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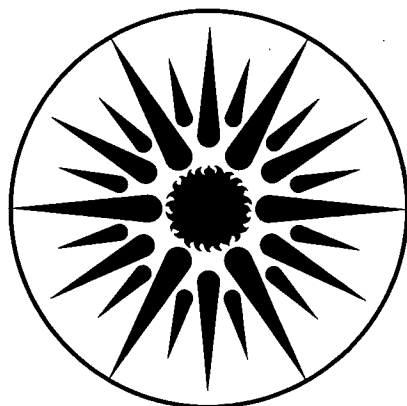
UNIVERSITY OF CALIFORNIA

## ENERGY & ENVIRONMENT DIVISION

### Technology Reviews: Lighting Systems

J. Schuman, F. Rubinstein, K. Papamichael, L. Beltrán,  
E.S. Lee, and S. Selkowitz

September 1992



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This research is part of "Envelope and Lighting Technology to Reduce Electric Demand", a multiyear research project for the California Institute for Energy Efficiency, University of California.

## **TECHNOLOGY REVIEWS LIGHTING SYSTEMS**

J. Schuman, F. Rubinstein, K. Papamichael, L. Beltrán, E.S. Lee, and S. Selkowitz

**Windows and Daylighting Group  
Energy and Environment Division  
Lawrence Berkeley Laboratory  
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Berkeley, CA 94720**

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# TECHNOLOGY REVIEWS : LIGHTING SYSTEMS

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## Executive Summary

We present a representative review of existing, emerging, and future technology options in each of five hardware and systems areas in envelope and lighting technologies: lighting systems, glazing systems, shading systems, daylighting optical systems, and dynamic curtain wall systems. The term *technology* is used here to describe any design choice for energy efficiency, ranging from individual components to more complex systems to general design strategies.

The purpose of this task is to characterize the state of the art in envelope and lighting technologies in order to identify those with promise for advanced integrated systems, with an emphasis on California commercial buildings. For each technology category, the following activities have been attempted to the extent possible:

- Identify key performance characteristics and criteria for each technology.
- Determine the performance range of available technologies.
- Identify the most promising technologies and promising trends in technology advances.
- Examine market forces and market trends.
- Develop a continuously growing in-house database to be used throughout the project.

A variety of information sources have been used in these technology characterizations, including miscellaneous periodicals, manufacturer catalogs and cut sheets, other research documents, and data from previous computer simulations. We include these different sources in order to best show the type and variety of data available, however publication here does not imply our guarantee of these data. Within each category, several broad classes are identified, and within each class we examine the generic individual technologies that fall into that class. Each technology section has the following format:

### I. TITLE PAGE & CONTENTS

### II. SUMMARIES

- Summary descriptions for each technology.
- Summary table(s) showing comparative performance characteristics or other comparative information.
- Brief discussion/summary of the most promising technologies and trends in this category. Emphasis is on electricity peak reduction and on potential for integration with other systems or technologies.
- List of product brand names for each sub-category.

### III. DATA ENTRY FOR EACH TECHNOLOGY

Each sample technology is characterized through one or more of the following. Sections may deviate as required:

- Description
- Sources
- Status of availability
- Pros and con
- Energy performance
- Comfort performance
- Impact on building design
- Cost, per unit basis
- Life cycle cost economics
- Market share, expected trends
- Case study installations

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## OVERVIEW

This assessment examines several lighting technologies that have the potential to significantly impact the energy use for lighting in commercial buildings over the next five to ten years. The technologies are divided into four categories: sources, controls, and lighting quality. This is not a comprehensive list of every available new lighting technology. Energy-efficient technologies that are currently considered "standard practice" (e.g. energy efficient core coil ballasts for fluorescent lamps) are not included. In addition, technologies that are not projected to reach the market before 10 years are not included. The intent of this assessment is to highlight some of the most promising new technologies that appear to have the largest widespread applicability in most commercial buildings. The fact that a particular technology does not appear on the list should not be construed to mean that the technology has no potential.

## LIGHTING SOURCES AND AUXILIARIES

This category covers technologies that improve the efficiency of light sources or auxiliary lighting equipment such as the ballast and fixture. We have excluded energy-efficient magnetic ballasts because, with the passage of the 1988 Appliance standard these are required by law and are therefore standard practice. This is a very rich field with new products appearing every month. We have selected here those light source technologies that seem to have the widest applicability for the commercial building sector.

**Compact metal halide lamps** are miniaturized versions of conventional metal halide lamps that are particularly appropriate for high lumen output downlighting applications where a point source is required for good optical control.

**Improved tungsten halogen lamps** represent incremental improvements in standard incandescent lighting. Some of these sources are significantly more efficient than incandescent lamps; others are only slightly more efficient. They offer small source size allowing good optical control and equivalent color rendition to incandescents.

**Improved phosphor fluorescent lamps** represent the family of fluorescent lamps that utilize new rare-earth phosphors to incrementally improve the efficacy as well as color rendition of conventional fluorescent lamps.

**Compact fluorescent lamps** are miniaturized fluorescent lamps that are suitable for replacing incandescent sources in many commercial, industrial and residential applications. Compact fluorescent lamps are approximately 3 times more efficient than incandescents with much longer life.

**Electronic ballasts** are replacements for conventional magnetic ballasts for fluorescent lamps. They are 15% more efficient than energy-efficient magnetic ballasts while providing no flicker and very little audible noise. They are available both as dedicated ballasts (non-dimming) or dimmable models.

**Improved thermal management** refers to a range of techniques that can be applied to existing and new fluorescent fixtures to improve their efficacy. All these techniques operate by cooling the lamps in the fixture so that the lamp operates at or near the temperature where the lamp is most efficient.

**Super-efficient fixtures** are a category of fixtures that have fixture efficiencies significantly higher than standard fixtures. For new construction, these fixtures have fixture efficiencies close to 90% (as compared to 65% for typical fixtures). Retrofit reflectors are also available to



improve the performance of existing fixtures. These systems generally improve fixture efficiency by 15-20%.

## LIGHTING CONTROLS

The field of lighting controls is characterized by a vast array of components but relatively few systems. This technology brief discusses most of the various controls components individually. This brief does not discuss lighting management systems per se. These are essentially energy management systems (EMS) that are specialized for lighting control. It is often possible to avoid the use of a separate lighting management system if the hardware and software requirements for lighting control can be "layered" onto a general-purpose EMS.

**Programmable timers** are used to implement time-based control of electric lights. The usual method of implementation is a system of low-voltage controlled relays that are controlled by a programmable timeclock. These systems are primarily used to efficiently schedule lighting system operation. To accommodate off hours lighting needs, these systems usually have overrides so that lighting can be obtained by building occupants either by means of low-voltage switches or telephone override systems.

**"Smart" switches** are similar in function to regular manual wall switches except that they can be controlled by means other than an occupant throwing the switch. In one implementation, this switch turns off its load when the power flowing to it is interrupted for 5 seconds (and then restored). These switches are particularly promising when combined with low-voltage relays that are controlled by a lighting management systems or building EMS. (See programmable timers).

**Occupant sensors** are essentially switches that are activated by detecting the presence or absence of people in the field of view. There are two basic types of occupant sensor: passive infrared sensing and ultrasonic. This is a mature technology that is supplied by many vendors.

**Photo-switches** are photo-electrically controlled switches that can be used to switch off lights in daylight perimeter zones. These devices are usually installed 1) on each fixture, 2) on groups of fixtures using intermediate relays or 3) as inputs to low-voltage programmable relay systems.

**Dynamic controls** are devices that allow standard lighting equipment (both fluorescent and HID sources) to be continuously dimmed to an intermediate level. These systems can control from a single lamp to entire branch circuits. Although these controls can typically provide any light level within the control range, they rarely permit dimming below 40% of maximum light and power. They generally accept an input from a photocell and/or an input from an EMS system.

**Static controls** are devices that allow the light output of standard lighting equipment to be reduced to one intermediate level. These systems can control from a single lamp to entire branch circuits. The larger systems generally accept an input from an EMS system for scheduling control. The smaller systems generally control only a single lamp or ballast - their sole function is to reduce input power (and light output). The primary application of these systems is in areas that are overlit.

**Dimmable ballasts** represent the state-of-the-art in controllable lighting. Dimmable ballasts allow fluorescent lamps to be dimmed over a very wide range. This technology is available both in magnetic ballasts and as dimmable electronic ballasts. The electronic ballasts are generally controllable through a low-voltage wiring network allowing them to respond to inputs from a photocell, occupant sensor and input from an EMS.

## LIGHTING QUALITY IMPROVEMENT TECHNOLOGIES

The technologies in this category reduce lighting energy indirectly. That is, they save energy not by providing more light for less power but rather by improving the quality of light so that lower light levels (and therefore lower energy) can be used.

**Scotopically rich lighting** arises from research at LBL and UCSF that suggests that equivalent visual performance can be achieved with lower energy consumption if the light source is rich in blue-green light. A 5000°K tri-phosphor lamp with an additional phosphor producing light at 510 nm is estimated to provide equal visual performance as a standard cool white lamp with a reduction in power of 23%.

**Polarized panels** are not a new concept but have not achieved widespread acceptance because the benefits of polarized lighting are difficult to quantify as they do not save energy directly. In principle, light that is polarized in the vertical plane can reduce veiling reflections off specular surfaces; thus lower light levels (and lower energy use) might be used to achieve equivalent visibility.

## TECHNOLOGY PERFORMANCE SUMMARY TABLE

The following table summarizes the expected energy efficiency improvements obtainable from each the technologies examined in this report. For each technology category, we present specific examples of the technology, a basecase system to compare the efficient technology against, and the estimated energy use of the new technology relative to the basecase with the added requirement that the level of service provided by the new technology be comparable to that of the basecase. Although the energy savings estimates are intended to be accurate relative to the specified basecase, the energy savings should not necessarily be generalized to all other applications. In several cases, the energy savings opportunities for the various technologies will vary drastically depending on the basecase assumptions and the particular implementation of the technology. Finally, the last column of the table gives our estimate of the effects of the technology on occupant comfort (as opposed to the energy savings which benefit the building owner/operator). This is necessarily a judgement call on the part of the authors. As much as possible, the effect on occupant comfort is a general assessment considering all the possible effects on comfort in typical applications assuming the technology is applied correctly to replace the basecase situation. Where necessary, the rationale behind a particular assessment is called out in footnotes.

