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Achieving energy efficiency with lighting technology : an end user's guide

M. Scott Gould
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Gould, Myron Scott, M.S.

San Jose State University, 1991

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**ACHIEVING ENERGY EFFICIENCY WITH LIGHTING TECHNOLOGY:
AN END USER'S GUIDE**

**A THESIS SUBMITTED TO
THE FACULTY OF THE DEPARTMENT OF ENVIRONMENTAL STUDIES
SAN JOSE STATE UNIVERSITY
IN CANDIDACY FOR THE DEGREE OF MASTER OF SCIENCE**

**BY
M. SCOTT GOULD**

DECEMBER, 1991

APPROVED FOR THE DEPARTMENT OF ENVIRONMENTAL STUDIES

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ABSTRACT

ACHIEVING ENERGY EFFICIENCY WITH LIGHTING TECHNOLOGY: AN END USER'S GUIDE

by M. Scott Gould

Products designed to reduce lighting energy consumption are of particular interest to facility engineers, lighting designers, and energy management professionals. Products such as electronic ballasts, occupancy sensors, and dimming systems are continually developed and refined, yet insufficient field data are made available to the end user. Sparse data exist on the effect that these products have on the building occupants and on building systems. This thesis briefly reviews lighting technologies, and then defines lighting product impact parameters such as system operation, maintenance, aesthetics, safety, occupant comfort, and potential for energy savings. Recommended (or tolerable) values for these parameters are given, followed by an illustrative evaluation of lighting products available in 1991 in view of these characteristics and recommended values. The thesis concludes with reprints of recent professional journal articles on these subjects by the author of this thesis.

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TABLE OF CONTENTS

	Page
ABSTRACT	iii
COPYWRITE.....	iv
ACKNOWLEDGMENTS	v
TABLE OF CONTENTS.....	vi
LIST OF ILLUSTRATIONS	viii
LIST OF TABLES	ix
LIST OF ABBREVIATIONS	x
GLOSSARY	xi
CHAPTER 1 INTRODUCTION	1
Research Statement.....	1
Background	1
The Quantity and Quality of Light	5
Scope of the Thesis.....	6
Qualifications of the Researcher.....	7
CHAPTER 2 RESEARCH METHODOLOGIES.....	8
Data Analysis and Interpretation.....	8
Performing Energy Savings Calculations	10
Performing Economic Payback Calculations.....	11
CHAPTER 3 FULL-SIZED FLUORESCENT LAMPS	12
What is a Fluorescent Lamp?	12
Types Of Fluorescent Lamps.....	13
Lamp Life	13
Effects of Temperature on Fluorescent Lamp Output	14
Energy-Saving Lamps	16
T-10 Fluorescent Lamps.....	16
T-8 Fluorescent Lamps.....	17
Savings Calculations Methods.....	17
Impact Analysis	18
Summary of Important Criteria for Fluorescent Lamp Selection	18
CHAPTER 4 COMPACT FLUORESCENT LAMPS	22
Savings Calculation Methods.....	24
Impact Analysis	24
Aesthetics, Safety, and Comfort Issues	27
Industry Directions.....	28
CHAPTER 5 OPTICAL REFLECTORS	31
Introduction.....	31
Materials Used to Construct Optical Reflectors.....	32
Reflector Design	34
Savings Calculation Methods.....	35
Impact Analysis	37

	Aesthetics, Safety, and Comfort Issues	39
	Case Study: Stanford University Cummings Art Building	39
	Industry Directions.....	40
	Summary of Important Criteria for Optical Reflector Selection	41
CHAPTER 6	ELECTRONIC BALLASTS.....	42
	Savings Calculation Methods.....	44
	Impact Analyses	44
	System Operation.....	45
	Aesthetics, Safety, and Comfort Issues	47
	Maintenance Considerations	48
	Industry Directions.....	50
	Summary of Important Criteria for Electronic Ballast Selection	51
CHAPTER 7	OCCUPANCY SENSORS.....	53
	Manual Control v. Occupancy Sensors.....	53
	Types of Occupancy Sensors.....	54
	Savings Calculation Methods.....	55
	Impact Analyses	57
	Wall Switch Sensors.....	61
	Case Study: Stanford University Mudd Chemistry Building	63
	Industry Directions.....	65
	Summary of Important Criteria for Occupancy Sensor Selection	66
CHAPTER 8	TOWARD A SYSTEMS APPROACH.....	68
	Combining Lighting Technologies	68
	Lighting Efficiency in New Construction	68
	The Future of Lighting Efficiency	69
	BIBLIOGRAPHY	71
	APPENDIX A.....	76
	CONVENIENT SOURCES OF INFORMATION.....	76
	Organizations and Publications.....	76
	Manufacturers Index.....	77
	APPENDIX B.....	78
	"Out of the Mechanical Room and Into the Work Place: How to Get Employees to Conserve Energy"	78
	APPENDIX C.....	79
	"Cautious Application of Electronic Ballasts"	79
	APPENDIX D.....	80
	"Lighting and Energy Conservation: A Review of Current Technologies"	80
	APPENDIX E.....	81
	"Using Submetering and Computer Modeling to Verify Energy Savings in New Construction"	81

LIST OF ILLUSTRATIONS

Figure	Page
1. Temperature v. Light Output of Fluorescent Lamps.....	15
2. Typical Efficacy Values for Fluorescent Lamps and Ballasts.....	19
3. Lamps Efficacy Gain v. Operating Frequency.....	43
4. Large Room Occupancy Sensors--Cost v. Simple Payback.....	58
5. Wall Switch Occupancy Sensor Hours off Required for a Two Year Payback	62

LIST OF TABLES

Table	Page
Table 1. Typical Compact Fluorescent Lamp Performance.....	23
Table 2. Power Factor of Common Fluorescent Lamps	26
Table 3. Typical Wattage Reductions from Installing Optical Reflectors.....	36

LIST OF ABBREVIATIONS

CBM	Certified Ballast Manufacturers
CRI	Color Rendering Index
EMI	Electro-Magnetic Interference
EMS	Energy Management System
EPA	Environmental Protection Agency
EPRI	Electric Power Research Institute (Palo Alto, CA)
<u>EUN</u>	<u>Energy User News</u>
HID	High Intensity Discharge
HVAC	Heating, Ventilation, and Air Conditioning
Hz	Hertz
IEEE	Institute for Electrical and Electronic Engineers
IES	Illuminating Engineering Society of North America (New York, NY)
IRR	Internal Rate of Return
LED	Light Emitting Diode
NPV	Net Present Value
PCBs	Poly Chlorinated Biphenyls
PG&E	Pacific Gas and Electric Company (San Francisco, CA)
ROI	Return on Investment
SI	International System of Units (<i>Système international d'unités</i>)
VDT	Video Display Terminal

GLOSSARY

Ballast. A device used with a fluorescent or HID lamp to provide the necessary circuit conditions for starting and operating by modifying the incoming voltage and current.

Ballast Efficiency Factor (BEF). The ratio of the relative light output to the input watts of the ballast.

Bulb. Glass outer envelope portion of a lamp.

Chromaticity. The aspect of color that includes consideration of the dominant wave-length and purity.

Color Rendering. General expression for the effect of a light source on the color appearance of objects in conscious, or subconscious, comparison with their color appearance under a reference light source.

Color Temperature. The absolute temperature of a blackbody whose chromaticity most nearly resembles that of the light source.

Current Crest Factor. The ratio between the peak current during the alternating current half-cycle to the root mean square (RMS) current value during the half-cycle. A non-standard crest factor can result in short lamp life.

Delamping. In overlit areas lamps can be removed from fluorescent fixtures to reduce energy consumption. Usually this means removing one lamp from a three-lamp fixture or two lamps from a four-lamp fixture.

Diffuser. A device commonly put on the bottom and sides of a fixture to redirect or spread the light from a source. It is used to reduce the brightness of the source and, in many cases, to control the direction of light emitted by the fixture.

Dimmer. A device used to control the intensity of light emitted by a luminaire by controlling the voltage or current available to it.

Efficacy. The ratio of light output from a lamp to the electrical power used, expressed in lumens per watt (l/w).

Efficiency. The ratio of the useful energy delivered by a dynamic system to the energy supplied to it.

Fixture. See Luminaire.

Fluorescent lamp. A low pressure mercury electric-discharge lamp in which a fluorescing coating (phosphor) transforms ultra-violet light energy generated by an arc discharge into light.

Footcandle. A quantitative unit for measuring illuminance; the illumination on a surface one foot square on which there is a uniformly distributed flux of one lumen.

Glare. Any brightness or brightness relationship that annoys, distracts, or reduces visibility.

Internal rate of return (IRR). The internal rate of return is the interest rate received for an investment consisting of payments and income that occur at regular periods.

Illuminance. The density of the luminous flux incident on a surface.

Lamp. A generic term for a man made source of light. By extension, the term is also used to denote sources that radiate in regions of the spectrum including, or adjacent to, the visible.

Lens. A glass or plastic element used in luminaires to change the direction and control the distribution of light rays.

Lumen. The SI unit of luminous flux.

Luminaire. A complete lighting unit consisting of a lamp or lamps together with the parts designed to distribute the light, to position and protect the lamps, and to connect the lamps to the power supply.

Luminaire Efficiency. The ratio of lumens emitted by a luminaire to that emitted by the lamp or lamps used therein.

Luminance. The luminous intensity of any surface in a given direction per unit area of that surface as viewed from that direction. All visible things have some luminance.

Luminous Flux. The time rate of flow of light.

Lux. The SI unit of illuminance (one lux is one lumen per square meter).

Net Present Value (NPV). Net present value computes the present value of a series of future cash flows, discounted at a fixed periodic interest rate.

Reference Ballast. A ballast that is specifically constructed, having certain prescribed characteristics and that is used for testing electric-discharge lamps and other ballasts.

Reflectance. The ratio of the light reflected by a surface or medium to the light incident on it.

Reflected Glare. A glare resulting from specular reflections of high luminance in polished or glossy surfaces in the field of view.

Task Lighting. Lighting directed to a specific surface or area that provides illumination for visual tasks.

CHAPTER 1

INTRODUCTION

Research Statement

This thesis has been developed as a response to the lack of lighting product data in a form suitable for decision making by the practical end-user. Specific energy-saving lighting products on the market in 1991 have been evaluated, such as electronic ballasts, compact fluorescent lamps, and optical reflectors, as an aid toward developing more universal methods of evaluating these products. Bench testing techniques, computer simulation methodology and more subjective methods of analysis are presented.

Background

In the United States, energy costs consume 30 percent of the operating budget of commercial buildings (Bevington and Rosenfeld 1990, p. 77). These same buildings also have the largest potential for reducing energy consumption. This is not a coincidence. First of all, much of the existing building stock was built when energy costs were not as significant. Second, in many buildings the initial construction costs are considered ahead of long-term operating costs. Finally, because maintenance budgets are generally cut to meet tight budgets, buildings are often not operated as designed.

The EPA claims that if energy-efficient lighting were used wherever profitable, annual savings would amount to \$18.6 billion, annual carbon dioxide

emissions would fall by 232 million tons, and sulfur dioxide emissions would be reduced by 1.7 million tons per year (Geberer 1991, p. 49). As with many statistics, the hugeness of the numbers makes them difficult to comprehend. The important point, however, is that by installing cost-effective, currently available energy-efficient lighting technologies, the United States can go a long way toward reducing its dependence on oil imports and slow the release of harmful gases into the atmosphere.

In describing the huge potential for energy-efficient lighting, it should not be forgotten that many businesses and institutions have already implemented aggressive energy management programs. In order to accrue additional energy savings, energy management projects will require more complete engineering, coordination, and preparation to ensure success, and no longer be able to depend solely on the easy "quick fixes."

