EFFECT ON BALLAST POWER COMBINED DAYLIGHT AND ELECTRIC LIGHT

TIME	L^{tar}	L^{day}	L^{elec}	$BP^{\%}$
0700	50	0	50	63.0
0800	50	18	32	44.0
0900	50	39	11	22.0
1000	50	50	9	20.0*
1100	50	60	9	20.0*
1200	50	63	9	20.0*
1300	50	60	9	20.0*
1400	50	51	9	20.0*
1500	50	38	12	23.0
1600	50	18	32	44.0
1700	50	0	50	63.0

*With contactor cut off = 0%
For symbol definition see Fig. 5. L^{day} = Daylight contribution.

5) The earlier example assumes that 100 percent of the daylight can be utilized and that there are no lighting design issues which would prohibit taking advantage of all the natural lighting available.

Load Shaving

Many utility districts calculate electrical energy charges in part on the highest kW demand. In some cases this demand charge can be a very significant factor in overall energy costs.

The microcomputer has the built in capability to shed some of the power used for lighting to minimize peak demand charges. This can be accomplished in one of two ways.

The first and the simplest way is to reduce lighting circuit loads by a predetermined amount in response to the building management system (BMS) or a peak demand meter. The lighting levels are restored when the peak demand period has passed. This can be accomplished with a relay closure logic input to the system.

The second way involves interface with another computer such as the BMS via the RS-232 interface. Under this approach the lighting levels and power are reduced at a subliminal rate by the external intelligence in response to the present and anticipated overall building load requirements. The BMS or other external intelligence can have total control to raise and lower lighting and power levels as the need dictates within the constraints programmed into the lighting control system.

VI. THE PROGRAM

The set of instructions which tell the microcomputer how to operate is called the program. Success or failure in the field depends as much on the program as it does on the hardware.

To discuss the method or technical aspects of writing computer programs is beyond the scope of this paper. It is sufficient to mention that there are many ways to accomplish the desired end results using a number of equally good but different programming languages.

One of the most important requirements is that the microcomputer be user friendly. It must accept commands and give statements in plain English that are familiar to those who must interface with it.

Five areas of commands explain the operation of the microprocessor program. These are

- lighting commands,
- event (alarm) commands,
- formula commands,
- time/date commands,
- miscellaneous commands.

The lighting control system is designed to control totally the lighting in a building, In summary, it will

- measure zone light levels using photosensors, compare the actual light levels against the designed levels, and adjust the zone lighting levels accordingly;
- modify the desired light levels as a function of time of day or date;
- allow building occupants to raise or lower zone light levels via switches located within the zones.

Lighting Commands

These are user-entered commands which change lighting levels and/or display existing system parameters. The commands used are in boldface.

M—Mode Set: Three options exist under the mode command; manual, automatic, and test. These commands are settable by zone.

In the manual mode the fixture light output is set to a fixed level without photosensor feedback. It is a "set it and forget" type adjustment. The exception is the UF command which uses photosensor calibration information to set light levels in footcandles. This is a convenience to the operator and once set will not change. The two manual commands are UP and UF.

UP: Sets zone light output as a percentage of maximum light available (0–100 percent).

UF: Sets zone light levels in foot candles.

In the automatic mode fixture light output is set to a particular footcandle level. Zone photosensor information is used to maintain that level in a closed-loop arrangement. This is the dominant mode and incorporates all of the control strategies previously discussed to whatever extent each is available. The commands are as follows.

L—Level Change in Foot Candles: Levels are settable by zone in the 0–250-fc range within the constraints of the light available in the zone.

LI—Level Increment: This command is usually input by zone switches and is used to modify zone light levels temporarily for a programmed period of time. The most common use is by after-hours workers to "bump" up zone light levels, thereby overriding the schedule program.

II—Increment Adder: This command affects only zones in the automatic mode and is used when it is desirable to brighten or dim the zone light levels immediately. In normal automatic operation the time it takes for the system to go from one light level to another is determined by the SK (skip count) setting discussed under Miscellaneous Commands.