## New Lighting Technology Performance Comparison

Technology Category	Typical example of technology	Basecase (common practice)	Power/energy use relative to basecase	Estimated effect on occupant comfort
Compact metal halide	32 watt metal halide	150 watt incandescent	25%	Slight Decrease <sup>a</sup>
Improved tungsten halogen	60 watt IR-reflecting quartz halogen PAR lamp	120 watt PAR lamp	50%	Neutral
Tri-chrome phosphors	"Thick" coat lamps	Standard cool white	92%	Slight increase <sup>b</sup>
Electronic ballasts	2-lamp F40 T12 electronic	Efficient core coil ballast	85%	Increase <sup>c</sup>
Low wattage compact fluorescent lamps	18 watt CF lamp	75 watt incandescent	25%	Slight decrease <sup>a</sup>
High wattage compact fluorescent lamps	27 watt CF lamp	100 watt incandescent	27%	Slight decrease <sup>a</sup>
Improved thermal management	Convective venting or thermal bridge	Standard 4-lamp 2x4 fixture	90%	Neutral
Super-efficient fixtures (new cons./ renovation)	2 lamp troffer with FE=88%	Standard 4 lamp recessed troffer (FE=65%)	74%	Neutral
Specular reflector inserts (retrofit)	3 lamp with reflector	4 lamp baked white fixture	75%	Decrease <sup>d</sup>
Programmable timers	Auto off sweep with overrides	Manual control	70-80%	Neutral
"Smart" switches	As overrides for programmable timer	Manual control	70-80%	Neutral
Occupant sensors	Individual offices	Manual control	50-75%	Slight decrease <sup>e</sup>
Photo-switches	Perimeter lights	No controls	70-80%	Decrease <sup>f</sup>
Dynamic controls	Overlight control plus scheduling	Manual control	65-80%	Neutral
Static controls	Overlight reduction	No control	70%	Decrease
Dimmable ballasts	Dimmable electronic ballasts with photocells and EMS	Manual controls	50-60%	Neutral
Scotopically-rich lamps	5000°K tri-chrome	Standard cool white	80%	Neutral
Polarized lighting	2x4 fixtures	No polarizing panel	?	Increase <sup>g</sup>
Task/ambient (new construction)	1/3 space to 50fc 2/3 to 20fc	50 fc uniform	60%	Neutral

- a Color rendition not quite as high and switch on time not as fast as incandescent.
- b Improved color rendition relative to standard fluorescent lamps.
- c Reduces flicker and ballast hum relative to standard magnetic ballasts.
- d Generally lowers wall brightness and decreases uniformity.
- e Occupant sensors can false trigger or otherwise switch lights unpredictably
- f Occupant response to lights switching on and off with respect to changing daylight levels has not been positive.
- g May result in improved productivity due to reduction in veiling glare off horizontal tasks.

## COMPACT METAL HALIDE LAMPS DATA SHEET

### DESCRIPTION

Metal halide lamps are high pressure gas discharge lamps that have additional metals that improve the efficiency of the light as well as the color rendition compared to standard mercury vapor lamps. They operate at high pressure, and require a ballast for operation. Over the years, the color rendering of metal halide lamps has improved, their life has increased and prices have dropped. In addition, phosphor coatings are being used on some of these lamps to produce light with color temperature close to that of an incandescent. Other lamps use different halides to produce a range of spectra varying from 3200 to over 6000° K. Until recently, 175 watts was the lowest wattage metal halide available. Most recently, several manufacturers have perfected low wattage, compact metal halide lamps that are suitable replacements for downlight incandescents.

### SOURCES

Compact, low wattage, metal halide lamps are manufactured by GE, Sylvania and Venture Lighting.

### STATUS OF AVAILABILITY

Sylvania has available 32 watt and 100 watt metal halide lamps. GE offers a 32 watt metal halide lamp and Venture Lighting offers a 50, 70 and 100 watt metal halide.

### PROS AND CONS

Some compact metal halide lamps have comparable color temperature as incandescents but with lower CRIs. But they last 7-10 times long than incandescents and are more efficacious. Their small light source allows high optical efficiency, fixture design. Unlike incandescents, all metal halide lamps require ballasts so they cannot directly replace incandescent sources unless a new fixture is installed. Also, metal halide lamps operate under high temperature and pressure. The arc tube inside the lamp can reach temperatures as high as 1100 C. The arc tube and outer bulb has the possibility to rupture. Thus some fixtures containing metal halide lamps of 175 watts or less require a glass lens/diffuser must be able to contain fragments of extremely hot glass in the event that the lamp should fail "non-passively." Not all metal halide lamps can be operated in any position. Metal halides tend to suffer from color inconsistency. Different lamps even from the same production run can have noticeably different color. The color from metal halide lamps also tends to change with age, accentuating any initial differences. One company has an electronic ballast for metal halide lamps that can provide more consist color rendition from the lamp, but this ballast is for higher wattage applications. Finally, as with all HID sources, metal halide lamps are slow to start and restrike, which will certainly limit their use in residential markets or for commercial applications where rapid switch on is required.

### ENERGY PERFORMANCE

A 32 watt, compact metal halide lamp can replace a 150 watt incandescent lamp. The total system power (metal halide lamp and ballast) is 38 watts. Installing this retrofit will reduce energy consumption by 75%. The compact metal halide lamp has a color temperature of 3000 K, a temperature close to that of incandescents. Its color rendering index is about 65.

### IMPACT ON BUILDING DESIGN

The best applications are for major renovation of incandescent fixtures requiring high lumen output where fast switch on is not required. Applications are lobbies, hallways, and other situations using downlighting.

### LIFE CYCLE COST ECONOMICS

These lamps are cost-effective if used in new construction applications to replace 150 watt incandescent downlights. But they may not be cost-effective for retrofit because the existing fixture must be replaced.

#### **MARKET SHARE, EXPECTED TRENDS**

As long as there are no compact fluorescent sources with lumen outputs similar to that of a 150 incandescent, the market share for compact metal halide will increase although possibly at a slow rate.

## IMPROVED TUNGSTEN HALOGEN LAMPS DATA SHEET

### DESCRIPTION

Tungsten halogen lamps are improved incandescent lamps. As with incandescent lamps, tungsten halogen lamps produce light by passing current through a tungsten filament (so-called "hot wire in a bottle.") But unlike standard incandescents, tungsten halogen lamps enclose the filament in a small quartz capsule filled with halogen gas (usually iodine or bromine). The presence of the halogen gas, and the high envelope temperature causes evaporated tungsten to be redeposited on the filament rather than on the envelope. This allows the filament to be operated at a higher temperature with commensurately higher efficiency without sacrificing lamp life. Because tungsten halogen (T-H) lamps deposit evaporated tungsten back onto the filament, T-H lamps can maintain a higher percentage of their initial lumens over life and have longer lives than standard incandescent lamps. Only 10% of the energy emitted by incandescent lamps is visible light; the remaining 90% is wasted heat. With T-H lamps a larger percentage of the total input energy is available as visible light.

The efficiency of T-H lamps can be improved even further by adding an infrared (IR) reflecting coating to the inside of the quartz capsule. (Durotest has also applied this technique to incandescent lamps without the halogen gas envelope). This selective film is similar to the types of films applied to windows. It selectively reflects IR radiation while transmitting visible light. This improved T-H lamp "re-cycles" some of the waste IR back onto the filament allowing the filament to operate at the same temperature with lower power draw.

Another technique used in T-H lamps (the so-called MR-style reflectorized lamps) is to use a different type of selective film coating that does not help to improve efficacy but does help to focus the emitted light and reduce heat in the light beam. To accomplish this, the reflector lamp is coated with a film that reflects visible radiation and transmits infrared.

### SOURCES

Halogen lamps can be purchased from just about all the major lamp manufacturers, namely; Duro-Test, GE, Osram, Philips, and Sylvania. The improved IR-reflecting lamps are available from GE. GE now has a family of PAR style lamps that replace the 150 PAR lamp and are a good indicator of the technology trend. Their 90 watt PAR lamp has about the same beam lumens as the 120 watt but, because of the quartz halogen capsule uses only 90 watts. (GE's 120 watt PAR replacement for their 150 PAR lamp accomplishes its improvements with better optical elements). They offer an even more efficient PAR lamp that exploits the IR reflecting coating to obtain the same beam lumens as the 90 watt PAR using only 60 watts.

### STATUS OF AVAILABILITY

T-H lamps are available in the following lamp shapes; A lamps, PAR lamps, and ER lamps. Improved T-H lamps with the IR reflective film are available in PAR lamps, tubular, and R lamps. T-H lamps with the IR transmitting film are available in MR lamps (mini reflector).

### PROS AND CONS

T-H lamps are moderately more efficacious and IR reflective T-H lamps are significantly more efficacious than standard incandescents. The lumen output of the T-H lamps are maintained at a high 93% of their initial lumens throughout their life. The small filament used in the T-H lamps allows extremely efficient optical designs. Since T-H lamps are essentially incandescent sources, they produce a warm light with a high color rendering index. Thus T-H lamps are an attractive, very efficient source for accent/display lighting. They can also be dimmed, but this reduces their efficacy and they should be burned at full brightness from time to time to allow the halogen gas to recycle any deposited tungsten back on to the filament.



Due to the high temperature of the T-H lamp, the filament capsule is usually made of quartz. Unjacketed T-H lamps with quartz capsules should not be touched directly with the hand since oils from the skin are deposited on the surface resulting in reduced lamp life. Also lamps should be covered with a lens or screen to prevent damage from a possible capsule rupture. Some lamp manufacturers place diodes within the T-H lamps. This causes the lamp to operate at a lower voltage and more efficaciously. But the diode causes flickering, particularly if the lamp is dimmed. Diodes also decrease power factor and increase line current harmonics. According to findings by Australian and British scientists, T-H lamps emit higher amounts of ultraviolet (UV) radiation than conventional lamps. But the UV radiation, which can increase the risk of cancer, sunburn, and cataracts, is only significant if the lamp is very close to the person, i.e. a desk lamp. The user is subjected to no danger if a glass lens is placed over the bulb.

#### **ENERGY PERFORMANCE**

A standard, 100 watt, incandescent lamp has an efficacy of 17.5 lumens per watt. T-H lamps have an efficacy of about 20 and IR reflective T-H lamps have an efficacy of about 30. But the high optical efficiency possible with the T-H lamps make many more lumens available to the space than is apparent from a simple comparison of efficacies. For example, applications using 150 watt standard, incandescent PAR lamps can exchange them for 60 watt IR reflective T-H PAR lamps for a similar luminous effect.

The T-H lamps have a CRI of about 100. Their color temperature may range between 3000K - 3200K. A standard incandescent has a CRI of 100 and a color temperature of 2800K. This means that the color of the T-H lamps is slightly whiter than standard incandescent sources but still provides excellent color rendition.

#### **IMPACT ON BUILDING DESIGN**

The IR reflective T-H lamps are particularly effective for replacing incandescents in deep fixtures. Although in many applications replacement of incandescents with compact fluorescents or another more energy efficient technology is most cost effective. But in situations where dimming and/or focused light is critical, T-H sources can provide the desired light at a reasonable cost.

#### **COST, PER UNIT BASIS**

GE gives a cost adder of \$1.50 for the 90 watt PAR flood as compared to the 150 PAR.