It is important to observe at the outset that reducing energy consumption is not the same as reducing comfort. Technologies and implementation techniques now exist for using electricity more efficiently while actually improving services (Fickett 1990, p. 65). In fact, many of the new lighting systems offer less glare, less audible noise, more pleasant color, and reduced flicker. These aesthetic improvements can mean increased visual performance and worker productivity. Since energy costs are significant and the potential for savings high, many companies view energy management as a worthwhile investment. Lighting accounts for the direct consumption of 40 percent of the electrical power load of commercial buildings. In specialized applications such as retail and display lighting, that percentage is often higher.

Current building regulations in California mandate that energy efficient features be included as part of new building and retrofit design, adding to the number of energy efficient products purchased annually. Since these products can require a large capital investment--and therefore must compete with investment or growth funds--project risk must be minimized. But a gap exists in the information available to lighting professionals. Although energy efficiency lighting products are tested, the results are often presented in a format to stimulate sales rather than to be useful to the end user.

Product research most often comes from three sectors: manufacturers, utility-sponsored research firms, and manufacturer-sponsored testing laboratories. Each sector has its own justifiable, separate bias:

- o **Manufacturers:** Manufacturers of lighting products often make available product specifications and performance claims as part of their advertisements or technical catalogs. Often these data highlight only the positive aspects of a product's performance. This is not usually an attempt at fraud, but rather an effort to put their product in the most favorable light.

Another potential problem with manufacturer's data is the lack of a reference standard against which results can be compared. In addition, critical evaluation factors that affect performance are often not standardized, making a comparison of similar products from different manufacturers difficult. These factors combine to make the evaluation of product literature difficult for the end user.

- o **Utility-Sponsored Research Firms:** Another source of information on the performance of lighting products is the utility-sponsored research firm, such as the Electric Power Research Institute (EPRI). Utility-sponsored research

firms collect data and organize research in areas that affect the operation of utilities.

In the case of lighting products, the utilities are primarily interested in learning the effect a particular product or class of products will have on their electric distribution system. For example, several utility-sponsored studies have focused on the electromagnetic interference or other power quality issues that new lighting technologies may present. These studies are not usually intended to be used as end-user product evaluations. Recently, however, EPRI has taken a larger role in developing brochures, information packets, and case studies describing the new lighting technologies to end-users.

- o Independent Research Laboratories: The third group involved in the evaluation of lighting product testing includes independent testing laboratories, such as the Lawrence Berkeley Laboratories Lighting Division. This group issues authoritative papers on all aspects of lighting product performance. Unfortunately, as in many areas where research is done, specific evaluations are only completed when a sponsor is interested in funding a specific research project. The research may also be too technical for many end users.

Despite these different perspectives, lighting products are particularly suitable for a thorough evaluation focused on the end-user. Lighting projects can often be implemented by non-technical facilities personnel or designers if the proper evaluation materials exist. There are two advantages that lighting projects have over heating, ventilating, and air conditioning (HVAC) or building-envelope energy-management projects that might not be so obvious: Electrical savings are generally easier to calculate and to verify with metering; and estimating the savings from a new HVAC control, for example, may involve variables such as

weather, internal heat loads, and occupant temperature preference factors that do not influence lighting project analysis.

The Quantity and Quality of Light

Extensive research is currently being done on the physical and psychological health aspects of artificial lighting. Not only is light important to our health and sense of well-being, but light regulates our biological rhythms, changes moods, and influences productivity (Davis 1987, p. 5). In addition, light is used to treat diseases such as jaundice in newborns, psoriasis, and some forms of depression (Smith 1986, p. 34).

Besides these complex medical relationships, light also influences impressions of a space and sometimes influences behavior (Davis 1987, p. 14). One example of this is the use of stage lighting to set the appropriate mood and focus the attention of the audience. Another example is a retail store with brightly lighted displays to attract customers to specific items.

Different tasks require different light levels in order to be performed safely and effectively. Because of this, the IES (Illuminating Engineering Society) has established guidelines to assist lighting professionals in determining appropriate and consistent light levels for both indoor and outdoor tasks. The following are the primary factors used to set these guidelines.

- o The object being viewed.
- o The age of the observer.
- o The importance of speed and/or accuracy for visual performance.
- o The reflectance of the task (i.e., the background against which the details are seen).

Absolute light levels, however, are only part of the equation. The quality and color of light are perhaps equally important. Two measurements are used to describe the color and quality of lamps. "Color temperature" in Kelvin (K) describes the "warmness" or "coolness" of light. For example, the flame from a wax candle is a very warm color at 1,500K. At the other end of the scale, blue sky is about 8,500K. Fluorescent lamps have color temperatures ranging from 2,700K to 6,300K. The most common lamps sold today are the "warm-white" lamp at 3,000K and the "cool-white lamp" at 4,100K. Warm-white lamps have a tendency to enhance red and orange colors while dulling blue tones. Cool-white lamps do just the opposite by enhancing blues and dulling reds.

Color temperature does not, however, describe the quality of light. The color rendering index (CRI) is used to measure the effect a light source has on the appearance of colored objects. The scale used is zero to one hundred, where one hundred represents a light that displays an object without color distortion or color shift, centered at the color temperature of the lamp. The CRI scale should only be used to compare lamps of similar color temperature, since the way color appears is also affected by the color temperature itself, i.e., the "warmness" or "coolness" of the color image.

Scope of the Thesis

This evaluation will be limited to indoor lighting products that conserve energy and offer a reasonable return on investment. "Reasonable" depends on many factors, including the end-user's liquidity, priorities, and alternative investment opportunities. Products that typically do not return their cost in simple payback energy savings within five years are generally of little interest to corporations or institutions, and therefore are not within the scope of this thesis.

This thesis will not deal with centralized switching schemes or energy control systems (EMS). Although centralized control techniques have been effective in load-shedding applications, the focus of this paper is on the localized application of lighting technologies.

Finally, the use of high intensity discharge (HID) lamps is not considered in this thesis because of some of the inherent properties of the lamp that limit their use in most indoor applications. HID lamps are traditionally used as outdoor lights but can also be found in indoor gymnasium or warehouse applications. Because HID lamps are being developed for a variety of new applications, as well as being reduced in size and with improved color characteristics, readers should watch these developments carefully. It is likely that in the near future HID's will join the stable of available lighting components.

The format of the main body of this thesis is organized to be the most useful to those planning and implementing energy efficiency projects. For this reason, each chapter ends with a one page "tear-out" that summarizes the major decisions to be made before a project is considered.

Qualifications of the Researcher

The research for this thesis is part of the on-going professional work of the author in the lighting energy management field. The recommendations and organization of this thesis represent nine years of investigating, recommending, and implementing lighting projects that save energy. Some of this work has been documented in professional papers that can be found in the appendices. Much of the information, however, has been gained from daily contact with staff electricians, utility representatives, lighting salesmens, and building occupants, all with their unique perspective on lighting projects.

CHAPTER 2

RESEARCH METHODOLOGIES

Data Analysis and Interpretation

The methods used to research a thesis and to prepare for a successful energy management project are essentially the same. Only the scale and depth of the research is different. Typically, this information gathering is done by the potential end user in four parts:

- o **Collection and Organization of Materials:** Product information is easily obtained from vendors and trade magazines. Warranties and service promises can be reviewed. Inappropriate or questionable products can be removed from further consideration.
- o **Bench Testing:** Depending on the product, this can include several objectives. A simple watt meter can substantiate a salesman's claims. More detailed testing can be completed as time, money, and interest allow.
- o **References and Referrals:** All vendors and salespeople should have a list of sites where their products have been installed. A quick phone call can substantiate a "success story."
- o **Field Testing:** Unfortunately, not all of the potential flaws can be revealed by collecting product literature, bench testing, or making phone calls. Most manufacturers encourage small field tests as a way to familiarize customers with their products. Often, substantial discounts on materials or labor will be

given in support of these tests. Not only do these small tests weed out inappropriate products, but in-house personnel can be trained and the installation experience can be used for larger projects.

It is particularly important that information be complete and up-to-date, since many new products are being introduced and new companies are being formed each year to supply energy-reducing equipment. As a result, some products not completely perfected are introduced. Sometimes products are marketed that neglect important productivity or ergonomic factors such as eye strain and glare.

Thorough preparation of the potential end-user has the added benefit of enhancing the energy manager's credibility. Building occupants are justifiably protective of their work environment and suspicious of changes. Similarly, shop personnel are reluctant to risk repeated trips to a project site when they know their area worked fine before any changes were made. Products, like people, earn reputations that can be long lasting. With sufficient research and investigation, a good track record can be established and acceptance will follow. But, the failure of one project might make future projects at the same institution difficult to implement.

This analysis is broken down into three areas that affect end-use decision makers: operation cost, user comfort, and compatibility. Operation cost is the direct energy cost of operating and maintaining the lamp and fixture. User comfort is related to light-level output, and to technical factors (to be defined later) such as voltage regulation and flicker factor. Compatibility refers to how a lighting product will affect other equipment at the installation site.

Performing Energy Savings Calculations

There are numerous ways to calculate lighting energy savings. The following method, as illustrated below, will be used in each section to predict energy savings.

Calculating energy savings for lighting projects.

*Annual Energy Savings =
Annual Energy Use of Existing Conditions - Annual Energy Use of
Proposed Conditions*

Existing Conditions=

$$kWh = (L_1 \times W_1 \times H_1) / 1000$$

Proposed Conditions=

$$kWh = (L_2 \times W_2 \times H_2) / 1000$$

Where:

L₁ = Number of luminaires existing

L₂ = Number of luminaires proposed

W₁ = Watts per luminaire existing

W₂ = Watts per luminaire proposed

H₁ = Annual hours of operation existing

H₂ = Annual hours of operation proposed

If one or more of the variables are reduced and the remaining variables remain constant, then energy savings will result. As each product or technology is discussed in turn, its impact on these variables will be identified. At the same time, important non-economic variables will also be discussed.

In some cases, such as new construction, there are no "existing conditions." The aforementioned technique can still be used if enough information is available in the construction drawings. However, if several design options are under consideration, it may be necessary to use a computer energy modeling program to determine potential energy savings. (See Appendix E for a more thorough discussion of computer energy modeling in new construction.)

Performing Economic Payback Calculations

The most straightforward method of determining potential savings is the simple payback method. Simple payback is the cost of the project, including materials and labor, divided by the first-year energy savings. This method is best used as a "first cut" to determine if a project is worth considering further. Other return on investment methods, such as internal rate of return (IRR) and net present value (NPV), should be used when ranking projects. These methods consider variables such as product life, the cost of funds, and annual maintenance costs.

Since the simple payback method is a lighting industry standard and the simplest to understand, it will be used throughout this thesis. Formulae for these methods are in the glossary. [A more detailed explanation of energy project economics can be found in the Handbook of Energy Engineering (Mehta and Thumann 1990, p. 19)]. Practically speaking, only projects with a simple payback of less than five years are considered for implementation by businesses or institutions. A five year paypack can also be expressed as a 20 percent return on investment—over double the typical "market" rate. In many cases, however, lighting projects will often have a payback in the two or three year range.

CHAPTER 3

FULL-SIZED FLUORESCENT LAMPS

This section describing the energy efficiency potential of full size fluorescent lamps serves three purposes. The first is to outline the different types of fluorescent lamps available to the end user. The second is to introduce the reader to relevant lighting concepts and terminology. And the third is to extract and summarize the identified criteria that are important for the decision-maker. The sections on compact fluorescent lamps, electronic ballasts, and optical reflectors build on the concepts introduced here.

What is a Fluorescent Lamp?

The fluorescent lamp is a low pressure gaseous discharge lighting source. There are three key elements of the fluorescent lamp that produce visible light; electrodes, gases, and phosphors. Electrodes, sometimes called cathodes, are located at each end of the fluorescent lamp. These electrodes are generally made of tungsten wire. The role of the electrode is to emit electrons into the lamp. Mercury is one of the gases contained in the fluorescent lamp. Current flowing through the lamp in an arc discharge causes the mercury to vaporize and then radiate energy. Other gases found in the fluorescent lamp include argon and neon. Phosphors line the inside of the lamp and produce visible light when they are excited by the ultraviolet radiation from the mercury. Fluorescent lamps,

unlike incandescent lamps, require a device to limit current and to supply the proper operating voltage. This device is called a ballast.