ZS—Zone Status: This command will display the status of one zone with 1-s updates to the display. A typical display would be

status for zone 1 (mode = automatic):

SP (fc)	SP adder	SP (sensor %)
50	5	68

sensor (%)	output (%)	error (sensor %)
70	79	2

This display means that zone 1 is in automatic operation and is set for 50 fc with an adder of 5 fc, so that the microcomputer is controlling the zone light level to 55 fc presently. A sensor reading of 68 percent represents 55 fc; the current sensor(s) reading is 70; the ballasts within this zone are currently driving the lamps to 79 percent of their maximum output; and the microcomputer is driving the ballast(s) output down until the first sensor reads 68 percent (the error signal tells the direction and amount the ballasts must move to achieve the desired results). If zone 1 were in manual the following display would be seen on the CRT terminal:

status for zone 1 (mode = manual):

output (fc)	output (%)	(sensor %)
50	79	83

Event (Alarm) Commands

These are a block of commands for use by the system and work in conjunction with the real-time clock and external switch inputs. An event message is the sequence of events that occurs when a time or date activated event occurs or in response to a switch input. A few of many possible event commands follow to give the reader some idea as to the flexibility of the system.

TS—Time Show: Display current time.

AA—Add Event: This command is used to add an event to the system. The event can be a function of time or a switch input. Further, it can be continuous, one shot, or if it is a switch the switch can be time range enabled. The event is entered by day type and can also be date delimited.

AD—Delete Event: Delete an existing event/alarm.

AS—Event Show: This command is used for displaying individual events.

AL—Event List: This is used to display all event/alarms in the system.

AR—Event Replace: This is used to replace one event with another.

AT—Event Test: This is used to force an immediate event and is very hand for load shedding purposes.

Formula Commands

Formula commands are used to modify input and output data to aid in developing greater accuracy of control. Simple formulas are addition, subtraction, multiplication, and division.

The most common use is with photosensor input data. All photosensor inputs are software patchable by the user. Any photosensor can be used as an input to any ballast control channel. Also multiple photosensors can be used with any ballast control channel. Formulas are used to assign one or more photosensors to a ballast control channel and to perform arithmetic functions. The following examples give a description of the function desired and the normal algebraic formula.

FUNCTION DESIRED		FORMULA
Average photosensor data for zones 1 and 2		
S1	photosensor 1	
S2	photosensor 2	
1:	ballast control channel 1	1:(S1 + S2)/2
Use photosensor 6 to control ballast channel 5		5: S6
Lessen zone 5 light output by 10 units		5: S6 − 10

The formula commands are as follows.

FR—Formula Replace: This command is used to change formula data.

FS—Formula Show: Display a particular formula.

FL—Formula List: List all formulas in system.

Time/Date Commands

Timekeeping commands are used to show and replace time and dates and are very similar to those previously discussed. They are necessary to keep the real-time clock updated and to initialize the system.

Miscellaneous Commands

Miscellaneous commands are used to calibrate photosensors, install the system in a particular building, set lighting contactor output channels, and other housekeeping type chores. A brief description of some of these commands follows.

CL—Calibrate Lamps: This command is used to calibrate the system to a particular installation. It is used to set the range of maximum and minimum footcandles expected within a space and also to correct for photosensor linearity.

CS—Calibrate Sensor: This command is used to calibrate each photosensor.

DO—Digital Output: This is used to assign particular lighting branch contactors to the microprocessor I/O ports.

IL—Integrator Limit: This is used to set the minimum light output in the zone. While the ballasts may be capable of dimming down to very low levels, it is not always desirable to do so. This command sets minimum light output irrespective of the ballast(s).

SK—Skip Count: This sets the amount of time it takes to go from one light level to another.

VI. COST

A proper economic analysis takes into consideration all elements of lighting costs in a building over the economic life of the proposed hardware. It takes into consideration all direct and indirect costs plus all of the direct and indirect benefits and savings.

While a detailed discussion on payback methodology is beyond the purpose of this paper, there are excellent references which can be used. From Verderber [1] we can state that based on a kWh cost above $0.05/kWh the type of system described is cost-effective with an installed cost up to $1.85/ft^2.

The system described has been installed for $1.02/ft^2 in two locations. The first has an energy cost greater than $0.16/kWh, and the payback is under two years. The second has a cost of $0.085/kWh, and the payback is calculated at slightly under four years. This is consistent with Verderber [1].

Payback is very sensitive to kWh cost and hours of use. Where buildings are operated more than 14 hours per day and the cost per kWh is greater than $0.10, payback is generally under two years with this system.

It should appear obvious that in some installations such as airports the payback is acceptable with kWh costs approaching $0.04. The key is not only the cost of electricity but the daily utilization rate and the installed base from which a comparison is made.

VII. CONCLUSION

Electrical energy and power can be significantly and dramatically reduced in the built environment by the application of microcomputers and controllable output ballasts linked together as a system. Most of the savings occur through the implementation of five control strategies which provide the correct amount of light at the minimum energy levels required to achieve those levels. The overall energy savings effect can be as much as 71 percent but is dependent on the physical plant and the proper selection and use of the strategies discussed.

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