#### **MARKET SHARE, EXPECTED TRENDS**

The market share of the T-H lamp will probably increase significantly over the next 5 years. Although they are only modestly more efficient than the incandescent, they are suitable replacements for the incandescent in many applications particularly where longer lamp life is desirable.

## IMPROVED PHOSPHOR LAMPS DATA SHEET

### DESCRIPTION

The recent introduction of fluorescent lamp coatings of rare earth, tri-stimulus phosphors (also called tri-phosphor lamps or tri-chrome lamps) have resulted in lamps having higher color rendering indices as well as higher efficacies. (Rare-earth lamps should be contrasted to conventionally phosphored lamps such as the "deluxe" style phosphored lamps, which increase color rendition at the expense of efficacy or "Lite-White" fluorescent lamps, which, conversely, offer improved efficacy but sacrifice color rendition). Rare-earth phosphors have been selected because they produce light at the most sensitive wavelengths of the eye's red, green, and blue retinal sensors. The tri-stimulus characteristics of the lamps give them excellent color rendering capabilities.

Rare earth lamps are classified according to their color rendition. The RE70 lamps actually have TWO phosphor coatings: the first coating being a conventional calcium halophosphate; the second, a coat of the rare earth phosphor. The RE70 lamps are slightly more efficient than the standard lamps with better color rendition (CRI 70-80). The RE80 lamps contain just the tri-stimulus phosphor and have CRIs between 80 and 90.

The light output from rare earth lamps drops only about half as much as conventionally phosphored lamps over the same time period. This allows the use of higher maintenance factors, which, in turn allows fewer lamps (and fixtures) to be used to supply the same illuminance level.

The tri-phosphor technology is what has allowed the introduction of "long twin-tube" fluorescent lamps, which stuff more lumens into a smaller package. These lamps look like oversize compact fluorescent lamps but are being used in 2x2 (and smaller) fixtures to replace full-size (i.e. 4 ft.) fluorescent fixtures. Because of their small size and high phosphor loading, these lamps must be manufactured with rare-earth phosphors. This results in high efficacy as well as more compact size. It also opens up opportunities for fixture manufacturers to design new fixtures that could be mounted nearer the workplane (rather than in the ceiling) allowing task illuminance levels to be provided to effectively.

### SOURCES

Fluorescent lamps with rare earth phosphor coatings are available from many lamp manufacturers. Philips, Sylvania, GE, Toshiba, Osram, and Duro-Test all carry the rare earth lamps. Only Philips and Aurora make the T10 lamp.

### STATUS OF AVAILABILITY

The rare earth lamps are available in many different tube lengths and diameters. Thinner diameter lamps (T-8 and smaller) use tri-phosphors almost exclusively since their higher phosphor loading precludes the use of conventional phosphors. Rare-earth phosphors are also used for the standard T12 width and the slimmer T10 lamps. Straight T8 lamps are available in 2' and 17 watts, 3' and 25 watts, 4' and 32 watts, and 5' and 40 watts. The color rendering index of these lamps may be in the mid-70s or in the mid-80s, depending on the manufacturer and whether they are pure tri-stimulus lamps or are "thin" coat. The lamps have color temperatures of 3100 K, 3500 K, or 4100 K. U-shaped, T8 lamps are also available at the same temperatures and CRIs as the straight lamps. The "long twin tube" fluorescents are available in 18, 27, 39 and 40 watts. The 39 watt lamp has approximately the same lumen output as a standard 4 ft. lamp but is only 22".

### PROS AND CONS

Rare earth lamps have better lamp lumen depreciation characteristics than halophosphor lamps. But tri-phosphors are expensive. The higher the CRI, the higher the price. Tri-phosphor

lamps also have somewhat higher flicker than equivalently colored calcium halophosphors, apparently because the rare earth phosphor that produces the red peak (at 613nm) has a faster decay rate than the calcium halophosphor. Flicker is not a problem if the lamps are operated at high frequency with electronic ballasts since no fluorescent phosphor can "keep up" with the much faster oscillating current.

Thin diameter lamps may improve the fixture efficiency slightly (perhaps 3%) because the thinner diameter allows for improved fixture optics.

Because T-8 lamps produce roughly the same amount of lumens as T-12 lamps but have smaller surface area, the brightness of T-8 lamps is higher than that of T-12 lamps. Some designers have noted that the T-8 lamp can appear overly bright. This means that the fixture designer should carefully account for the smaller T-8 lamp diameter in designing the fixture's cutoff angle.

### ENERGY PERFORMANCE

Tri-phosphor lamps produce more lumens per watt than halophosphate lamps. The efficacies of the RE70 and RE80 lamps are 5% and 8% higher, respectively than standard, cool white, halophosphate fluorescent lamps of the same diameter.

Tri-phosphor lamps are available at color temperatures of 2700, 3000, 3500, 4100, and 5000 K. Lamps with these temperatures have CRIs measuring in the 70s and in the 80s. To put this in perspective, the color temperature of incandescents is about 2800 K, 3000 K for warm white fluorescent, 4100 K for cool white fluorescent, and 6300 K for daylight fluorescent. The corresponding color rendering indices for these lamps (excluding the incandescent) are approximately 53 for warm white, 62 for cool white, and 76 for daylight. The deluxe versions of cool white deluxe and warm white deluxe achieve CRIs about 10 points higher but at the expense of efficacy.

### IMPACT ON BUILDING DESIGN

For most commercial interior lighting applications, the RE70 lamp is an excellent choice. They have better color rendition than cool white lamps, are slightly more efficient and are only slightly more expensive. If excellent color rendition is required, then the RE80 coat lamps are the best choice. They are more efficient than the RE70 coat phosphor lamps and are much more efficient than the "deluxe" phosphor lamps that were traditionally used for high color rendition fluorescent applications. But the higher lamp cost may not justify the change if a lower CRI lamp is adequate.

Because they can operate off existing ballasts, T10 lamps are good for retrofit applications where more lumens are needed than are available from standard lamps. The F40T10 lamps can provide more light using existing T12 fixtures/ballast without significantly increasing power requirements. In new systems, the high output of the lamp will decrease the number of luminaires needed to maintain a set light level. Installation of T8 lamps requires a different ballast. In new designs, substantial savings can be achieved when T8 lamps are coupled with T8 ballasts and fixtures.

### COST, PER UNIT BASIS

The RE70 phosphor lamps are somewhat more expensive than conventional cool white lamps. Prices vary widely, but a recent survey of lamp prices in the Oakland area is attached. This price list mixes "open" schedule and GSA (General Services Administration) prices. Note that these prices are continuously updated. The RE70 lamp is 66% more expensive than the standard lamp on the "open" schedule. The RE80 lamp, though is about 3 times as expensive as the CW lamp.

### **MARKET SHARE, EXPECTED TRENDS**

Over the next ten years, the triphosphor lamps will likely replace calcium halophosphate lamps as the dominant lamp type. The penetration of the RE80 lamp will be slower due to their much higher cost. Industry sources indicate that the rare earth phosphors are much more expensive to purchase than conventional phosphors. It is not known how much economies of scale will improve this situation.

## ELECTRONIC BALLAST DATA SHEET

### DESCRIPTION

All gas discharge lamps require a ballast to regulate current flow in the lamp and to provide a sufficiently high voltage to initiate the lamp arc. Electronic ballasts provide these same functions and can do so more efficiently than conventional (i.e. magnetic) ballasts.

Electronic ballasts are more efficient than standard ballasts for two reasons. First, electronic ballasts drive the lamps at high frequencies (typically 20 to 60 kHz) which results in more efficient lamp operation because of reduced losses in the electrode region. For 4 ft. systems this results in about a 10% improvement in efficacy. This improvement is a function of lamp length; the efficacy improvement is more significant in shorter lamps than longer lamps. Secondly, electronic ballasts have lower intrinsic losses in the ballast than equivalent magnetic ballasts. The combined effect of these two factors is about a 20-25% improvement in lamp/ballast system efficacy compared to standard core-coil ballasts. Relative to efficient core-coil ballasts, the improvement is about 15%.

There are two basic ballast circuit types: instant start and rapid start. With instant start ballasts, the ballast provides no filament voltage during starting or operation. With rapid-start circuits the electrodes are preheated before initiating the arc which permits a lower starting voltage. The filament voltage is also maintained during normal operation. The effects of starting lamps at higher voltages causes instant start lamps to fail earlier than rapid start circuits. Dimming electronic ballasts are all rapid start. This is because the lamp electrodes must be heated during dimmed mode operation if lamp life is not to suffer. (See controls section for dimming ballasts).

Although virtually all magnetic ballasts run lamps in series, some electronic ballasts operate lamps in parallel. There is some advantage to parallel operation since the other lamps will still operate even if one or more of the other lamps should fail. However, ballast efficiency may be slightly lower.

### SOURCES

Electronic ballasts are available from the major ballast manufacturers as well as from some smaller manufacturers specializing solely in electronic ballasts. These manufacturers include Advance, EBT, MagneTek, Lutron, Thomas, Valmont, ETTA, Osram and Motorola. (See attached list of electronic ballast manufacturers from Energy Users News).

### AVAILABILITY

Electronic ballasts are often in short supply. It is anticipated that this situation may continue for well over a year.

A few electronic ballasts operate all three diameter lamps. But this practice is being abandoned because it is not possible to operate all lamp types optimally from one ballast. Electronic ballasts can control 1-4 lamps. Some are designed to operate the lamps in series, others in parallel. Different control options are available with electronic ballasts. These options include step dimming or full-range dimming with automatic adjustment from a photosensor. Very few electronic dimming ballasts offer individual ballast control. There are few T8 type ballasts for 3 or 4 lamp systems that have 100% dimming capabilities.

### PROS AND CONS

Electronic ballasts operate lamps at higher frequencies than standard ballasts (typically 20-40 khz compared to 60 hz). Lamps operate more efficiently at higher frequencies. Electronic ballasts have less energy losses than standard ballasts and their cooler operation also

contributes to improved lamp performance. Electronic ballasts can also include feedback circuits that improve regulation with respect to changing temperature and voltage conditions.

Full dimming capabilities are available with electronic ballasts but more frequently the dimming range is somewhat restricted at the low end so that the lamps do not dim below about 20%. Depending on how the filaments are operated, this may mean 30% power is consumed even when the lamps are maximally dimmed. It is possible to operate lamps so that only the filaments are kept hot and the lamps produce virtually no light but this is a very inefficient mode of operating the lamps.

When electronic ballasts were first introduced, some manufacturers produced equipment that failed prematurely. But as the technology has matured, reliability has improved greatly. Manufacturers who have been in production almost 10 years have documented failure rates of less than 1% for ballasts that have been in operation for over 3 years.

### ENERGY PERFORMANCE

Electronic ballasts result in a 20-25% improvement in lamp/ballast system efficacy compared to standard core-coil ballasts. Relative to efficient core-coil ballasts, the improvement is about 15%.