Types Of Fluorescent Lamps

Fluorescent lamps are available in different lengths and diameters. The most common fluorescent lamp is the forty-watt, four-foot-long variety found in most schools, offices, and hospitals. Manufacturers use the designation F40T12 to describe this lamp. The "F" identifies the lamp as fluorescent, the "40" identifies either the length or wattage family, the "T" means tubular, and the number that follows is the diameter in eighths of an inch (T12 equals $12/8 = 1\text{-}1/2$ inches in diameter). Additional information may describe the lamp's color in degrees Kelvin equivalent, or identify it as an energy-saving or high-output lamp, and describe the starting characteristics.

Other sizes of fluorescent lamps are available to meet specific needs. Eight-foot fluorescents (F96T12) can be found in many grocery stores and manufacturing areas. Although not as common, two-foot, three-foot, and five-foot lamps are manufactured to give lighting designers additional creative flexibility. Four-foot lamps bent into a "U" shape to fit inside two-foot by two-foot luminaires are also available.

Lamp Life

Fluorescent lamps burn out for two reasons. The first reason is that each time the lamp is started some of the electron emissive coating on the electrodes erodes. The second reason is that during operation, evaporation of this emissive material takes place. In 1973, a collector gas was introduced, substantially reducing the boiling off of the electron emission material from the electrodes.

The rated life of a typical fluorescent lamp is twenty thousand hours. This is based on the lighting industry standard of three hours of operation, or burning cycle, per start. (Actually, rated life means the point where 50 percent of tested lamps are still operating.) By continually operating a fluorescent lamp, lamp life may be extended beyond the rated life by a factor of 2.5 or more. (Helms and Belcher 1991, p. 92)

Other factors besides burning-cycle-per-start can affect fluorescent lamp life, for example, improper voltage supplied by the ballast, poor lamp-holder to lamp connections, and improper line voltage all have a negative affect on lamp life. It is often difficult to trouble-shoot these problems and money can be wasted in both lamps and labor before these problems are discovered.

Effects of Temperature on Fluorescent Lamp Output

The light output of a fluorescent lamp directly depends on the temperature of the lamp wall. Light output and luminous efficacy reach optimum values at about 38°C (Kaufman ed. 1984, p. 8-28). This is the temperature found in most of the newer, well-designed indoor luminaires. It should be noted, however, that most luminaires in use today operate at much higher temperatures.

The temperature of the lamp is measured at the coolest point on the fluorescent lamp, termed the minimum bulb-wall temperature. The actual change in light output is a function of the changing pressure with temperature of the mercury vapor inside the lamp. Figure 1. shows the relationship between lamp-wall temperature and light output. Notice that an increase of 20°F reduced the light output by 15 percent.

Existing and developing technologies have been shown to reduce lamp wall temperatures inside fluorescent luminaires. These techniques include air-

flow fixtures (natural convective cooling of the lamp compartment) and direct lamp spot-cooling using thermoelectric and heat pipe devices. By removing heat from the luminaire the lamps can be operated at or near their optimum, and this can result in significant energy and capital-cost savings when applied to a lighting layout (Siminovitch 1990, p. 47).

Figure 1. Temperature v. Light Output of Fluorescent Lamps.
(Source: Kaufman, John, ed. 1984. Illuminating Engineering Society Lighting Handbook, Reference Volume. New York, New York: Illuminating Engineering Society of North America.)

Energy-Saving Lamps

Installing 34-watt F40T12 lamps to replace 40-watt F40T12 lamps is a very popular energy-saving strategy. By changing the composition of gases in fluorescent lamps, the lamp voltage, and therefore wattage, can be reduced. The energy consumption of a lamp is reduced by 14 percent at the expense of some light output. This is an easy conversion, since the 34-watt lamps are designed to use the same ballast as the 40-watt lamp.

In some cases, however, this simple conversion is inappropriate. Since energy-saver lamps reduce light output, they should never be installed in an area that is already at or below recommended light levels. Also, 34-watt energy-saving lamps should not be used in new construction applications. With less light output per luminaire, more luminaires may be required to obtain the desired light levels. Although this point seems obvious, energy-saver lamps can be found in many recently completed buildings. Some energy-saving lamps have trouble starting at ambient temperatures below 60°F (Kaufman ed. 1984, p.8-24). In addition, some energy-saving lamps have compatibility problems with older standard fluorescent ballasts, leading in some cases to local overheating and explosive destruction of the older ballasts.

T-10 Fluorescent Lamps

These lamps are designed to be an interchangeable alternative to the T-12 lamp. The principle advantage of the T-10 is increased lumens-per-watt ratio and a small increase in optical efficiency when compared with T-12 lamps (Eley, Benya, and Verderber 1990, p. 8). Two disadvantages are that the lamp cost is higher and that they are currently produced by only a few of the lamp manufacturers. Since T-10 lamps are rated to consume 42 watts-per-lamp they

do not reduce energy consumption if they are replaced one-for-one with T-12 lamps. (The use of T-10 lamps is also discussed in the optical reflector section.)

T-8 Fluorescent Lamps

The T-8 lamp uses a tri-stimulus rare earth phosphor coating which provides higher efficiency, improved lamp lumen depreciation, and good color rendering when compared to the T-12 lamp (Verderber 1989, p. 9). By comparison, the total light output of the 32-watt T-8 lamps is less than the typical 40-watt T-12 lamp. The efficacy, however, is higher--at ninety lumens-per-watt--than the 40-watt T-12, which is around eighty lumens-per-watt. T-8 lamps can be used in the same fixtures as T-12 lamps, but because of their 265 milliampere current requirement, they require a ballast that is incompatible with T-12 or T-10 lamps (standard fluorescent lamps are designed for 430 milliampere operation). The cost of a T-8 lamp and ballast is comparable to that of a T-12 lamp and ballast.

It should be mentioned that before tri-phosphor lamps were introduced, designers had to decide between lamps with high light output or lamps with good color rendering. For example, a standard cool white lamp has a CRI of around sixty-two and a lumen-per-watt ratio of seventy-nine, while a deluxe cool white lamp has a higher CRI of eighty nine but a lower lumen-to-watt ratio of fifty-five. By comparison a typical T-8 lamp in the cool white color temperature range (4,100K) has a CRI of seventy-five and a lumen-per-watt ratio of ninety, combining excellent efficiency with very good color rendering properties.

Savings Calculations Methods

By using the simple payback energy-saving calculation presented in the introduction, a rough idea of the potential energy-saving between lamp options

can be estimated. With the hours of operation and the number of luminaires held constant, the unknown variable is the change in watts per luminaire. When considering this unknown, it must be realized that a lamp cannot be thought of as independent of the ballast used to operate it. Ballasts can operate lamps at very different light output levels as well as energy consumption levels. (This relationship is more fully explained in the section on electronic ballasts.) Typical values for different lamp and ballast combinations are listed in Figure 2.

Impact Analysis

Maintenance: Institutions or businesses with a large and diverse building stock are often reluctant to specify more than one type of lamp to be used in their facilities. Many of these groups attempt to settle on a standard lamp in order to simplify ordering and stocking. In addition, there is no guarantee that a special lamp will be replaced with a comparable lamp after it burns out. Training must be provided to maintenance crews so that they understand why different lamps are specified for different areas. These potential problems should be considered and special arrangements should perhaps be made when evaluating different lamp options.

Summary of Important Criteria for Fluorescent Lamp Selection

The first step in selecting a fluorescent lamp is not to consider the lamps but rather the space where the lamps will be used. Whether these priorities are based on first cost, aesthetics or energy cost, once the needs of occupants have been decided the following lamp selection criteria can be used:

Figure 2. Typical Efficacy Values For Fluorescent Lamps and Ballasts

- o Color Rendering Index: Generally, the more important the aesthetics of a lighting design the higher the CRI should be. A lamp with a CRI of seventy-five or higher is considered adequate for most office and school situations.

- o Color Temperature: "Warm" or "Cool" colors can be selected depending on preference. Warm White lamps are typically rated at 2,700K and Cool White lamps are 4,100K. Mixing lamps of different color temperature is not recommended.

- o Lumen Output: Each brand of fluorescent lamp has a rated light output that can be obtained from lamp manufacturers. Most engineers and designers involved with fixture selection and layout use this number. A better guide to lamp performance is the lumen-per-watt ratio.

- o Lumen-Per-Watt Ratio (Efficacy): This is the best direct measurement of performance. This value is a function of many factors including the type of ballast used and the lamp operating temperature. Manufacturer's literature can be helpful in making rough comparisons.

- o Compatibility: The proper size and shape lamp must be selected to fit the proposed fixture. Selecting standard shape and length lamps can reduce ordering and stocking costs. It is important to note that T-12 and T-10 lamps can operate on the same ballast while T-8 lamps require a ballast with a different input rating. Multi-lamp ballasts are now available that can operate all kinds, but apparently not with the greatest efficiency for any one type.

Once these factors have been weighed, the decision-maker can balance the benefits of improving color quality and aesthetics with potentially higher first costs. While these factors are important when weighed independently, they

cannot be thought of separately from the associated ballast, fixture, and lens that make up the complete luminaire.

CHAPTER 4

COMPACT FLUORESCENT LAMPS

Compact fluorescent lamps are available as energy-saving alternatives to standard incandescent lamps. Although these lamp-ballast combinations can initially cost as much as ten times more than incandescent lamps, compact fluorescents are often cost effective. While specifications vary from manufacturer to manufacturer, an eighteen watt compact fluorescent usually replaces a sixty to seventy watt incandescent, in view of equivalent light output. (See Table 1., Typical compact fluorescent lamp performance.) In addition, compact fluorescents have an operating life of 10,000 hours, compared with 750 hours for a standard incandescent.

Compact fluorescent lamps generally can be used as replacements for incandescent "A" or "T" lamps. But because most compact fluorescents are larger, heavier, and shaped slightly differently than incandescents, they cannot be used to replace incandescents in all situations.

Two different types of compact fluorescents are available, an integral type and a modular type. Integral compact fluorescents are sold as an inseparable single lamp and ballast unit. Most integral lamps look like a slightly oversized incandescent bulbs. Modular compact fluorescents, often referred to by the trade name "PL" lamps, have a separate plug-in lamp and ballast. The advantage of the modular approach is that the ballast can be reused when the lamps burn out.

Table 1. Typical Compact Fluorescent Lamp Performance

Lamp type	Ballast		Rated Hours	Watts	Lumens	Lumens/ Watt
	Type					
5 watt	Core-Coil		10,000	9	250	27.8
7 watt	Core-Coil		10,000	11	400	36.4
9 watt	Core-Coil		10,000	13	600	46.2
13 watt	Core-Coil		10,000	17	860	50.6
15 watt	Core-Coil		10,000	20	900	45.0
18 watt	Core-Coil		10,000	22	1,250	56.8
27 watt	Core-Coil		10,000	34	1,800	52.9
10 watt	Electronic		10,000	10	600	60.0
13 watt	Electronic		10,000	13	900	69.2
18 watt	Electronic		10,000	18	1,250	69.4
26 watt	Electronic		10,000	26	1,800	69.2

(Source of Data: Charles Eley, Jim Benya, and Rudy Verderber. 1990. Advanced Lighting Technologies Application Guidelines. Sacramento, California: Building and Appliance Efficiency Office, Division of the California Energy Commission. PB400-90-014. p. 6)

Typical modular compact fluorescent can be found with lamp wattages ranging from five to thirteen watts. Most integral models are between fifteen and twenty watts.

Savings Calculation Methods

Calculating the energy savings for installing compact fluorescents is straightforward and without the pitfalls that make some energy calculations difficult. The only variables needed are the hours of operation, the wattage of the existing lamps, and the wattage of the proposed lamps. A more rigorous estimate of the total savings resulting from compact fluorescent lamping or relamping project would have to include other economic factors such as maintenance and relamping savings, which are project specific.

Impact Analysis

System Operation: Compact fluorescent projects generally require less planning and have a quicker payback than most other types of lighting projects. Potential mistakes can be avoided by considering the following factors:

- o **Compatibility:** When compact fluorescents first became available, there was an incentive for manufacturers to design and produce lamps quickly. Because of this, there are many different sizes and shapes of lamps and bases on the market. Stocking replacement lamps for a variety of models and manufacturers is cumbersome. Versatility should be considered when selecting lamp models. Standardization of lamp sizes and bases will alleviate this problem.
- o **Power Factor:** Power factor is the ratio of watts input divided by the line volts multiplied by the line amps.

$$\text{Power Factor} = (\text{Watts input}) / (\text{line volts} \times \text{line amps})$$

Non inductive or capacitive loads such as an incandescent light bulb have a 100 percent or "unity" power factor. If high power factor equipment is specified in new construction, more luminaires can be placed on a given circuit than with lower power factor equipment. Also, most utilities charge a penalty to customers with a total power factor under 85 percent. According to the IES, a high power factor is above 90 percent (Kaufman ed. 1984, p. 8-35).

Currently, not all compact fluorescent lamps have built-in power factor correction. Table 2., Power factor of common compact fluorescent lamps, lists the power factor and wattage of several brands of compact fluorescent lamps. Most of the lamps listed have a power factor of around 50 percent. (It is important to remember that although a high power factor is usually preferred, a fifteen-watt low power factor compact fluorescent is still half the amperage load of a sixty-watt incandescent.)

- o Flicker: Some compact fluorescent lamps have electronic ballasts that reduce or eliminate flicker. Flicker may be noticeable in some task lighting applications, but is generally not a problem in most compact fluorescent installations. (There is a more detailed discussion of flicker in the electronic ballast section.)

- o Heat Buildup: There is strong evidence that the light output of compact fluorescents decreases as the temperature of the lamps increases. A 1990 Advance Lighting Technologies report prepared for the California Energy Commission points out that rated lumens are measured at 77°F, a condition that is likely to occur only in an open fixture. At 95°F the light output of compact fluorescents decreases by 7 percent, at 113°F the light output decreases by 17

Table 2. Power Factor of Common Compact Fluorescent Lamps

Compact Fluorescent Manufacturer	Ballast Type	Test Voltage	Test Amperage	Measured Power Factor	Measured Wattage	Rated Wattage
Alzac (Lumatech)	Core Coil	118.0	0.23	43.0%	11.8	13
Fluorever	Core Coil	117.2	0.13	94.0%	14.1	16
GE Compax FLB15/T	Core Coil	118.1	0.23	53.0%	14.4	15
Lights of America 2202	Electronic	117.2	0.30	62.0%	21.6	22
Lights of America FDL18LE	Electronic	117.6	0.22	64.5%	17.0	18
Osram Dulux EL	Electronic	118.0	0.25	57.6%	16.9	20
Panasonic EFD 27LE	Electronic	115.4	0.33	60.3%	23.0	27
Panasonic EFT 18LE-T	Electronic	115.6	0.22	60.3%	15.0	18
Panasonic BFT 15EX/A	Core Coil	118.1	0.26	51.0%	15.7	17

percent, and so on. Since a common application of compact fluorescents includes recessed-can luminaires and other reduced air circulation luminaires, some light loss should be expected. Both lighting researchers and manufacturers are developing products with built-in heat sinks to address this problem (Siminovich, Rubenstein, and Verderber 1990, p. 1).

Maintenance: Relamping costs can be significantly reduced with compact fluorescent lamps when compared to incandescent lamps. Most compact fluorescents have an operating life from between 9,000 and 10,000 hours. In many cases, the reduced replacement costs are greater than the energy savings! For example, a compact fluorescent rated at a 10,000 hours life will last for just over three years in a typical nine-hour-per-day 360 days-per-year environment. Under these same conditions, a 750 hour incandescent will need to be changed over four times per year (or thirteen times for every time a compact fluorescent is changed). Using costs at Stanford University in this example, with energy at \$.06/kWh and labor rates at \$30 per hour, the energy savings would be \$8.16 per year, whereas the maintenance savings would be \$21.60. Even with long-life incandescent lamps (2,500 hours rated life) there still is a \$6.50 annual maintenance savings with the compact fluorescent. This simple example points out an important side benefit of compact fluorescents.

Aesthetics, Safety, and Comfort Issues

Aesthetics: The color "quality" of compact fluorescent lamps is generally very high because of the use of high color rendering rare earth phosphors. Most of these lamps have a good to excellent color rendering index (CRI) rating over 80 and up to 85. There is also a wide range of color temperatures available, from 2,700K to 5,000K. The 2,700K color temperature is most often selected because

it most closely resembles the color of the standard incandescent lamp (Eley, Benya, and Verderber 1990, p. 2). Caution should be taken to avoid mixing lamps of different color temperatures in the same area.

Industry Directions

Compact fluorescent lamps have improved significantly since they were originally introduced. Most new compact fluorescent lamps are well constructed and reliable. In addition, luminaire manufacturers are designing luminaires and reflectors to take advantage of the size and shape of compact fluorescents to improve light output.

High power factor compact fluorescents are now available with a power factor of 90 percent for magnetic ballasts and 105 percent for the electronic ballasts. These lamps offer the same color temperature and color rendering indices as the other compact fluorescents with the poorer power factor.

Higher wattage compact fluorescents with greater light output are also now available. Some can be used in traditional applications, such as replacements for incandescent lamps. Other compact fluorescents will be used for more innovative luminaire designs or to replace standard fluorescent luminaires.

A final development is the recent introduction of dimmable compact fluorescents. One of the main reasons that incandescent bulbs are still used is that they can be inexpensively dimmed. Dimmable compact fluorescents provide an energy efficient alternative to incandescent bulbs. These dimmable compact fluorescents have special dimmers and ballasts that can dim output to 5 percent of full light output.

Summary of Important Criteria For Compact Fluorescent Lamp Selection

Compact fluorescent lamps have proven to be a cost effective alternative to incandescent bulbs. Since most compact fluorescents fit into the same socket as incandescent bulbs they can be used in many commercial and residential applications.

- o Color Rendering Index: As with standard fluorescent lamps, the selection of a specific compact fluorescent depends on the space intended for use. If a compact fluorescent lamp is replacing an incandescent bulb in an area where aesthetics are important, then a high CRI should be selected. On the other hand, if the compact fluorescent lamps are installed in a non-critical area, the higher CRI may not warrant the extra cost.

- o Lumen Output: Early compact fluorescent lamps could only supply the equivalent lumen output of a sixty-watt incandescent. Today there are compact fluorescents with much higher lumen output. Caution should be taken to purchase the model of compact fluorescent with the proper desired light output.

- o Lumen-Per-Watt Ratio (Efficacy): As with standard fluorescent lamps, this is the best direct measure of performance. Manufacturer's literature can be helpful in making rough comparisons. Compact fluorescent lamps with electronic ballasts can be expected to have a higher lumen-per-watt ratio than compact fluorescent lamps with a core and coil ballast.

- o Color Temperature: "Warm" or "Cool" colors can be selected depending on preference. Warm White lamps are typically 2700K and Cool White lamps are 4100K. Mixing lamps of different color temperature is not recommended.

- o **Compatibility.** The proper size and shape lamp must be selected to fit the proposed fixture. When buying compact fluorescents with a modular lamp and ballast, the price and availability of obtaining separate replacements should be considered. Selecting standard shaped and length lamps can reduce the number of lamps and ballasts needed to be stocked as replacements.

- o **Power Factor:** Many compact fluorescent lamps are considered to have a low power factor. A small premium price can be paid to purchase compact florescent lamps with built-in power factor correction. In extreme cases, low power factor may lead to electrical circuit overloading and potential penalties from the electric utility.

- o **Heat Buildup:** Compact fluorescent lamps produce peak light output at about 77° F. Higher temperatures found in many enclosed fixtures cause a decrease in light output. Compact fluorescent lamps are available with heat sinks to help alleviate this problem.

CHAPTER 5

OPTICAL REFLECTORS

Introduction

A common method of increasing the efficiency of fluorescent luminaires is to install optical reflectors. If a reflective material is installed on the inside of a fluorescent luminaire, more of the lumens produced by the fluorescent lamps will be emitted from the luminaire. When the efficiency increase is sufficient to enable lamp removal, energy savings result.

The standard four-lamp, two-foot by four-foot fluorescent luminaire is the product most often targeted by reflector manufacturers and represents about 90 percent of sales. (Phone conversation 1-24-91, Matt Tracy, Product Manager, Spectrum Lighting.) Optical reflectors are also available for two-foot by two-foot and eight-foot luminaires.

When optical reflectors were first introduced, performance claims were often exaggerated. Advertisements implied that after an optical reflector was installed, two lamps could be removed from a four-lamp luminaire without any loss in light output. This type of oversimplification, combined with the large numbers of inexperienced manufacturers/distributors marketing reflectors, caused the reputation of the reflector industry to suffer. The reputation of the industry has, however, improved, now that performance claims are more

consistent with actual performance. At the same time, the industry has a better understanding of the best applications and limitations of optical reflectors.

Two steps should be taken before considering the installation of optical reflectors. The first step is to obtain light level readings with a high quality light meter. The second step is to compare those readings with the light levels recommended by the Illuminating Engineering Society (Kaufman ed. 1987) for the particular tasks performed in that space. Only if the light levels are above the IES recommended levels should optical reflectors accompanied by lamp removal be considered.

Materials Used to Construct Optical Reflectors

Optical reflectors are either rigid or filmlike. Rigid reflectors must be cut and bent to fit in a particular luminaire. The three most common materials used to make optical reflectors are:

- o **Anodized Aluminum:** Aluminium reflectors are cut from a specular polished aluminum sheet. (In the reflector industry, the word "specular" describes a mirror-like quality where the reflection is predominantly regular.) The range of total reflectivity is 85 to 90 percent.

- o **Anodized Aluminum with Dielectric Coating:** A dielectric coating is added to an anodized aluminum sheet to increase reflectivity. The range of total reflectivity is 88 to 94 percent.

- o **Specular Silver Laminate:** Silver reflectors are made by coating or impregnating a polyester film with elemental silver. The film is typically bonded to an aluminum substrate. The range of total reflectivity is 91 to 95 percent.

By comparison, the white enamel paint found in most older luminaires and some new luminaires has a reflectance of 80 to 85 percent. Modern white

powder paints generally exhibit a reflectance of about 90 percent (Lindsey 1989, p. 110).

Choosing among these three types of reflectors depends on priorities defined by the user. These priorities include cost, reflectivity, and additional maintenance required, if any. The anodized aluminum reflectors tend to be the least expensive (thirty dollars), and the dielectrically coated reflectors the most expensive (forty-five dollars). The price of specular silver reflectors falls between the two. Installation of the reflectors is commonly quoted at between ten dollars and twelve dollars. This usually includes installation of the reflector, cleaning the fixture, and replacing the lamps. Labor costs will, of course, increase for nonstandard fixtures and high ceilings. These are 1991 estimated costs and vary among manufacturers, but they give an idea of the cost of this technology.

According to a February 1991 survey of reflector manufacturers conducted by the Energy User News, there are currently twenty-four manufacturers of optical reflectors. Many of these make more than one type. Eighteen manufacture specular silver reflectors, eighteen make anodized aluminum, and two make the dielectric coated mirror reflectors. All the manufacturers offer warranties of at least five years and up to twenty-five years.