When comparing ballast performance, it is important to examine the light output as well as the input power. Two important parameters of ballast performance are the ballast factor and the ballast efficiency factor. The ballast factor (BF) is the ratio of lumen output of the lamps on the ballast to the rated lumen output of the lamps. Thus BF is a relative measure of how much light is produced using a specific ballast. Lumen output is measured under ANSI conditions in an environment maintained at 25°C.

The ballast efficiency factor (BEF) is the ballast factor times 100 divided by the lamp/ballast system input power. BEF *only* provides a meaningful comparison for *different ballasts operating the same type and same number of lamps*. A standard, energy efficient ballast will operate two 40 watt lamps (rated lumen output of 3050 lumens each) with a BF = .94 at 86 watts giving a BEF = 1.08. A typical electronic ballast using the same lamps has a BF = .88 at 71 watts giving a BEF = 1.24. Because we are comparing different ballasts driving the same lamps, the % change in the BEFs are identical to % change in lamp/ballast system efficacy (i.e. 15%).

### COMFORT PERFORMANCE

Standard core-coil ballasts operate with 60 hz power, causing the output of the fluorescent light to oscillate at 120 times per second. This may result in a noticeable flicker. Flicker is largely eliminated with electronic ballasts since fluorescent lamp phosphors cannot "keep up" with the much faster oscillating current.

Electromagnetic ballasts by nature can produce an audible hum. Although "A" rated (highest sound quality) ballasts are mostly used, even these can produce an audible sound in a quiet space. The hum worsens if the ballast is exposed to high temperatures and can be amplified by metal fixtures. Electronic ballasts operate more quietly than even the most quiet magnetic ballast.

Independently dimmable ballasts may be used to improve lighting quality if fixtures in the offending "veiling reflection" zone are dimmed down selectively.

### IMPACT ON BUILDING DESIGN

Electronic ballasts should always be considered in new buildings. Electronic ballasts should always be considered for lighting system retrofits although replacing energy efficient electromagnetic ballasts may not always be cost effective.

A ballast electrical parameter which affects electric load is the power factor. Power factor is defined as the ratio of delivered system watts to line volt-amps. Lower power factors cause the lines to carry higher loads even though the actual power consumption may be the same. Higher line voltages result in greater line and transformer losses. Some utilities incur rate penalties to customers with low power factors.

Electronic ballasts that have lower harmonic content and better power factor than standard ballasts are available from most major manufacturers.

## COMPACT FLUORESCENT LAMPS DATA SHEET

### DESCRIPTION

Compact fluorescent lamps are miniaturized fluorescent lamps. They are somewhat larger than the incandescent lamps that they replace but they are approximately three times more energy efficient and they last ten times as long. Typically, a 13 watt compact fluorescent lamp is a suitable replacement for a 60 watt incandescent lamp in terms of lumen output.

Some compact fluorescent systems include an Edison base adaptor enabling the use of the lamp in a standard incandescent socket. Other systems are "hard wired" specifically for compact fluorescents. In the dedicated systems, the single ended compact fluorescent lamp is installed directly in the fixture. Compact fluorescents equipped with screw base adapters are available as integral units or as modular components. The integral units contain the lamp, ballast, and adapter. In the modular units, the ballast/adapter is separate from the lamp. Since lamp life is much shorter than ballast life, integrating the units forces the ballast to be discarded before the end of its useful life.

Integral or modular compact fluorescents can have either a standard, electromagnetic ballast or an electronic ballast. The ballast can consume between 1 to 3 (? probably not for the 26 quad) watts, depending on the ballast. This energy consumption is in addition to the rated wattage of the lamp and needs to be accounted for in determining system efficacy.

The fluorescent lamp circuit type is generally preheat or instant start. The preheat lamps will take 1 to 2 seconds to light when switched on. The instant start lamps turn on almost immediately but have a shorter life. These lamp types can not be dimmed without lamp life seriously being effected. The lamps are also classified by their shape and size. Compact lamps come in T-4 and T-5 diameters (4/12 inch and 5/12 inch). They are available as twin tube or quad tube. The 26 watt quad tube is the largest wattage CF lamp currently available. It has a lumen rating of 1500 lumens; slightly under the 1750 lumen rating of a standard 100 watt incandescent. Recently introduced to the market is a flat, central-based lamp appropriate for square or round fixtures (see attached product literature).

All compact fluorescent lamps use the rare earth, tri-phosphors. This is the reason for their high color rendering, in the low 80s for almost all lamps. They are available in color temperatures equivalent to that of incandescents. When used as replacements for incandescents, concerns about acoustic noise and potential flickering from electromagnetic ballasts should be addressed. The twin tube lamps are suitable for replacing task lights. The higher output quad tubes can be used for downlighting or wall washing.

### SOURCES

(See attached list from EUN).

### STATUS OF AVAILABILITY

Manufacturers have been producing compact fluorescent lamps for over ten years. Currently about two dozen companies manufacture the lamps, including GE, Philips, Panasonic, and Osram.

### PROS AND CONS

Not all incandescent fixtures will accept a CF lamp substitution because of physical size incompatibilities. There is no way around this except to try out the lamp to see if it fits without jutting down out of the fixture.

Compact fluorescent lamps are rated under ANSI thermal conditions that may not be achieved in typical applications. Because fixtures tend to run hot when installed in a static plenum, the



actual lumen output from the lamp may be considerably lower than the rated lumens. This may result in under-illumination if the thermal factor is ignored. In addition, the lumen output and, to a lesser extent, input power are affected by the lamp burning position. All other things being equal, a CF lamp produces roughly 15% less light burning base down than it does base up.

Many CF lamps have relatively high harmonics and poor factor. Although this is rarely a problem in residential settings where lighting is only a small portion of the electrical load, it is a concern to utilities in commercial buildings. Low harmonic CF systems can be developed; it is a question of cost.

Fixtures hard wired for compact fluorescent lamps should be considered if regressing back to incandescent-use is a possibility to be avoided.

#### **ENERGY PERFORMANCE**

The efficacy of compact fluorescent lamps is generally between 45 and 70 lumens per watt (compared to 17 lpw for incandescent). CF lamps systems generally achieve efficacies at the lower end of this range if they are magnetically ballasted and/or are mounted in thermally restricted volumes. Electronically-ballasted CF lamps in higher wattages under benign thermal conditions (i.e. bare) can achieve efficacies near 70 lpw.

#### **IMPACT ON BUILDING DESIGN**

Compact fluorescent lamps should be specified for most commercial building applications where an incandescent lamp of 100 watts or lower would otherwise be used. There are many downlighting fixtures available today that are designed to accommodate the CF lamp.

#### **COST, PER UNIT BASIS**

The most expensive CF lamps (electronically ballasted) lists for about \$30. They can be purchased at \$10-\$12 when purchased in quantities.

#### **MARKET SHARE, EXPECTED TRENDS**

The market for CF lamps is expected to expand at a rapid rate over the next few years both to supply the retrofit demand and for new construction. Many utility programs are helping to drive this market by offering direct rebates on the purchase of CF lamps.

## IMPROVED THERMAL MANAGEMENT DATA SHEET

### DESCRIPTION

Many technology developments have been made to increase lighting system efficacy by improving lamp phosphors and ballasts. An area often overlooked but equally significant is increasing efficiency by optimizing the thermal operating condition of the fluorescent system. The operating characteristics of a lamp/ballast system is dependent on its environmental temperature. That is, the lowest temperature of the lamp wall determines the vapor pressure of the mercury within the lamp, which in turn affect the quantity of mercury available to the discharge.

Generally, lamps and ballasts placed in fixtures operate at temperatures above their optimum. It is possible to redesign many fixtures so that lamps operate at cooler temperatures. Some techniques that have been tested for their thermal management effectiveness are: including slots in the fixture to permit natural convection, incorporating the HVAC return air vent within the fixture, placing a conductive thermal bridge between the lamp wall and the fixture housing, attaching thermo-electric Peltier cooling devices to the lamp wall, or using a heat pipe to conduct heat away from the wall.

### SOURCES

The most available method to improve thermal management today is the use of air-handling fixtures. These are available at a premium cost and allow return air to be drawn through the lamp compartment to reduce MLWTs closer to optimum.

### STATUS OF AVAILABILITY

Many thermal management techniques are being researched at Lawrence Berkeley Laboratory and are in the process of being implemented by some fixture and lamp manufacturers. Most designs are not yet available to the public.

### PROS AND CONS

The benefits of improved thermal management are a function of the thermal environment that the lamp is subjected to. In small thermally restricted fixtures, the efficacy benefit of improved thermal management may increase efficacy by 10%. In some applications though (i.e. 2-lamp fixtures with low wattage lamps), the lamp wall temperature may be close to optimum. Use of thermal management in this instance would be counter-productive.

It is important to recognize that thermal management techniques increases input power as well as light output. Thus improved thermal management would be less appropriate for retrofit applications unless a space is considered to be slightly under-illuminated.

### ENERGY PERFORMANCE

The rated lumen output of fluorescent lamps is based on standardized tests conducted in a controlled environment at 25°C. Based on laboratory tests, this corresponds to a MLWT of about 37°C, close to the optimal temperature for light output of standard fluorescent systems. When standard fluorescents are operated in typical, enclosed fixtures, their MLWTs are closer to 55-60°C. At these temperatures, light output is about 25% lower than the rated output and efficacy is down 12%. Researchers have correlated system efficacy and light output to the minimum lamp wall temperature (MLWT). Different lamp/ballast systems operate most efficaciously at different MLWTs. Lawrence Berkeley Laboratory reports that a four lamp lensed troffer without any air flow operates with 22% less light output and 11% less efficacy than the lamps are rated at. Placing vents in the fixture which establishes natural convection improves light output and efficacy by about 1%. Incorporating air flow into the fixture (20 to 50 cfm) gets the performance just about up to the rated values. Comparable results are obtained in four lamp parabolic troffers.

Compact fluorescent lamps can operate 20% below rated lumen output and efficacy due to elevated temperatures inside fixtures with severely restricted thermal geometries. LBL has developed two prototype fixtures that address this problem. One incorporates a heat sink rod between the lens and the lamp in a reflector-type compact fluorescent screw-in lamp. The other introduces venting to a down light fixture fitted with two 26 watt compact lamps. Both these techniques were able to bring the lamps' performance back up to rated values.

#### **IMPACT ON BUILDING DESIGN**

In new construction, thermal management techniques may allow fewer fixtures to be used to provide the design light level. The reduction in the needed number of fixtures is roughly proportional to the improvement in system efficacy. This results in a reduction in capital cost that is not generally available in retrofit applications where the fixture spacing cannot be changed. However, with appropriate thermal control, it may be possible to use a high lumen output CF lamp to replace an incandescent of 100 watts or higher where it could not otherwise be used because of insufficient lumen output.