To reduce some of the costs associated with optical reflectors, self-adhesive reflective film has been marketed. Unlike reflective material bonded to a rigid substrate, the film consists of a reflective material with an adhesive backing, and is placed on the inside of fluorescent luminaires. Although material costs are cheaper, these savings may be absorbed by the additional labor required to line the luminaires with this adhesive film. There is also a fundamental design restriction. According to Lindsey (1989 p.111), "Reflectors

which are applied directly to the interior surfaces of the fixture are generally less efficient than semi-rigid reflectors since they conform to the fixture contours and cannot be formed to direct light in any specific manner." DiLaura and Kambich (1987, p. S-2) found that luminaires with sloped sides exhibit an increase in efficiency when lined with film, whereas luminaires with straight sides did not. In a fixture with straight sides, the light output is reduced by the multiple reflections that occur before the light is emitted.

Although manufacturers and vendors consider reflectivity an important part of sales promotions, from a building occupant's perspective the difference between materials may not be significant. Depending on the reflector design, the material used may have little effect on light output (Paumgarten 1989, p. 104). For example, specular silver is more reflective than polished aluminum, yet even the most attentive user is unlikely to be able to tell the difference between the two once an installation is complete. When a reflector is installed, it must be remembered that lamps and ballasts are often replaced and the luminaire lens is also cleaned. These changes are often more significant than differences in reflectivity between reflector materials.

Reflector Design

Many authors agree that the design of the reflector is critical to performance (Lindsey 1989, p. 111) and (Brekken 1987, p. 72). In this case the word design refers to bending the reflector to maximize the light output of the luminaire. Not only can light output be increased, but an optical reflector can be designed to fit different lighting tasks. In an office environment, for example, the reflectors are designed to focus the maximum amount of light at desk level. In a hallway, however, the amount of light concentrated on the floor is usually not

important. So, instead of focusing the light downward creating a tunnel like appearance, the reflector can be designed to focus the light outward onto the hallway walls.

Savings Calculation Methods

Once it has been determined that adequate light levels will be maintained after the optical reflector installation, performing the energy savings calculation is simple. Of the three variables outlined in the introduction, both hours of operation and number of luminaires remain constant. The third, watts per fixture, is the unknown. If two lamps are removed from a four-lamp fixture, the luminaire wattage will be reduced by half. Therefore, if one lamp is removed from a three-lamp luminaire the energy consumption will be reduced by one-third. (In fact, the saving could be slightly higher.)

There are two common ways to wire a three-lamp luminaire. The first is to connect two outside lamps to one ballast and have the middle lamp operated by a one-lamp ballast. The second method also has the two outside lamps connected to one ballast but instead of a single-lamp ballast, two adjoining luminaires share a ballast to operate the center lamps. In other words, for every two adjoining luminaires, there are three two-lamp ballasts. Since a single-lamp ballast and lamp is less efficient per lamp than a two-lamp ballast, the energy savings are slightly higher in the first case. Table 3., describes several energy-saving scenarios.

Since all lighting sources emit heat as well as light, removing lamps will reduce the building heat load and possibly reduce air-conditioning costs. This kind of energy savings is very building specific and therefore difficult to calculate accurately. Complicating the matter further, during the heating season heat from

Table 3. Typical Wattage Reductions from Installing Optical Reflectors

	Remove	Install	Wattage			Percentage Reduction
			Before	After		
Case 1	Two 34 watt lamps + two lamp ballast	34 watt lamps	144	72		50.0%
Case 2	Two 34 watt lamps + two lamp ballast	40 watt lamps	144	88		38.9%
Case 3	One 34 watt lamp + one lamp ballast	34 watt lamps	115	72		37.4%
Case 3b	One 34 watt lamp + one-half of two lamp ballast	34 watt lamps	108	72		33.3%
Case 4	One 34 watt lamp + one lamp ballast	40 watt lamps	115	88		23.5%
Case 4b	One 34 watt lamp + one-half of two lamp ballast	40 watt lamps	108	88		18.5%

the lights, although not a very efficient heat source, is still a part of the heat supply in some buildings. A rough figure that seems to have some industry acceptance is that for every kilowatt of lighting power reduction, .25 kilowatts of cooling power are saved. It is the opinion of the author, however, that project economics should be acceptable without adding this additional factor.

Impact Analysis

Considering Optical Reflector Alternatives: A cost-conscious energy manager will consider other luminaire modifications before considering optical reflectors. As stated earlier, a light meter is required to determine the potential for installing optical reflectors. It is also important to consider that the lamp output will be reduced as the lamps age (lumen depreciation) and the fixture will get dirty over time. These factors combine to reduce total luminaire output.

Once light level measurements are taken, the energy engineer can use this simple key to decide if optical reflectors are appropriate. (Although the costs will vary, cheaper options are listed first.)

If an area is overlit:

- o Delamp without an optical reflector.
- o Install more efficacious lamps with lower wattage and light output.
- o Delamp without a reflector and replace remaining lamps with higher output lamps/ballasts.
- o Replace the old luminaire with a new fixture consisting of fewer lamps.
- o Delamp and install an inexpensive reflector.
- o Delamp and install a carefully designed high-quality reflector.

If an area is properly lit:

- o Install a more efficacious lamp/ballast system with the same light output.
- o Delamp without a reflector and replace remaining lamps with higher output lamps/ballasts.
- o Delamp and install a carefully designed high quality reflector; replace remaining lamps with higher output lamps/ballasts.

If an area is underlit:

- o Install lamps/ballasts with increased light output.
- o Optical reflectors could be installed instead of adding additional lamps and ballasts to boost light output. This does not reduce energy consumption, but rather avoids additional energy consumption (Brekken 1987, p. 68).

System operation: When retrofitting with optical reflectors, the possibility of two-level or "dual" switching is often lost when lamps are removed from a fixture. In mixed use areas, having two lighting levels adds versatility. For example, when viewing a computer screen, glare and eye strain can be reduced with lower light levels. If higher light levels are required for reading or writing that is easily accomplished. Fixtures could be rewired to retain this capability, but only at a large extra expense.

Maintenance: More attention to maintenance is required in areas with optical reflectors. Since the luminaires have fewer lamps, burnouts are more noticeable. The reflector should also be cleaned periodically so light levels are maintained. In most office areas dusting the lamps and cleaning the lens and reflector may only be necessary every two or three years. In more dusty

environments, one or more cleanings per year may be required. The specular silver reflector scratches easier than either the dielectric coated reflector or the anodized aluminum reflector. Because of this, repeated cleaning could diminish the specular ability of the specular silver reflector.

Aesthetics, Safety, and Comfort Issues

Once installed, optical reflectors change the characteristic of a luminaire. In the best installations, light output is at or near original levels and energy consumption is reduced. In poor installations, energy savings may still be realized but dark spots and uneven light distribution may result. Unless the building occupant is directly underneath a luminaire, he or she may have substantially less light. A study performed at the University of California, Berkeley found a 16 to 19 percent decrease in uniformity of light levels over a test room (Kessel 1990, p. 25). A small test installation is a prudent method of verifying claims made by the manufacturer and ensuring acceptable uniformity. In doing so, there is the added advantage that the building occupants can see how the reflectors will look before they are installed in their area. In this way the building occupants become a part of the energy management team and help to ensure the project's success.

Case Study: Stanford University Cummings Art Building

The Cummings Art building has 44 four-lamp four-foot recessed fixtures in the main hallway of the building. Art work is displayed on the walls of the hallway (highlighted with supplemental track lighting).

In most cases, optical reflectors are used to focus light downward to increase light levels at the work plane. In a hallway however, the light levels are not crucial. Instead of focusing the light downward, the reflectors are used to

obtain a high cut-off angle and wash the walls with light (a non standard approach). As is the case in many older buildings, the fixture lenses in this building were discolored and cracking. In addition, the existing ballasts were over ten years old so new lenses, lamps, and ballasts were installed at the same time as the reflectors. Energy savings results from the removal of two lamps from every four-lamp fixture.

Now that the project is complete, there are slightly higher light levels (due to the new lamps and lenses).

Energy Savings Analysis (See introduction)

Existing Conditions (per room)=

kWh/year = (44 x 184 x 4500)/1000= 36,432 kWh/year.

Proposed Conditions (per room) =

kWh/year = (44 x 92 x 4500)/1000= 18,216 kWh/year.

Annual Energy Savings =

Existing Conditions - Proposed Conditions

36,432 - 18,216 = 18,216 kWh/year

Project Cost:

Labor \$ 308

Materials \$ 2,464

Total \$ 2,722

Energy Savings: 18,216 kWh @ \$.06 per kWh= \$1,093

Simple Payback= Project Cost/Energy Savings = \$2,722/\$1,093= 2.5 years.

Industry Directions

Several optical reflector manufacturers have turned to the new construction market to increase sales. These manufacturers claim that a two-

lamp luminaire with a factory installed reflector can be used to get the same light output as the three-lamp luminaire that is the new construction standard. The cost for these reflectorized luminaires is between \$75 and \$105. The cost of a standard three-lamp luminaire starts at about \$35 (Howard 1990, p. 22).

Summary of Important Criteria for Optical Reflector Selection

Unlike electronic ballasts or compact fluorescent lamps, optical reflectors are not in themselves energy savers. Optical reflectors increase the light output of fluorescent fixtures, often allowing lamps to be removed. Although optical reflectors are a proven lighting technology, other, often cheaper, techniques can also be used. Simple delamping or lower output lamp/ballast combinations can also save energy and at the same time provide the desired light levels. After other options are considered, the following factors should be included in the selection of optical reflectors:

- o **Materials:** Optical reflectors are constructed from either anodized aluminum, anodized aluminum with a coating, or a specular silver laminate. The aluminum class of reflectors may perform better in dirty or dusty environments.
- o **Design:** From a performance perspective, optical reflector design is more critical than material selection. Since there are too many fixture designs to standardize reflector shape, reflectors must be custom designed for each project. Poor optical reflector design can focus too much light downward leaving the space with uneven levels of light.
- o **Combining Technologies:** Since labor is an important component of reflector projects, it may be cost effective to also consider installing electronic ballasts, T8 lamps, and a new fixture lens at the same time.

CHAPTER 6

ELECTRONIC BALLASTS

Electronic ballasts have shown great promise as energy-saving devices. Manufacturers claim a 10 to 20 percent energy reduction when compared with core-and-coil ballasts. Electronic ballasts perform the same function as standard core-and-coil ballasts (i.e., to regulate current flow and voltage to the fluorescent lamps), but use solid state technology to rectify the incoming 60 Hz power and convert it to a much higher frequency (typically 25,000 Hz.). This high frequency operation has the double benefit of allowing the ballasts to operate with lower losses, making them more efficient than core-and-coil ballasts, and at the same time improving the operating efficiency of the fluorescent lamps. Figure 3., shows the relationship between efficacy and operating frequency with fluorescent lamps.

Aside from energy savings, electronic ballasts offer several other advantages over core-and-coil ballasts. One advantage is the potential for reduced flicker, a problem for those who work around video display terminals (VDT's), as well as a suspected cause of adverse physiological reactions to fluorescent lights. In addition, some electronic ballasts offer a dimming control feature that can increase energy savings and flexibility.

Three factors have made energy managers cautious about purchasing electronic ballasts: a high premature failure rate with early electronic ballasts; a potential for excessive harmonics and conducted electro-magnetic interference

Figure 3. Lamp Efficacy Gain v. Operating Frequency
(Source: Kaufman, John, ed. 1984. Illuminating Engineering Society Lighting Handbook, Reference Volume. New York, New York: Illuminating Engineering Society of North America.)

(EMI); and a higher cost per unit. Many manufacturers have improved internal ballast circuitry and quality testing techniques to diminish these problems.

Savings Calculation Methods

Accurately calculating the energy savings for electronic ballasts is difficult. Ballast manufacturers claim 14 to 20 percent energy savings, but several factors influence the actual energy savings: the existing ballast/lamp combined energy consumption; the proposed ballast/lamp combined energy consumption; and the hours of operation. To complicate the evaluation further, there are no universally accepted standards against which to compare electronic ballasts. To remedy this problem, the American National Standards Institute (ANSI) is working (1991) on an update of Standard C82 to include electronic ballasts.