#### **COST, PER UNIT BASIS**

Air-handling fixtures have a large associated per unit cost relative to static fixtures. This is partly due to inventory constraints that would be alleviated in a fuller market.

The added cost of some of the thermal management approaches currently under research at LBL are expected to cost under \$0.50/fixture in large quantities.

## SUPER EFFICIENT FIXTURES DATA SHEET

### DESCRIPTION

Super Efficient fixtures are lighting fixtures with fixture efficiencies equal to or exceeding 90%. Fixture efficiency is defined as:

$$\text{Fixture Efficiency (\%)} = \frac{\text{Fixture lumens (@ 25 ° C ambient)}}{\text{Bare lamp lumens (@ 25 ° C ambient)}}$$

Super efficient fixtures use interior surfaces that are both highly reflective and specular. The increase in fixture efficiency relative to fixtures with white-painted interior finishes is due both to the highly reflective nature of the reflecting surface and to the specular nature of the surface. A specularly reflecting surface assures that light emanating from the lamp exits the fixture after suffering at most one reflection. By contrast, in a white-painted fixture, light rays striking the fixture surface are reflected diffusely. Thus a light ray may suffer several bounces before it exits the fixture resulting in lower efficiency due to absorption losses.

For retrofit applications, one can purchase specular reflector inserts that improve the fixture efficiency of existing fixtures. However, these fixtures will achieve efficiencies of 80% at best with 75% a more typical value.

The difference between super-efficient fixtures and specular reflectors for retrofits is usually the degree to which all reflecting surfaces are replaced with specular surfaces. Specular reflectors for retrofits are manufactured from single sheets that are bent in a break to form the proper surface angles. In a super-efficient fixture, all reflecting surfaces within the fixture enclosure are specularly finished including the ends and lens frame.

Specular reflectors are manufactured in one of three ways:

1. A highly polished anodized aluminum.
2. Silver deposition on plastic film glued to a metal substrate.
3. Multi-layer dielectric coatings deposited on an anodized aluminum substrate.

There are trade-offs with each of the above approaches. Anodized aluminum is robust and is the least expensive but also has the lowest reflectivity (about 87%). Silver films have higher reflectivity but are more expensive. Furthermore, there are unresolved questions concerning the long-term robustness of these films. Multi-layer dielectric coatings have high reflectivities (~94%) and are as robust as anodized aluminum but are also the most expensive.

### SOURCES

Brayer Corporation (San Rafael, CA) has a 2-lamp fixture with a fixture efficiency of approximately 85%. With appropriately chosen lamps, the Brayer fixture could probably achieve a 90% fixture efficiency albeit with a slight penalty in total fixture lumen output. The following is a list of manufacturers of specular reflector inserts for retrofit applications.

[Use listing from Energy User's News]

A number of these companies also supply fixtures with specular reflectors already installed for use in new construction. However, the efficiencies of these fixtures are comparable to the retrofit fixtures.

### STATUS OF AVAILABILITY

Specular reflectors for retrofit applications are available from many vendors. Super-efficient fixtures are currently manufactured by a handful of companies.

## PROS AND CONS

Super efficient fixtures tend to direct more light straight down than most conventional fixtures. From the standpoint of lighting uniformity, the more concentrated light distribution pattern tends to result in lighting layouts with fixtures on close centers (i.e. the spacing-to-mounting heights are less). This in turn requires more fixtures and commensurately higher initial installed costs. For retrofits, the fixture spacing cannot be changed when the specular reflectors are installed. This can result in dark areas between fixtures and lower wall brightnesses than for conventional fixtures. On the other hand, in areas with CRT screens, the reduction of high angle light may be a benefit because less light from the fixtures will be reflected off the CRT screen thus reducing veiling reflections.

Another potential disadvantage of specular reflecting materials is their performance with respect to aging. The reflectivity of both specular and white-painted surfaces decreases with time due to dirt accumulation and surface degradation. However, this effect is probably worse with specular reflectors because these surfaces will also lose some of their specularly as well. The durability of specular reflectors is a subject of some controversy. The film-based reflectors have been found to bubble and peel more than the anodized aluminum reflector or the multi-dielectric coated reflectors.

## ENERGY PERFORMANCE

Super-efficient fixtures result in an energy saving potential of about 20% compared with good standard practice fixture (i.e. FE  $\approx$  75% for a good quality parabolic-type fixture with 2-lamps). Compared to a standard prismatic lensed troffer, the efficient fixture has a CU approximately 30% higher.

Specular reflector inserts intended to be easily installed in existing fixtures, increase efficiency approximately 15% compared to standard fluorescent lensed troffers although this is dependent on the specific reflector design and the geometric constraints imposed by the existing fixture.

## COMFORT PERFORMANCE

Super-efficient fixtures for new construction can have candlepower distributions approaching that of conventional fixtures. In this regard, there is no comfort performance penalty associated with this technology. Specular reflector inserts in existing buildings may result in dark areas between fixtures and do not wash walls as effectively as standard lensed fixtures. This can result in a cavelike atmosphere in some spaces. On the other hand, if CRT glare is a problem, specular reflectors may help alleviate glare off CRT screens especially if the fixtures are lensed (rather than parabolic).

## IMPACT ON BUILDING DESIGN

As described above, in new construction it may be possible to use fewer super-efficient fixtures than conventional fixtures with a resulting savings in initial cost.

## COST, PER UNIT BASIS

Installed costs for specular reflectors are generally \$25-\$60 depending on the type of reflector and the attachment mechanism.

At the present time, super-efficient fixtures are considerably more expensive than standard fixtures. This will decrease in a mature market.

## MARKET SHARE, EXPECTED TRENDS

The market potential for super-efficient fixtures is largely untapped at this point.

## CASE STUDY INSTALLATIONS

Many case studies available but veracity would need to be confirmed.

## PROGRAMMABLE TIMERS DATA SHEET

### DESCRIPTION

This sub-category of lighting controls refers to the time-based control of electric lights. The usual method of implementation is low-voltage controlled relays that are controlled by a programmable timeclock. These systems are primarily used to schedule lighting system operation to reduce after-hours lighting waste. To accommodate off hours lighting needs, these systems usually have overrides so that lighting can be obtained by building occupants either by low-voltage switches or telephone overrides. The relays are usually mounted in electrical panels immediately adjacent to the lighting circuit breaker panels in the electric room with each relay controls one branch circuit.

A typical relay is the General Electric RR-7 relay, which is almost a standard for this type of control component. This is a latching-type relay that requires power only to open or close. The input control is a 24 volt pulse that is generated by a programmable time clock. These time clocks are essentially multi-channel schedulers. They range in size from systems controlling only a few relays, to those capable of controlling several thousand. Most take into account weekday and weekend schedules as well as holiday operation. Most have battery backup.

Countdown timers are the simplest method for achieving scheduling control. These are switches equipped with spring-wound timers that switch off after a desired time interval. These may be appropriate for limited applications such as storage rooms and other areas where good override capabilities are not required.

### SOURCES

See attached list from Energy Users News. General Electric is a well-known supplier of this control unit. See also Triad Technologies.

### STATUS OF AVAILABILITY

This is a mature lighting product that is offered by several vendors.

### PROS AND CONS

This type of control is an excellent choice for retrofits and major renovation. It facilitates rational lighting energy management for a relatively low installed cost. Generally, access to the ceiling plenum is not required since the relays are usually installed in the electrical closets. This also minimizes disruptions to the occupants.

This control is generally only appropriate for scheduling control, and to a lesser extent, simple daylighting switching control.

### ENERGY PERFORMANCE

Because of the many variables, it is difficult to predict the energy savings from programmable timers. An monitored installation at the World Trade Center reported an energy savings of 35% relative to the original operating schedule.

The energy performance of programmable timer systems is improved if the timers are set for manual on/auto off control. In this mode, the programmable timers are used only to switch lights off, not on. With this technique, the occupant is responsible for switching on his or lights when they first enter the space. The programmable timer will switch off the lights at appropriate times assuring that lighting energy is not used at times when the space is unoccupied.

### IMPACT ON BUILDING DESIGN

The most important effect of this system on building design is with regards to the branch circuit wiring for the lighting system. To be used most effectively in new construction, the electrical consultant should specify that the inboard tubes on multi-lamp fixtures be wired on separate branch circuits than the outboard tubes. This permits multiple light levels in each zone simply by appropriate switching of the relays and/or local switches.

#### **COST, PER UNIT BASIS**

These systems are generally costed out on a cost per control point (i.e., relay) basis. Costs of \$125-\$150 per control point are typical for commercial building applications. This cost includes the relay and associated wiring. The EMS may be an additional cost (sometimes significant) depending on the building. The cost per control point is somewhat higher for retrofit than for new construction but not significantly so.

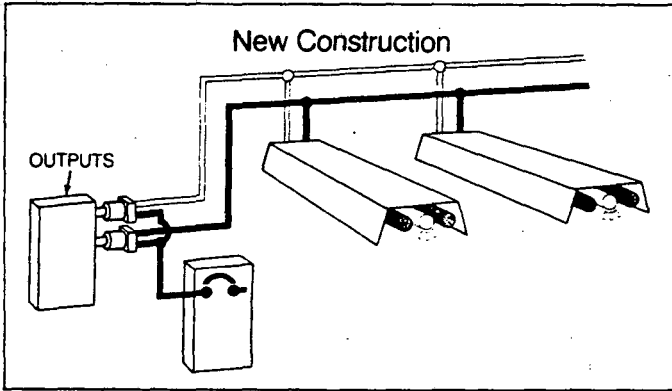
#### **LIFE CYCLE COST ECONOMICS**

Assuming a total lighting load of 1.5 watts per square foot, an operating schedule of 4000 hours per year, and an energy cost of \$0.085/kWh, lighting energy will cost slightly over \$0.50/square foot/year without added controls. The added installed cost of the control system will be approximately \$0.30/square foot (assuming 2 control points per 1000 square foot control zones at \$150/control point). Conservatively assuming that lighting hours can be reduced 25% (relative to 4000 hours/year operation) with programmable timers would result in a simple payback of 2.4 years.

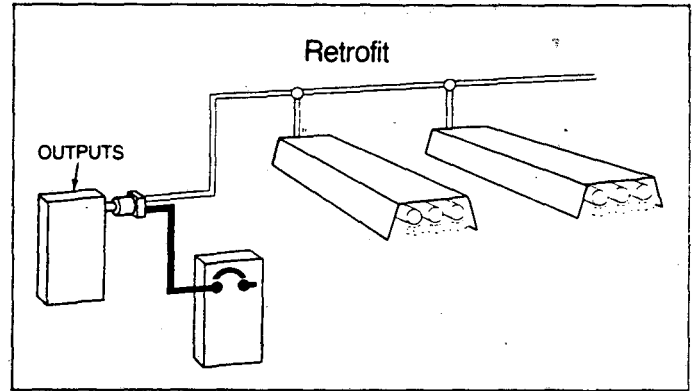
#### **MARKET SHARE, EXPECTED TRENDS**

In the new California Title 24 code for 1992, this type of control will be the minimum automatic control that must be installed in new non-residential buildings. It is expected that this will greatly accelerate the market share for this type of technology.

Multiple Level Control Provides Maximum Flexibility  
(Recommended zone size ... 1000 sq. ft. with two relays per zone)



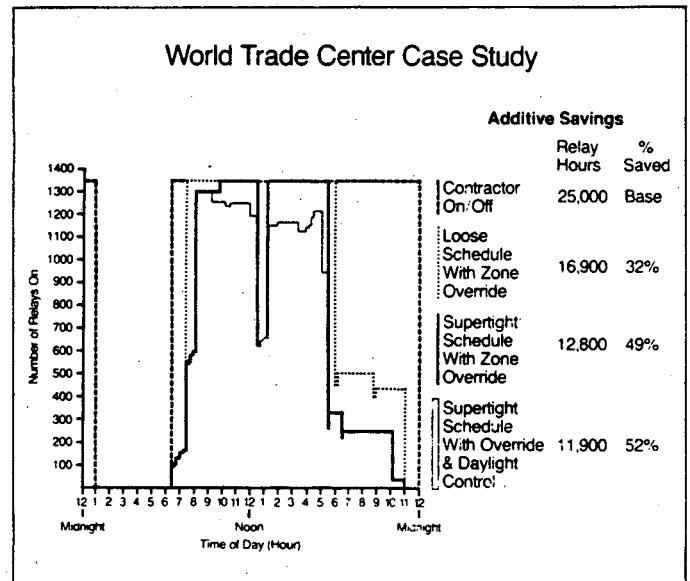
Retrofit Application Typically Limited to ON/OFF Control by Circuit





## Lighting Control Impact on Energy Usage

The impact will vary by application, but savings of 20-50% are common. Primary savings occur from the occupancy control function as documented in an experiment at the World Trade Center funded by the Department of Energy. The baseline operation was provided by lighting contactors controlled by the building automation system. Providing multiple level control of 1000 sq. ft. zones allowed tight scheduling *when coupled with simple telephone override for the occupants*. At a projected cost of \$0.30/sq. ft., this degree of control showed a payback of less than one year.



## **“SMART” SWITCHES DATA SHEET**

### **DESCRIPTION**

Remotely-controllable switches (“smart” switches). These switches are installed in wall-boxes like any other wall switch. However, unlike a wall switch, these switches turn off their load when the power flowing to them is interrupted for 5 seconds. Thus, one can turn off a whole circuit of “smart switches” by switching off the branch circuit for 5 seconds and then restoring power. The smart switch becomes a very effective override if the branch circuit is controlled using low-voltage controlled relays. When an entire branch circuit is swept off by means of a programmable relay, then the individual in an occupied space can restore his lights simply by switching on their smart switch. Furthermore, they only affect their own local area, not the entire circuit.

### **SOURCES**

Sentry Switch is the only vendor known of this type of switch.

### **PROS AND CONS**

This switch is an effective means for overriding the lights when used in conjunction with programmable timers. It is probably superior to the use of either telephone override systems or low-voltage switches because local switches are often required by code anyway.

There are two disadvantages of this technology when used in conjunction with programmable timers. First, if the lighting system is not “split-wired” (see section on programmable timers for discussion of this), then there is the possibility that the occupant may be plunged into darkness when the programmable controller sweeps the lights off. This effect is mitigated somewhat by the fact that the switch illuminates when then input is turned off allowing the individual to locate it more easily. The second disadvantage is that this system no longer allows the programmable timer system to serve as an auditor since the controller only knows whether a relay is open or closed; not whether there is actually any load on it.

### **ENERGY PERFORMANCE**

See section on programmable timers.

### **IMPACT ON BUILDING DESIGN**

See attached figure from Sentry Switch applications sheet illustrating typical installation of this technology.

### **COST, PER UNIT BASIS**

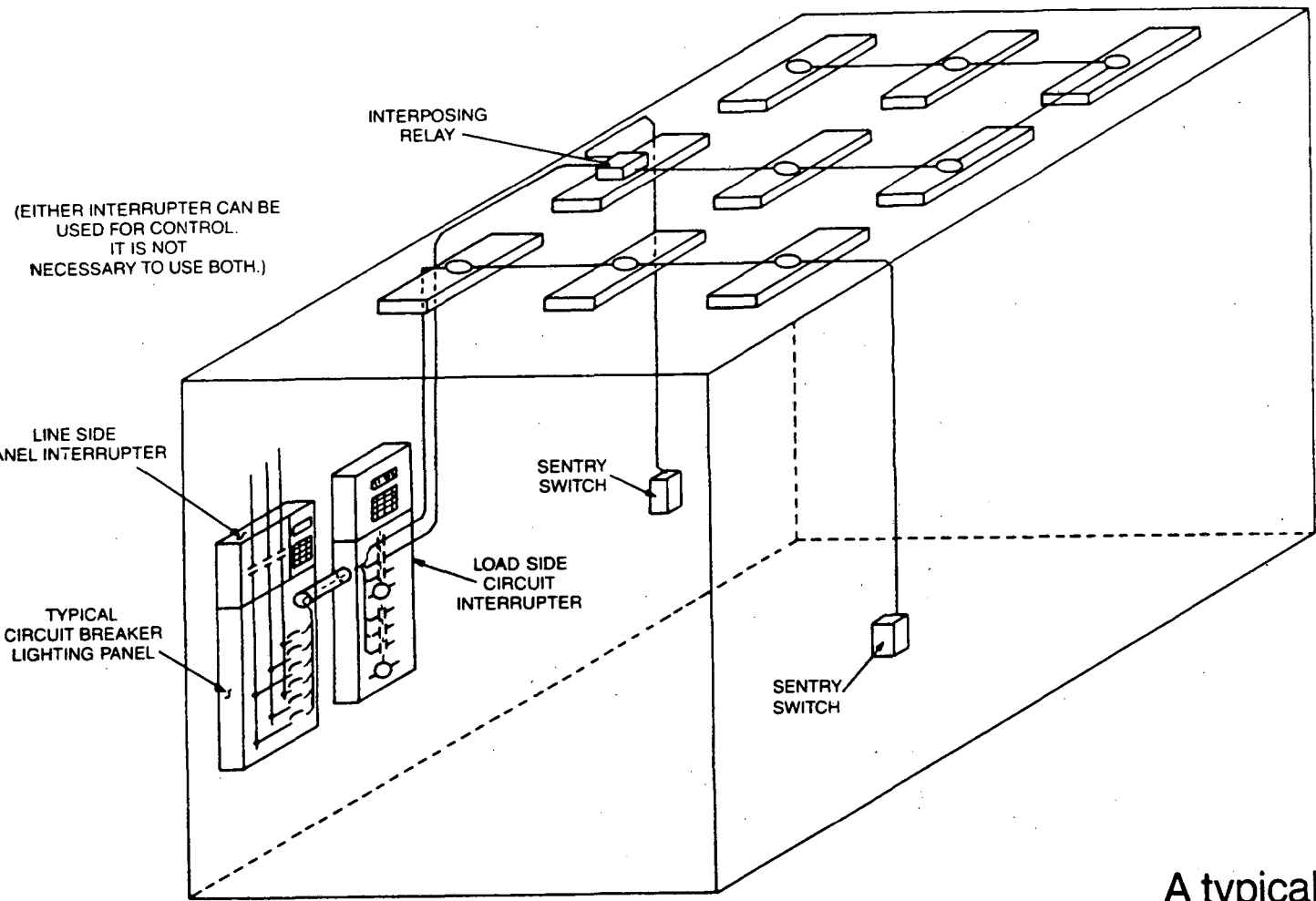
The Sentry Switch costs \$30 each if purchased in quantity. Installation costs are the same as for a regular wall switch. Note also that in California, Title 24 building code waives the requirement for dual switching control if a Sentry switch is installed. This could be a significant savings in labor (though not in equipment since standard wall switches are very inexpensive).

### **LIFE CYCLE COST ECONOMICS**

See section on programmable timers.

### **MARKET SHARE, EXPECTED TRENDS**

With the new California Title 24 standard, the market share for products of this genre will likely increase dramatically.



A typical  
**SENTRY SWITCH**<sup>™</sup>  
 lighting system  
 installation

## OCCUPANT SENSORS DATA SHEET

### DESCRIPTION

Occupant sensors are essentially switches that are activated by detecting the presence or absence of people in the field of view. There are two basic types of occupant sensor: passive infrared sensing and ultrasonic. This is a relatively mature technology that is supplied by many vendors.

Most recently, one company offers a occupant sensor with both infrared sensing and ultrasonic sensing capabilities. This combination is supposed to assure reliable operation without false triggering.

In addition to the specific sensing technology, there are two mounting configurations: ceiling- and wall-mounted. The ceiling-mounted sensors typically activate a low-voltage relay that is in series with the lighting load that is controlled. This sensor also needs to be provided with power, typically from a 24 volt DC circuit. Some wall-mounted occupant detectors have photocell control too. With these, the lights will not switch on if the daylight level is above some (adjustable) level even if the room is occupied. However, the location of the photocell in a wall switch is a poor location for determining the illuminance at the task. Thus this capability must be used with caution.

With all occupant detectors, it is very desirable to be able to control both the sensitivity and the time delay of the detector. It should be noted that California Title 24 regulations require this.

Some occupant sensors are designed so that they only turn lights off, not on. These sensors require that occupant take action to switch on their lights when entering the room. The sensor will turn off the lights a desired time interval after last detecting movement. This technique is somewhat more efficient than fully automatic control since the occupant may sometimes be present but not turn on their lights (either because of the presence of daylight or because the task being performed at that particular time does not require additional lighting).

### SOURCES

(See attached list from Energy Users News)

### STATUS OF AVAILABILITY

This is a relatively mature technology with products being offered by many companies (see attached list from Energy Users News).

### PROS AND CONS

Correctly applied, occupant sensors are the most efficient method to prevent lighting usage in unoccupied spaces. But the placement of occupant sensors (i.e. in wall switch panel or in ceiling) is important and is often done incorrectly. Wall-mounted switches are more easily installed but their field of view is usually more restricted. These devices don't always work properly in partitioned spaces (especially the IR type which are line-of-sight devices). Ultrasonic types work better in partitioned areas but are somewhat more sensitive to false triggering due to vibrations, etc.

If an incorrectly applied wall-mounted occupant sensor contains a manual override, the occupant can easily disable automatic operation, negating the effectiveness of the sensor.

Anecdotal evidence suggests that some occupants do not like having their lights off when their space is unoccupied presumably because it is easier for their co-workers to know that they are not present.