Electronic ballasts are priced from twenty-two to seventy-five dollars per ballast. (By comparison, an energy-saver magnetic ballast costs from twelve to sixteen dollars.) The more expensive electronic ballasts generally have special features such as dimming capabilities or supply power to three or four lamps instead of two lamps. Among the electronic ballasts with common features there is no evidence that there is a correlation between cost and quality. Before paying a higher cost for dimmable ballasts, users should be certain they need to be able to vary the light levels over such a large range. (Often only two light levels are necessary. This can usually be accomplished with dual switching at a lower cost.)

Impact Analyses

Since most ballasts are hidden inside luminaires, building occupants are unaware of ballast changes or retrofits. Unless there is an unusually high number of early ballast failures, the ballast project should be transparent to the building

occupants. The following factors should be studied before a ballast installation is considered:

System Operation

- o **Ballast Factor:** Ballast factor is a comparison of the lumen output from a laboratory reference ballast with that of the commercial ballast and is commonly expressed as a percentage. Ballast factor can also be described as the lumen output of actual lamp-ballast divided by the lumen output of a reference lamp-ballast. Typical values range from 80 to 95 percent, although some newer ballasts have a ballast factor of greater than one. A single ballast will have a different ballast factor for different lamps. (For example, the ballast factor will typically be lower for F40T12 energy-saving 34 watt lamp when compared to the standard 40 watt F40T12 lamps). In a retrofit situation, the new ballast factor should be at least equal to the ballast factor of the ballast being replaced (unless the light level is too high). In new construction, the ballast factor should be considered as a part of the lighting design. A higher ballast factor means more light output, possibly reducing the number of luminaires required. As an example, the Certified Ballast Manufacturers (CBM) require a ballast to have a minimum ballast factor of .925 with a 40 watt F40T12 lamp (Verderber and Morse 1985, p.3-3).

- o **Voltage Regulation:** Because small voltage changes occur from time to time, the ballast should be able to accommodate these with a minimum of change in light output. A large change in light output may disturb building occupants. An electronic ballast should be expected to handle a 10 percent voltage fluctuation without affecting user comfort. Voltage regulation is commonly expressed as a percentage output variation compared to a percentage input. For

example, an acceptable light variation for a standard 120 volt ballast might be minus 8 percent at 108 volts and plus 8 percent at 132 volts.

- o **System Efficacy:** Efficacy—efficiency expressed in lumens per watt—is the best cost performance measure of the lamp and ballast system performance. Electronic ballasts have been shown to be more efficacious than core-and-coil ballasts. Sometimes this efficacy improvement is at the expense of light output. This is a problem when light levels are already close to or below minimum recommended levels. The total amount of light output, along with system efficacy, should be considered in every electronic ballast installation.

- o **Harmonics and Conducted Electro-Magnetic Interference (EMI):** In simple terms, harmonics are high frequency variations of the fundamental sixty Hz sinusoidal wave form. In three phase balanced distribution systems, the load can become unbalanced from harmonics, causing the neutrals to carry additional current and in some cases to become over loaded. The electronic switching in the ballast can introduce harmonics that are transmitted back into the power supply. A small percentage of harmonics will go unnoticed, but larger amounts can disturb sensitive electronic equipment. Many electronic ballasts now manufactured have levels of harmonics and EMI that meet or are below the levels proposed by ANSI and IEEE (Eley, Benya, and Verderber 1990, p. 6).

- o **Power Factor:** The section on compact fluorescent lamps has a discussion of power factor. Many of the electronic ballasts produced in 1991 have a power factor above 90 percent.

- o **Crest Factor:** Crest factor is the ratio of the peak lamp voltage to the root mean square (RMS) voltage. This value should be between 1.4 and 1.8. Values out of this range will shorten lamp life.

Aesthetics, Safety, and Comfort Issues

- o Percent Flicker: One of the important advantages of electronic ballasts is the potential to reduce or eliminate flicker. The IES Reference Manual describes flicker as a cyclic variation in instantaneous light output (Kaufman ed. 1984, p. 8-30). Since this variation is twice the input frequency (120 Hz modulation when 60 Hz power is supplied), flicker can be virtually eliminated at the frequency range that electronic ballasts operate in (between 20 and 30 kHz). Magnetic ballasts operate at 33 percent flicker. A reduction in percentage flicker can improve lighting conditions, especially for those who work around VDT's (Helms and Belcher 1991, p. 144). It should also be noted that when designing particular circuits, some manufacturers may choose between improving power factor and increasing the percentage of flicker (Verderber and Morse 1985, p. 3-3). Not all electronic ballasts reduce flicker. Electronic ballasts without rectifier output filters can have flicker as high as standard magnetic ballasts.

- o Audible Noise: Ballast noise or hum is the result of vibrations caused by the magnetic elements in a core-and-coil ballast. The vibration is from the expanding and collapsing magnetic field in the laminated core of the ballast. This magnetic vibration may be amplified if the ballast is improperly seated into a metal fixture. A properly manufactured solid state ballast should reduce or eliminate the buzzing noise associated with conventional core and coil ballasts (Alling 1990, p. 5). Each company publishes sound ratings that indicates a relative sound output. The highest sound rating "A" is used for most indoor applications.

- o PCB Ballasts: Until the middle 1970s polychlorinated biphenyls were used in the capacitors of core and coil ballasts. Federal law no longer

allows the use of this chemical. Ballasts without the "Contains No PCB's" label may need to be treated as hazardous waste. (Ballasts containing PCB's are generally not considered a health risk unless they are leaking.)

Maintenance Considerations

- o Lamp Life: Some manufacturers claim that electronic ballasts extend the life of fluorescent lamps. In most cases this claim is based on accelerated life bench testing. Most of the electronic ballasts available today have not been on the market long enough for longevity field test data to be complete. Since lamp life is a function of many factors, it may be difficult to extrapolate test data to other sites. In addition, the many possible combinations of lamps and ballasts further complicates the issue. Although some buyers have experienced reduced lamp life when electronic ballasts were first introduced, installations at Stanford University have been free of this problem (Gould 1990, p. 61).

- o Lamp Burnouts: There are two strategies for controlling fluorescent lamp burnouts. Sometimes the electronic ballasts will only operate if the circuit is complete (e.g., if one lamp burns out the ballast will shut itself off along with any other lamps powered by that ballast). This "series" strategy is intended to protect the ballast circuitry. The second "parallel" strategy is to let the good lamps operate even with a burnt out lamp. There are several advantages to this parallel strategy. When new ballasts are installed, new lamps are usually also installed. If one of the new lamps happens to be defective, it will be unclear to the installer if it is the lamp or ballast that is not working. This can waste time, especially if the ballast supplies three or more lamps. In areas where few luminaires are present, if the whole luminaire goes out there may not be enough light available

for safe egress. This can be a problem particularly in areas with dispersed luminaires.

- o **Warranty and Service:** Not all of the companies that have marketed electronic ballasts are still in business. High failure rates and the associated bad publicity is the main reason those companies were not able to stay in business. Warranty and service should therefore be part of the product evaluation. Most companies offer at least a two-year warranty. Some warranties include a labor allowance of up to ten dollars per ballast. Service is managed either factory-direct or through the distributor. For further protection, ballast buyers should consider the financial strength of the company offering the warranty.

Stanford University electronic ballast study: As a preliminary step to the installation of solid state ballasts, Stanford conducted independent bench testing of several solid state ballasts (Gould 1989). The results of this study are described here. The complete study is included as Appendix C.

Results of Stanford University Ballast Study:

- o Efficacy of electronic ballast systems is 14 percent to 20 percent higher than core-and-coil ballast systems.
- o Electronic ballasts result in energy savings at the expense of some light output relative to core-and-coil ballasts.
- o Electronic ballast systems appear to be more sensitive to voltage fluctuations than core ballast systems. However, the observed variations are not considered significant.
- o As expected, electromagnetic interference (EMI) was generally more pronounced with electronic ballasts. However, except for environments where equipment is operated in certain frequency

ranges (coinciding with 20-30 kHz fundamental), EMI effects were secondary.

- o Electronic ballasts performed well in the power factor tests and in all cases had flicker levels below core-and-coil ballasts.
- o No one brand of electronic ballast exhibited across-the-board superiority in performance (with respect to measured parameters).

Industry Directions

An important recent advance in electronic ballasts is the use of integrated chip technology. By using microchips, manufacturers may be able to sell electronic ballasts at a lower price, making them more competitive with core-and-coil ballasts. (Interestingly, some of the more expensive electronic ballasts on the market in 1991 are using microchips. Perhaps these companies are trying to quickly amortize the cost of the research and development in the per-unit cost.) In addition, these microchips can be designed to improve dimming capabilities.

In cases where full light output is not needed and dimming ballasts are too expensive, some manufactures can preset a lower light output at the factory. Energy savings will be proportional to the percentage of reduced light output. The extra cost for this varies and is usually a function of the quantity of ballasts ordered. For example, in an area that is overlit and impractical for delamping, ballasts can be factory set to produce 75 percent light output. This could add a few additional watts of power reduction to the project savings.

Electronic ballasts have also become available for a wider range of indoor lighting applications. Initially, ballasts could only be found to operate four-foot lamps. Now electronic ballasts can be purchased to operate eight-foot lamps, and high-output lamps. In addition, one, two, three, and four lamp models are

available. Manufacturers are also stocking electronic ballasts to operate T-10 and T-8 lamps. Most of these combinations can be found in either 120 or 277 volt configurations.

Summary of Important Criteria for Electronic Ballast Selection

When planning an electronic ballast project, ballast performance, manufacturer warranty, and ballast cost are the key considerations. Since no universally accepted standards exist for electronic ballast comparison, it is difficult to rate different makes and models. At a minimum, each manufacturer should have the following criteria available:

- o Lumen-Per-Watt Ratio (Efficacy): Although this is the best direct measure of ballast performance, the fluorescent lamp used to obtain this measurement strongly contributes to the end result. Efficacy figures are available from manufacturers, but care should be taken to verify that the same types of lamps or class of lamps are used in each comparison.

- o Percentage Flicker: The potential to reduce flicker is an important benefit of the electronic ballast. This value should be published in the manufacturer's sales literature.

- o Harmonics: The amount of harmonics and electromagnetic interference generated by each model of electronic ballast should be low. Although most electronic ballasts emit acceptable amounts of harmonics, high values of harmonics can disturb sensitive electronic equipment.

- o Crest Factor: Crest factor values should be between 1.4 and 1.8 since values outside this range can reduce lamp life.

Other important ballast performance selection criteria should also be presented in the manufacturer's sales literature, such as voltage regulation, power factor, and ballast factor.

In addition to ballast performance, the warranty offered by the manufacturer should be an important part of the ballast selection criteria. A two year warranty is an acceptable minimum. It is also prudent to estimate the ability of the manufacturer to honor the warranty.

Although cost is an important part of every energy efficiency analysis, the wide difference in the per-ballast-cost of different electronic ballasts warrants special mention. This higher cost may be due to extra energy saving features built-in to the electronic ballast. If this is the case, the additional benefit of these features must be made a part of the economic analysis.

CHAPTER 7

OCCUPANCY SENSORS

Manual Control v. Occupancy Sensors

One of the most frustrating tasks for the energy manager is convincing building occupants to turn off the lights. Light switches are simple to operate, yet even a short stroll through any school or office building reveals lights left on. People either forget to turn off lights or, in larger areas, are reluctant to turn lights off in large areas where others might be affected. But manual control, where possible, is still the preferred method of on/off lighting control and should be considered before any discussion of occupancy sensors. The advantages of manual control are obvious: no additional installation or engineering costs, no nuisance shutoff or "ghost" detection, and very little training. Users may also get in the habit of thinking about energy and may turn off computers, printers and other office equipment.

Despite these advantages, experience shows us that manual lighting control can only be used effectively in controlled areas. These might include laboratories or libraries where a single person is responsible for watching a large area. Public areas such as classrooms, conference rooms, hallways, and open offices are places where manual switching is often wasteful. They are the only devices that can automatically respond to unpredictable occupancy of a space

(Verderber 1988, p. 25). (See Appendix B for a more complete discussion of building occupants and non-technical methods of saving energy.)