### ENERGY PERFORMANCE

Energy savings potential is highly dependent on baseline assumptions and operation but values of 35% are typical and probably conservative. Occupant sensors are more cost-effective than programmable timers in spaces that are randomly occupied but less cost-effective if usage is more predictable. Occupant sensors are available that are capable of detecting signals over very large area (1,500 sq. ft.). But this is usually not useful because of line-of-sight limitations.

#### **IMPACT ON BUILDING DESIGN**

Occupant sensors have relatively little impact on building design since they can generally be used instead of a standard wall switch.

#### **COST, PER UNIT BASIS**

See attached list from EUN.

#### **MARKET SHARE, EXPECTED TRENDS**

The market share of this technology will probably expand at a good rate since they are a relatively simple but effective controls technique that can be easily understood and installed by electricians.

#### **CASE STUDY INSTALLATIONS**

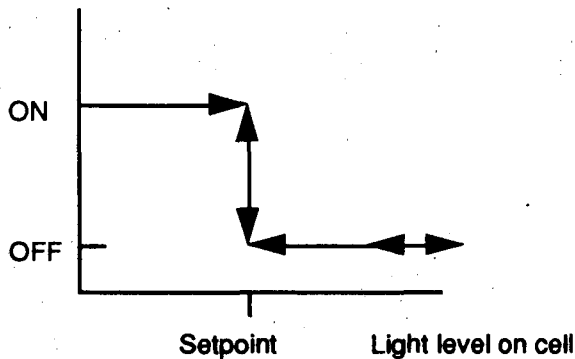
Occupant sensors installed at the World Trade Center reduced lighting energy use by 50% compared to circuit breaker control. An installation at another New York office building indicated a 25% energy savings compared to operation with manual wall switches.

## PHOTO-SWITCHES DATA SHEET

### DESCRIPTION

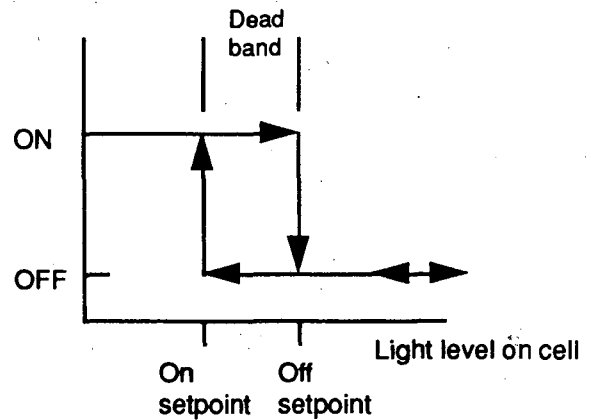
Photo-electrically controlled switches can be used to switch off lights in daylight perimeter zones. These can be field adjusted to control the light level at which they switch (Figure A). These switches usually incorporate a "dead-band" (Figure B) so that the lights will not "hunt" between levels if the ambient light level is near the sensor trip level.

State of lights



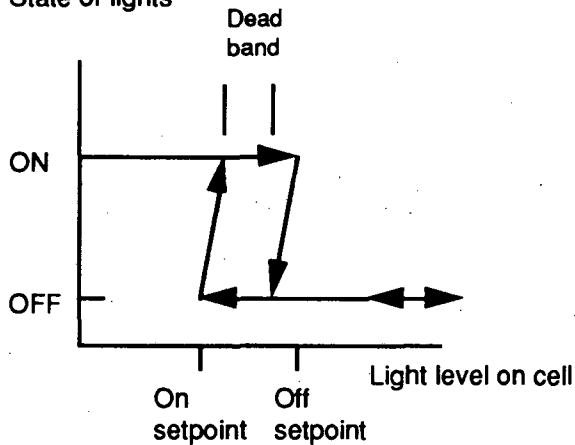
**A** Response of simple photo-switch without deadband; cell sensitive to controlled light

State of lights



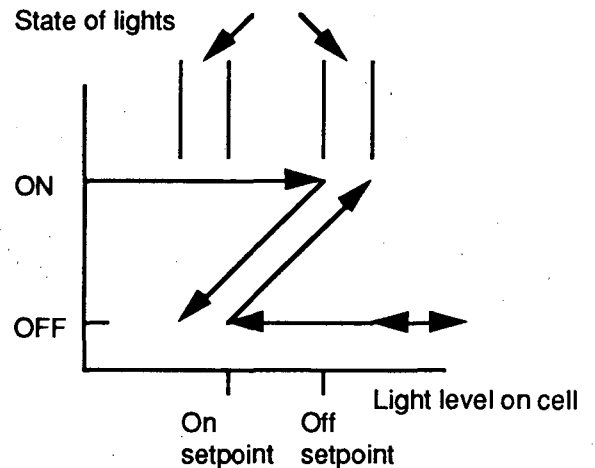
**B** Response of photo-switch with deadband; cell insensitive to controlled light

State of lights



**C** Response of photo-switch with deadband; cell sensitive to controlled light. System stable but effective deadband decreased

State of lights



**D** Response of photo-switch with compromised deadband; cell sensitive to controlled light and conditionally unstable

Some also allow the user to adjust a time delay constant that also reduces the likelihood of hunting. These switches have significant savings potential in new construction where the wiring can be done correctly (probably 50% in those areas where it is applicable). Switches installed on a fixture-by-fixture basis may be cost-effective in retrofit situations, but the ability to switch banks of lights (which is less costly than individual control) is largely constrained by the existing branch circuit wiring.

Photo-switches can be configured so that the switch will only turn lights off, not on. In this mode, the occupant entering the space would have the choice as to whether or not to turn on their lights depending on the amount of available daylight. The photo-switch would then turn off lights if the daylight detected was greater than the setpoint level. This may be an efficient method to control the lights with respect to daylight availability, especially since no light would be provided if the occupant does not consider it necessary. On the other hand, it is important to set the "off" setpoint sufficiently high that the automatic control does not "contradict" the user's preferences.

#### **SOURCES**

Surprisingly few manufacturers produce this type of switch for building interior applications although they are commonly used in streetlights and parking lots. Precision Multiple Controls makes these switches for exterior applications as well as one for interiors. Conserval (a Canadian company) has photoswitches that can be installed on a fixture by fixture basis or, when used with relays, can switch an entire circuit.

#### **PROS AND CONS**

Photo-switches are an inexpensive method to implement light level switching based on the amount of ambient daylight. But studies suggest that occupants do not like having their lights switch on and off during the day. Thus photo-switches should not be used in occupied spaces unless the daylight levels are very high throughout the entire course of the day. In this case, the lights will be off during the day anyway and the occupants will not be bothered by the lights cycling. If the photocell can detect the electric light that it controls, though, (as might be the case of a photo-switch that is wall-mounted), the deadband can be compromised (Figure C). If the detected light level change caused by the lights switching on and off is large enough (Figure D), there can even be light levels at which the system will be unstable. This will cause the lights to "hunt" between on and off states until the ambient light level increases enough to bring the system out of the unstable region.

One advantage to photo-switches compared to dimming systems is that lights that are switched off by a photo-switch consume no electric energy while most dimmers continue to consume power even when maximally dimmed.

#### **IMPACT ON BUILDING DESIGN**

Photo-switches are most effective when applied to the outermost row of lights. Thus it is important to wire these fixtures on separate circuits from other lights if photo-switch is to be used to control several lights (thus reducing initial cost).

#### **COST, PER UNIT BASIS**

Costs: The Conserval switch sells for about \$25 in quantity.

#### **MARKET SHARE, EXPECTED TRENDS**

This is currently such a small market that it will likely expand as manufacturers identify new market opportunities.

## DYNAMIC CONTROLS DATA SHEET

### DESCRIPTION

This control sub-category refers to add-on control devices that allow the dimming of light sources operating with standard magnetic ballasts. Unlike electronically-ballasted dimming systems, dynamic controls usually have only a limited dimming range. These systems though are available in many sizes and configurations. On the largest scale, there are autotransformer-based systems that can dim entire phases (i.e. several kW) of lighting circuits. Depending on the connected load, auto-transformer based systems can dim from full light output to 75-80% of full. There are many dynamic control systems configured to dim individual branch circuits (20 amps maximum). These generally dim standard ballasts from 40% to full light output. Input power is typically proportional to light output over the operating range. Finally, there are dynamic controls that dim small groups of fixtures (typically 4-8 lamps total) or individual ballasts. These small block systems often have somewhat larger dynamic range; one system can dim to about 30% of full light output.

Except for controls systems that work at the individual fixture level, most of these control systems can accept inputs from a building EMS system or a specialized lighting control system. These are most often useful for implementing scheduling control, i.e., reducing lighting loads after main operating hours. Many also accept analog inputs such as from a photocell or building demand monitor.

### SOURCES

Peschal Energy produces autotransformer-based systems for most available light sources, i.e., fluorescent, HID, etc.

### PROS AND CONS

The autotransformer-based controls work by lower the input voltage to the load. To get a decent dimming range often requires taking the input voltage outside the range allowed by the equipment manufacturer's warranty. End-users should verify that warranties are not being voided by using this equipment.

Branch circuit based controls and individual ballast controls, usually accomplish dimming by "wave-chopping". This technique can result in the introduction of harmonics onto the building distribution system. It may also compromise the power factor of the installation. Usually, these techniques are applied to a sufficiently small percentage of the entire lighting load that the added harmonics are not a problem. However, in older buildings with undersized neutral wires, the introduction of large amounts of third harmonic may result in overloading of the neutral. Calculations must be performed by a qualified engineer to ascertain whether a problem may exist.

Many of these systems cause the filament voltage in the fluorescent lighting systems to be reduced out of ANSI-specified range (2.5 - 3.5 volts). There is some concern that lamp life may be sacrificed if fluorescent lamps are operated for long periods at reduced filament voltage.

### ENERGY PERFORMANCE

When used for fluorescent lighting systems, dynamic controls reduce light output in direct proportion to the reduction in input power.

### IMPACT ON BUILDING DESIGN

If large block dimmers are used for new construction, it is important to consider how the lighting system is circuited to use dynamic controls effectively. Lighting fixtures should be zoned according to the control strategy implemented. Thus fixtures in similarly daylit areas should be on one circuit.



**COST, PER UNIT BASIS**

Branch circuit based dimming controls are available for \$700-\$1000 per branch circuit.  
Individual or group control systems generally cost \$50-\$100 not including labor costs.

## STATIC CONTROLS DATA SHEET

### DESCRIPTION

This category refers to controls that reduce light output and input power to one level only. These devices are also offered in a range of sizes. The largest of these systems can be used to reduce the light levels of an entire branch circuit. The small systems usually operate only one ballast or individual lamp.