Types of Occupancy Sensors

Occupancy sensor operation is simple. When no movement is detected in a controlled space for a given period of time the sensor will operate a relay to shut the lights off. The two most popular methods of doing this are with either ultrasonic or infrared sensing. Although limited, microwave and audio sensors are also available. In a 1991 directory of lighting products, fourteen manufacturers are listed (EUN). About two-thirds of the companies make infrared units, and the remaining third specialize in ultrasonic. At least two companies manufacture both types, and a single unit utilizing both technologies simultaneously has recently been introduced.

Although the specific method of operation varies, ultrasonic sensors detect movement by responding to frequency changes produced by interference with a moving object (Doppler shift). Infrared sensors, on the other hand, are passive and respond to movement of heat sources within the unit's range. They are called passive because they detect, rather than transmit, energy (Khosla 1986, p. 8-14).

Most sensors have two adjustable controls. The first is a time delay that allows the operator to set the interval between the last time the sensor detects motion and the time the lights switch off. The second adjustment allows the user to set the unit's sensitivity, or, more specifically, how much movement is required to activate the sensor. Even though different models of sensors are available for use in specific room shapes and sizes, the sensitivity adjustment allows for more precise coverage. For example, cubicle walls, carpeting, movement outside

windows or doors, and air movement from HVAC ducts, can all affect the sensor's operation. In addition, rooms are occupied differently. Active areas such as cafeterias require a different sensitivity level than a quiet office with someone working on a personal computer. Potential problems can be moderated by the sensitivity adjustment.

Neither type of sensor is intrinsically better than the other. Because they are not directional, ultrasonic sensors work well in areas with obstacles such as cubicle walls or partitions. This, however, can also be a disadvantage when the coverage area spills into areas such as corridors or adjacent rooms. Infrared sensors, on the other hand, are cheaper to manufacture and somewhat simpler in design, so they are generally less expensive.

Savings Calculation Methods

Although the equation for determining energy savings from occupancy sensors is straightforward, obtaining accurate assumptions for the calculation can be difficult. The most accurate method is to set up a simple field test. All that is required are two inexpensive hour-meters and an occupancy sensor. The first hour-meter is used to determine how much time the lights are on during a given period of time. The second hour-meter records only the amount of time the sensor would operate if it was controlling the lights instead of just the hour-meter (actually, this is sensing the hours the space is occupied). The difference in these two readings gives an accurate idea of potential energy savings. Of course, the longer the test the more accurate the results. Take caution to select a site that represents the potential project.

At Stanford University, such a test was performed on seven classrooms. The number of hours saved on an annualized basis ranged from 600 hours to

2,730 hours. The average number of hours saved was 1,300. Because the amount of "off" time used in the equation really drives the savings calculation, care should be taken to determine this number accurately.

A detailed study performed at TRW Inc. identified nearly 3,000 hours of annual off-time from using occupancy sensors (Andis 1988, p. 42).

A device called an "Occupancy Auditor" is marketed that performs this same test described above. Because these devices are expensive (\$280), and not significantly different from the "homemade" version, they are not recommended. High quality large room sensors cost between 115 and 155 dollars per unit, including the cost of a relay/transformer. Wall switch units cost from fifty to sixty-five dollars (1991) and do not require a separate relay or transformer.

Installation Cost Elements: Several things affect the cost of installing occupancy sensors:

- o Room size, shape and obstructions (large and/or odd sized rooms require more sensors for complete coverage).
 - o Ceiling Height (ceilings higher than twelve feet may require the construction of temporary scaffolding during installation. This can be further complicated by sloping floors, or permanent furniture).
 - o Type of Ceiling (T-Bar or "drop" ceilings allow easy access for the low voltage wiring from the switch to the relay/transformer and the sensor.)
- Without an access space, some sort of wire mold or conduit will be needed to protect the wiring. The disadvantage of using wire molding is that it takes more time to install and, because it is visible, may need to be painted.
- o As an extra precaution in areas with special safety requirements, such as laboratories or hospitals, it may be advisable to remove one or two

luminaires from the circuit switched by the sensors. Then, in the unlikely event that a sensor fails or is falsely tripped, there will be enough light for occupants to leave the room safely. (Laboratories or rooms with safety hazards may require extra sensors or extra wiring for a night light.)

Cost Effective Installations: As discussed in the Savings Calculation Methods Section, not all rooms are good candidates for sensor installations. Labor and material costs may be the same for a room with two luminaires or twenty luminaires. The energy savings, however, are a direct function of the number of luminaires (and the hours they can be turned off). Therefore, a room must have a certain number of luminaires to be cost effective (depending on the watts per fixture). Figure 4., shows the relationship between simple payback and the number of lamps per room. The simple payback is based on a materials and labor cost of three-hundred dollars. (The abscissa is listed in lamps rather than luminaires for simplicity. For example, twelve lamps represents three four-lamp-fixtures, four three-lamp-luminaires or six two-lamp-luminaires.)

Impact Analyses

The following issues should be considered as part of any occupancy sensor installation. Each particular item should be weighted according to the pattern of occupancy, type of space, and economic priorities of the company or institution.

System Operation: Aside from the time and sensitivity adjustments, most occupancy sensors include an LED to indicate sensor operation and range, a bypass to remove the sensor from the lighting circuit, and an override used to switch off the lights for showing slides or movies. Several manufacturers offer "slave sensors" to work in combination with a "master sensor" to extend coverage

Figure 4. Large Room Occupancy Sensor Cost v. Simple Payback

range. Since adding features to a sensor usually only requires additional circuitry, lack of a particular feature may reflect the manufacturer's design philosophy. For example, not all sensors include a bypass switch. Some claim that the occupant will use the bypass to defeat the sensor, and thus impede energy savings. Others claim that making a bypass available is preferable to having someone not familiar with sensor operation or lighting circuits attempt to adjust or repair it. Ideally, the bypass can be used to reduce the inconvenience to the building occupant. Sensor adjustments or repairs can be made by competent personnel after the sensor has been disabled.

System Design and Maintenance: The success of any sensor installation is largely dependent on proper design and maintenance to insure proper operation. Several things must be done early in the engineering and installation parts of the project to avoid problems.

- o Enough sensors must be used to cover the space properly.

Although this seems obvious, competitive bidders often reduce the number of sensors used to gain the low bid. This can result in nuisance shutoff.

- o Sensors should not be used to the limits of their coverage capabilities. If a room is one-thousand square feet, a sensor should be selected that can cover a larger area, or two six-hundred square foot sensors should be used.

- o In-house personnel must be trained in sensor operation.

Unfortunately, the newest or most unfamiliar item will be the first suspected in any lighting problem. If the electricians know how the sensors operate and how they were installed, the chances increase that they will be adjusted correctly.

- o If a large project is completed with many different types of rooms and wiring schemes, a single line sketch of the room should be required of the installer to show the location of new relays or transformers. This is especially critical in areas that have complicated switching layouts. Trouble shooting time can be reduced with simple, organized installation details.

- o Two features make testing and trouble shooting easy: the first is the LED indicator and the second is the short time test mode. The LED is illuminated when the sensor detects motion. This is necessary to check the sensor's range. The short-time test-mode bypass sets the sensor timer to shut off the lights after only 15 seconds. Both of these features decrease the amount of time needed to trouble shoot the sensors.

- o Although the cost of energy is much greater than the cost of lamps, the time delay and sensitivity should be set to avoid excessive lamp cycling. This will help prevent early lamp burnout.

- o It is useful to mount and wire a sensor to something portable so it can be used for demonstration or training purposes. This is especially easy to do with the wall switch units.

Aesthetics, Safety, and Comfort Issues: Unlike electronic ballasts or optical reflectors, occupancy sensors are a high visibility product. Building occupants are quickly aware of sensor malfunctions. For this reason, proper installation is critical. Although many people will put up with early tuning adjustments, few will put up with repeated problems.

In 1983, the health impact of ultrasonic occupancy sensors was considered by the California Energy Commission. Ultrasonic sensors are "active" by nature: that is, they emit high frequency sound. This tone is above the levels

audible to the human ear (25 kHz). Two groups, (the American National Standards Institute and the Department of Health Services) have concluded that the sound pressure levels (dB) emitted by ultrasonic sensors do not adversely affect the health of workers. A high quality sensor will also be free of any subharmonics and emit only a "pure" tone. Infrared sensors, by virtue of their passive operation nature, have no potential adverse effects.

Wall Switch Sensors

In an effort to expand the cost effective use of occupancy sensors manufactures have recently developed the wall switch sensor. These units replace normal single-pole electrical switches. Wall switch sensors use the same infrared or ultrasonic technology as large room sensors. By only replacing the existing wall switch, labor and material costs are significantly reduced over the large room units.

Wall switch sensors are not cost effective in many small office settings. (A small office, for the purpose of this discussion, is a completely enclosed space less than 300 square feet in size and with local lighting controls.) Figure 5., shows how many hours the sensors will need to turn the lights off to get a two year payback. It is important to mention that a typical office is occupied nine hours a day, two hundred sixty days per year (2,340 hours per year). If the building occupants already turn the lights off manually at night, there are few hours to reap energy savings. An office with six 40-watt lamps (two three-lamp luminaires) must have the annual on time reduced by over two-thousand hours to gain a two year payback, assuming a sensor cost of fifty-five dollars and an energy cost of six cents per kWh. On the other hand, in office settings where the lights are continually left on at night the simple payback is usually quick.

Figure 5. Wall Switch Occupancy Sensor Hours off Required for a Two year Payback

Although this sort of time reduction is possible, it is certainly not a conservative estimate. (Even the most remiss building occupant is likely to turn out the lights when locking up for the night.) With the lights already off at night, the sensor must be able to turn off the lights for over eight hours per day 260 days per year to reach the 2,000 hours needed for a two year payback. Rooms with more lamps, higher energy costs and cheaper sensors will, of course, pay back quicker.

Although some wall sensors will cover areas as large as eight-hundred square feet, perhaps their best application is in single offices or conference rooms with few obstructions.

Several manufacturers have introduced a wall switch sensor with a built-in photocell control. Not only will the sensor turn off the lights when no one is in the room, but it will also turn off the lights when a preset amount of daylight available, making the fluorescent lights unnecessary. Since traditional indoor photocell control is rarely cost effective in small areas, this sensor will be particularly useful in perimeter offices and other daylit rooms.

Case Study: Stanford University Mudd Chemistry Building

The Mudd Chemistry building is a 24-hour/day research facility and one of the largest energy users on the Stanford University campus (over \$500,000 per year). Normally, the undergraduate laboratories are only used for classes in the afternoon. During the morning hours, laboratory technicians check chemical and equipment inventories and set up experiments. At night the experiments are removed and the rooms cleaned by janitors. Since no single group or researcher is responsible for these labs, the lights are rarely turned off.

The overriding consideration of this project was the need to maintain a safe environment for undergraduate research. Since the occupants in these rooms are often working with unfamiliar chemicals and equipment, it was crucial that under no circumstances would the lights turn off when people were in the room. In addition, there are shelves and partitions that at least partially block the view of each work station. Even though one high-output sensor would cover the entire class room, two sensors were installed (one at the front of the classroom and one at the back) to provide overlapping coverage.

Despite installing these extra sensors, the project is still cost effective. A year after this project was completed there were no reports of accidental shutoff. Part of the labor cost includes the construction of special brackets to attach the sensors to a non-standard ceiling.

Energy Savings Analysis (See introduction)

Existing Conditions (per room)=

$$kWh/year = (12 \times 215 \times 5280)/1000 = 13,622 \text{ kWh/year.}$$

Proposed Conditions (per room) =

$$kWh/year = (12 \times 215 \times 2080)/1000 = 5,366 \text{ kWh/year.}$$

Annual Energy Savings =

Existing Conditions - Proposed Conditions

$$13,622 - 5,366 = 8,256 \text{ kWh/year}$$

$$kWh/year \times 10 \text{ rooms} = 82,560 \text{ kWh/year}$$

Project Cost:

Labor \$ 4,031

Materials \$ 2,821

Total \$ 6,852

Energy Savings: 82,560 kWh @ \$.06 per kWh= \$4,953

Simple Payback= Project Cost/Energy Savings= \$6,852/\$4,953 = 1.4 years.