### SOURCES

Sylvania makes a lamp called the "ThriftMate" that lowers the light output and input power of both lamps of a two-lamp ballast to 33 or 50%. Several companies make gadgets that can be slipped in between the lampholder and the fluorescent pins to reduce the input power. A few companies also make devices that are connected upstream of the ballast to reduce the input power draw of the connected ballast.

### PROS AND CONS

These systems are effective at reducing power usage but they may negatively affect the appearance of lighting fixture by making it appear less uniform and dimmer.

### ENERGY PERFORMANCE

When used for fluorescent lighting systems, static controls reduce light output in direct proportion to the reduction in input power.

### IMPACT ON BUILDING DESIGN

These devices are generally only appropriate for retrofitting into existing buildings that are overlit. These devices are not appropriate for new construction where the light provided should be calculated correctly so that light reduction equipment is unnecessary.

## **DIMMABLE ELECTRONIC BALLASTS DATA SHEET**

### **DESCRIPTION**

Dimmable ballasts for fluorescent lights represent state-of-the-art in lighting controls. With dimming ballasts, light levels can be varied between 15% (typical) and full light output. Dimming ballasts are available as magnetic or electronic ballasts. However, the electronic dimming ballasts have many distinct advantages over the core-coil technology. In particular, electronic dimming ballasts are well-suited to low-voltage control; thus the control wiring can be implemented with less costly Class II wiring. (With dimming core-coil ballasts, the dimming is accomplished using "high-power" switching. This results in greater initial cost to install the controls).

### **SOURCES**

Dimmable electronic ballasts are available from ETTA, Advance, and Lutron. All these vendors also offer dimming for T-8 systems as well.

Dimming magnetic ballasts have been available from major ballast manufacturers for many years (Universal and Advance).

### **STATUS OF AVAILABILITY**

Electronic ballasts are generally in short supply with lead times of several months not uncommon.

There are no known suppliers of dimmable ballast of T-8 lamps that allow individual control.

### **PROS AND CONS**

Dimming ballasts are generally slightly less efficient even at full output than dedicated systems. This is generally because of the extra power required to keep the lamp filaments at the appropriate temperature over all dimming conditions.

### **ENERGY PERFORMANCE**

Most lighting systems suffer some degradation in efficiency when they are dimmed. With fluorescent lighting systems, this is unavoidable especially at heavily dimmed levels because it is necessary to maintain nearly full filament voltage even when the source is dimmed.

### **IMPACT ON BUILDING DESIGN**

The dimming range of the proposed lighting system should be considered in the building design process. Few systems dim to 0% light output although many dim to 20%. It may be desirable to switch off lights that are heavily dimmed for long periods of time since parasitic losses are highest under these conditions.

The choice of control strategy(ies) should be a major determinant for selecting the appropriate lighting hardware and technique. However, this is young field with relatively little written on approaching this problem from a procedural standpoint.

### **COST, PER UNIT BASIS**

A dimmable electronic ballast is currently about \$45-55. Most industry experts would agree that in a mature market, the cost could drop to \$25 - \$30. Dimmable magnetic ballasts are also available (and have been available for many years) at similar prices.

### **MARKET SHARE, EXPECTED TRENDS**

This market will likely expand as end-users start demanding highly efficient lighting control systems. At the present time, Advance is the only large manufacturer of dimming electronic ballasts.

### **CASE STUDY INSTALLATIONS**

A recently-concluded study that was sponsored by PGE R&D at a building in Emeryville demonstrated that an electronically-ballasted lighting control system exploiting all lighting control strategies can save over 50% compared to the usage without the controls.

## SCOTOPICALLY RICH LIGHTING DATA SHEET

### DESCRIPTION

Recent research suggest that it should be possible to reduce lighting energy requirements for many tasks by the use of light sources whose spectral output is rich in the blue-green wavelengths. Previously, photometric brightness as determined using a photopic response curve (the spectral sensitivity curve of the cones in the human eye responsible for day-time adapted vision) was thought to be the primary determinant of visual performance at interior light levels. Light sources producing whitish light but with different spectra were thought to be visually equal provided they produced equal luminances. Photopic luminance is measured with a common "color-corrected" light meter.

However, research at LBL demonstrated that, when viewing under full field conditions at typical interior light levels, the pupil size is largely determined by the *scotopic* response curve - the spectral sensitivity curve of the rods in the human eye responsible for night-adapted vision. Previously, the rods were thought to have negligible effect on visual performance at typical interior light levels.

The smaller pupils caused by blue-green rich sources are thought to allow energy efficiency gains in two ways since pupil size affects both depth of field and visual acuity. (Visual acuity is the ability to resolve fine detail. Depth of field is the ability to maintain objects in good focus over a range of object distances.) LBL findings suggest that the energy requirements for lighting a space can be decreased by trading off lumen output (and therefore energy cost) against increased scotopic content of the source. Thus, with a scotopically rich source, the same pupil size could be obtained by using less photopic light (and therefore consuming less power) than a source that is deficient in the blue. This can be done either by using existing lamps that are scotopically rich or designing new lamps that are optimized to provide more scotopic lumens while preserving color rendition and good photopic efficacy.

### SOURCES

Lamps developed specifically for scotopic richness have yet to be developed. But some lamps currently available, namely the 5000 °K rare earth, tri-phosphored lamp (Philips Ultralume 5000) are relatively rich scotopically. Other specialty lamp manufacturers also offer the 5000 K lamp. Note that "daylight" fluorescent lamps are also scotopically-rich as well as most sources of higher color temperature (such as natural daylight).

### STATUS OF AVAILABILITY

### PROS AND CONS

A number of poorly understood past studies on visual performance and brightness perception can be readily explained in terms of scotopic sensitivity (Berman 1991). Effective pupil lumens can be determined for full field of view if the spectrum of light entering the eye is known. For surfaces with broad spectral reflectivity this spectrum is approximately that of the illuminating light source. Brightness perception is also dependent on the scotopic context of the illumination (Berman et al 1990) but the precise combination of the relative contributions of photopic and scotopic luminance has yet to be determined. Full field scenes with variable luminances have also not been studied but since pupil size and brightness perception are rather coarse measures of visual response, average luminance is expected to be the primary determinant.

### ENERGY PERFORMANCE

Based on Berman's model, effective pupil lumens are equal to  $P(S/P)EXP.78$  where P and S are photopic and scotopic luminances based on the spectral distribution of the light source. Using this model, four fluorescent light sources were evaluated as indicated in Table 1. In

comparison with a cool white lamp, A 5000 K tri-phosphor lamp uses 24% less energy to maintain the same pupil size compared to a cool white lamp. A scotopically-enriched rich lamp would require 31% less energy.

**Table I**  
**(40 Watt Fluorescent Lamps)**

<u>Lamp</u>	<u>Photopic Lumens</u>	<u>Scotopic Lumens</u>	<u>Effective Pupil Lumens [P(S/P).78]</u>	<u>Relative Power Level for Equal Pupil Sizes</u>	<u>Pupil Lumens Per Watt</u>
Warm White Fluorescent (WW)	3200	3100	3125	136	78
Cool White Fluorescent (CW)	3150	4630	4254	100	106
Narrow Band Phosphor Fluorescent (5000°) [NB(5000)]	3300	6468	5578	76	139
Scotopic Rich Narrow Band (SR-NB)	3000	7500	6130	69	153

Source: Berman, Energy Efficiency Consequences of Scotopic Sensitivity, Proceedings of the 1991 National Illuminating Engineering Society, Montreal.

High color temperature rare-earth phosphor lamps (tri-phosphor lamp) are scotopically rich and energy efficient. It is proposed that an even richer scotopic lamp be developed by adding a phosphor having a sharp emissive peak at 508 nm (the scotopic response function peak) to a high temperature tri-phosphor lamp. Thus high CRIs should be maintained although cooler temperatures will be standard. This may pose problems for applications where a warm color temperature is desired.

#### IMPACT ON BUILDING DESIGN

Because scotopically rich lamps can elicit the same pupil size as scotopically-poor lamps with less input power, a 4-lamp fixture with 4 40 watt cool white lamps could be replaced by 3 40 watt scotopically rich lamps (Berman 1991). This would result in a 24% drop in installed lighting load. There will also be a cost reduction associated with using fewer lamps, ballasts, and smaller fixtures.

#### MARKET SHARE, EXPECTED TRENDS

Accumulating evidence about the eye's scotopic sensitivity under interior light conditions may promote lamp manufacturers to make scotopically rich lamps simply by incremental improvements to existing technologies. But it is difficult to estimate future market directions until the benefits of scotopically rich lighting are more generally recognized.

## POLARIZED LIGHTING DATA SHEET

### DESCRIPTION

It has long been known that light polarized in the vertical plane is not well reflected from specular horizontal surfaces if the angle between the incident light and the surface normal are close to  $57^\circ$  (Brewster's angle). At this angle, no vertically polarized light from the incident beam will be reflected by a shiny horizontal surface. This means that the veiling reflections caused by overhead light striking a horizontal task surface can be largely eliminated. Since veiling reflection impairs visual performance by reducing contrast, vertically polarized light could be supplied at a lower light level (and therefore use less power) than unpolarized lighting systems while preserving visibility.

### SOURCES

1. Polarized International Inc.
2. PCTechnologies

### STATUS OF AVAILABILITY

Polarizers for commercial lighting systems typically consist of 2x4 sheets of a special panel that fits above the standard lens in a regular fluorescent fixture. In addition, polarizing panels that replace the standard fluorescent diffuser are available.

### PROS AND CONS

Polarized lighting may well allow equal visibility to be achieved for some tasks with lower lighting energy use than a non-polarized lighting system.

However, the benefits of the polarized lighting effect depend strongly on the geometry of the lighting system, the viewing direction and nature and orientation of the task surface. Polarized lighting is most beneficial at an angle ( $57^\circ$ ) that is considerably higher than the normal viewing angle ( $20^\circ$ ). At the normal viewing angle, the benefits of vertically polarized light are significantly reduced, though not entirely eliminated. A recent study at LBL (Clear and Berman, "Polarization and Glare on VDUs and Other Tilted Specular Surfaces", Proceedings of the Illuminating Engineering Society, 1991) showed that there were no direct benefits of vertically polarized lighting for reducing glare on computer screens. This study, though, did not examine the effects on horizontal tasks.

The visibility of certain types of industrial tasks (viz. identifying vernier marks on a metallic, horizontally oriented cylindrical device or machine) may be significantly improved with vertically polarized light because of the geometry. But more work is required to identify what tasks and orientations are most benefitted by polarized light and to what degree.

It should be noted that commercial polarizers only partially polarize the light emitted from the fixture. As shown in the attached product sheets, of all the light emitted by the polarized luminaire above  $30^\circ$  (where polarized lighting would be most effective), only 66% of the lumens were vertically polarized; the remaining lumens were horizontally polarized producing no effect.

### ENERGY PERFORMANCE

Without further research, it is not possible to state what the energy savings benefits are of vertically polarized lighting.



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