Industry Directions

Although recent changes in occupancy sensor design are subtle, they warrant discussion. Manufacturers have been working to increase coverage areas, to improve the transmitting and receiving electronics in the ultrasonic sensors, and to improve the lens optics in the infrared sensors. Wall switch sensors have become increasingly popular, and sensor installers have improved their application techniques.

In an effort to reduce nuisance shutoff, one manufacturer has increased the time delay from ten minutes to fifteen minutes. The amount of energy-saving lost is minimal, yet complaints due to accidental shutoffs are reduced.

Another method one manufacturer has selected to reduce nuisance shutoff is to combine both the infrared and ultrasonic technologies into one sensor. In this way, the sensitivity of each technology can be increased, allowing the time delay to be reduced. The advantages of this combination are better detection and increased energy savings.

The ability to identify the most appropriate application for occupancy sensors is another of the important recent achievements in the sensor industry. Although technical features have improved, the experience gained from innumerable sensor installations has helped increase the success rate of new installations.

One manufacturer has recently introduced a sensor to control HID (High Intensity Discharge) luminaires. These sensors are used differently from sensors

with fluorescent lamps. Instead of turning the lights completely off, the sensors reduce the level of light by a preset amount (usually one-half) if the sensor does not detect motion. HID lamps typically have a long restrike time, so they cannot respond quickly to an immediate need for light. One application for this type of sensor would be a large warehouse where not all of the warehouse is used all the time.

Summary of Important Criteria for Occupancy Sensor Selection

Occupancy sensors can be used to provide local on/off lighting control for unoccupied areas. Occupancy sensors can be installed in most areas, but areas with high ceilings, non-rectangular shapes, and with obstructions tend to require more sensors and therefore are often less cost effective. Because there are so many different types of occupancy sensors most manufacturers provide both engineering and product selection assistance.

There are two major types of occupancy sensors, passive infrared and active ultrasonic. The selection to use one type over the other will depend on the project specifics.

The following additional factors should be considered:

- o Enough sensors should be used in each area to assure full coverage.
- o Sensors should not be used to limits of their coverage capabilities.
- o In-house personnel should be trained in occupancy sensor installation and repair.
- o Single line drawings should be made for areas with complicated switching schemes.

- o Each sensor should have both sensitivity and time delay adjustments.
- o A bypass to remove the sensor from the lighting circuit is an important feature.
- o For testing the sensors range, a built-in LED indicator light is vital.

CHAPTER 8

TOWARD A SYSTEMS APPROACH

Combining Lighting Technologies

In order to organize this thesis in a manner that is most clear to readers, each lighting technology has been presented in a separate section. This organization also reflects the fact that most of these technologies are designed and manufactured by different companies and are seldom blended to achieve maximum energy system savings. For example, if fixture ventilation characteristics could be optimized for a specific lamp-ballast combination, the lamps could operate in their maximum output temperature range. Another example: choosing the most appropriate reflective coating, lamp holder placement, and lens design for a specific lamp and ballast could also improve system efficiency. Designing such fixtures as a system would allow for better light quality and greater energy savings than could be achieved by taking a separate approach.

Lighting Efficiency in New Construction

New construction projects offer an energy-saving potential that is not, for economic reasons, generally suitable to retrofit projects. New buildings can be designed to optimize the use of natural daylight illumination. When possible, the building structure, position, and fenestration systems can be designed to accommodate the best lighting control techniques (Verderber 1988, p. 26). Such

construction features would not be cost effective as retrofit projects, but might add little to new construction design or building costs. Installing daylighting controls is one example. Most buildings do not have separate circuits that control the lighting fixtures nearest to windows. The price alone of dimmable ballasts and a photocell control may be cost effective, but the additional labor cost of rewiring would be prohibitive in a retrofit situation.

The Future of Lighting Efficiency

Although this thesis has focused on the specific details of implementing successful lighting energy management projects, it is important to put energy efficiency in a broader context. Who benefits most from energy efficiency? The obvious answer is those who sell efficiency equipment and the businesses that are able to reduce their overhead by implementing successful energy efficiency projects. Perhaps the group with the biggest stake in energy efficiency, however, is the utility companies. Electric utilities such as the Pacific Gas and Electric Company have committed large sums of capital in their energy efficiency effort. In 1990, PG&E invested 138 million dollars in customer energy efficiency programs and in the next two years plans to spend an additional 300 million dollars. The reason for this huge investment is simple. The cost of the customer energy efficiency programs is about one-half of the cost of building major power plants. A large power plant (one billion watts) costs more than one billion dollars to build (Fickett 1990, p. 65). As a result, utilities are using energy efficiency both to meet growth projections and to avoid the financial and environmental uncertainty of building new power plants.

Energy efficiency projects that reduce peak electrical power demands are of particular interest to utilities. Most lighting efficiency projects have the

advantage of reducing energy consumption as well as power (demand) consumption. These factors point to the continued importance of lighting energy efficiency projects.

With a bright future ahead, what is the next logical step for the lighting efficiency industry? Quantum leaps have already been made with the introduction of new technologies such as the electronic ballast and the compact fluorescent lamp. Continued progress will be made as researchers refine existing technologies and introduce still newer technologies. These technologies, however, will not realize their full environmental and economic potential unless manufacturers, researchers, utilities, and government agencies work to help end-users properly implement lighting efficiency projects.

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APPENDIX A

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Directory of Certified Fluorescent Lamp Ballasts and Certified Luminaire Manufacturers, California Energy Commission 1989 P400-00-026

Directory Of Certified Occupant Sensing Devices,

California Energy Commission P400-000-027, March 1989. Regularly updated.

Electric Power Research Institute (EPRI), Palo Alto, California (415) 855-2000

Energy User News Annual Product Guide (Published in December)

Lighting Design and Application Annual Lighting Equipment and Accessories Directory. Published Every February. (212) 705-7926.

Pacific Gas and Electric Company, Energy Services, San Francisco, California (800) 468-4PGE

Manufacturers Index: Electronic Ballasts

Advance Transformer
Electronic Ballast Technology (EBT), Torrence, California
ETTA Industries
Lutron Electronics
Magnetek Universal/Triad
Toshiba Electronics
Valmont Electric

Manufacturers Index: Fluorescent Lamps

General Electric, Cleveland, Ohio.
GTE Sylvania, Danvers, Mass.
North American Philips Lighting Co., Somerset, N.Y.

Manufacturers Index: Compact Fluorescent Lamps

General Electric, Cleveland, Ohio.
GTE Sylvania, Danvers, Mass.
Mitsubishi
North American Philips Lighting Co., Somerset, N.Y.
Osram Corporation, Montgomery, N.Y.
Panasonic (Matsushita Electric)

APPENDIX B

"Out of the Mechanical Room and Into the Work Place: How to Get Employees to Conserve Energy"

OUT OF THE MECHANICAL ROOM AND INTO THE WORKPLACE:
HOW TO MOTIVATE EMPLOYEES TO CONSERVE ENERGY

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ABSTRACT

Technical engineering techniques do not exhaust all the energy saving opportunities available to the energy manager. At Stanford University, a public awareness program has successfully promoted the wise use of energy for the last eight years. A quarterly newsletter, individual electricity consumption reports, and a catchy advertising campaign are prepared by the central Energy Management Group. Each building or department has a designated Building Energy Manager (BEM) who provides local assistance, keeping track of over 400 campus buildings. Many BEMs are enthusiastic participants in the program, tracking energy consumption patterns and promoting conservation to others in their building. In addition, the Energy Managers help schedule the centralized Energy Management and Control System (EMCS), a vital energy saving task when building schedules change quarterly.

HISTORY OF THE ENERGY MANAGEMENT GROUP

When energy prices rose dramatically in the 1970's, the Stanford community was called on to make sacrifices to avoid financial hardship. Staff, faculty and students responded well to these initial efforts. Local news media reinforced the importance of saving energy. At the time, energy conservation was an important priority. Most were willing to withstand a small amount of discomfort to benefit the campus community. Economic motivations were not yet necessary. The imminent depletion of nonrenewable energy resources such as oil was an incentive for most to conserve. Simple changes, such as vacation shutdowns and different scheduling, were implemented.

Keeping conservation awareness in the limelight is a relatively difficult task: other important issues compete for faculty, staff and student attention. The mission of the university is, after all, education and research, not energy conservation. Some would argue (fortunately very few) that any interruption from their work is a nuisance and not their responsibility. However, most people realize that utility costs must be paid, as opposed to discretionary items in the budget. Money paid for energy directly competes with funds that could be used for teaching,

research or other educational needs. Because Stanford is large the energy cost figures are impressive--annual energy costs exceed \$12,000,000. A large portion of this cost is difficult to reduce. For example, several of the lab buildings require 100 percent outside air due to the types of research being done. Other areas have mainframe computers that have large power and cooling loads.

In 1980 an energy group was formed with the specific charter of reducing campus energy consumption. A two-pronged approach was taken. The first part was technically based. Engineers familiar with building systems such as lighting and H.V.A.C. develop and implement modifications to improve the efficiency of building and utility energy systems. The second part of the group was responsible for public awareness and the implementation of the Building Energy Managers Program.

PUBLIC AWARENESS HURDLES

A good deal of attention has been given to the difficulty of public awareness or informational programs for energy conservation. Several factors contribute to this problem. Perhaps the most significant is the lack of direct accountability for energy costs. At Stanford, individual campus departments are not charged directly for energy. Ways must be found to motivate employees to save energy without using economic incentives. Direct feedback such as meter readings is the most effective tool available. Continuing expansion of facilities, weather variables and occupant changes complicate attempts to calculate the success of an awareness program. Although most people on campus are rational and understand that saving energy is saving money, most underestimate the effect of their individual participation.

BUILDING ENERGY MANAGERS PROGRAM

Because Stanford has over 400 buildings of varying age and usage, keeping track of building schedules, maintenance conditions and energy usage is difficult for a small energy management group. This problem is amplified since schedules change quarterly. Even continually updated records kept by the EMCS and maintenance groups cannot reflect completely how the building is performing. Still missing

are the human factors or the attitudes occupants have about their building. To assist the EMG in monitoring local conditions and attitudes, an individual was chosen in each building to act as an "energy representative," later named Building Energy Manager. Those chosen come from a variety of backgrounds depending on what department they work for or what type of building they work in. For example, in the humanities building energy managers usually are secretaries or administrative assistants. Many of the laboratory buildings, however, have more technical personnel as the BEM, since building systems are complex.

All of the BEMs have other duties and can only allot a certain amount of time to this responsibility. It is important that the BEM know how the building is operated and what the specific needs of the occupants are. These needs might include humidity requirements, special scheduling requirements or emergency power provisions. To be successful, a building energy manager should have an interest in energy conservation, be skilled in persuading others, have the support of those responsible for running their department, and be able to allow for time to promote energy conservation.

RESPONSIBILITIES OF THE BUILDING ENERGY MANAGER

Appealing to a sense of community or "team spirit" is much more effective than mandating participation. A sense of individual commitment comes from several sources. These include the personal sense of responsibility and encouragement from outside sources such as the EMG or their own department. The list below is an outline of the recommended tasks of the Building Energy Managers.

- o Update EMG on schedule changes to make most efficient use of the EMCS.
- o Identify areas of energy waste. Refer technical problems to the EMG.
- o Update graphs describing their building's energy usage. Both the graphs and consumption reports are supplied by the EMG.
- o Post and distribute flyers and a quarterly newsletter provided by the EMG.
- o Act as a project liaison for work done by the EMG in their building. For example, BEM's will know when rooms are available for lighting changes or when fan systems can be shut down.
- o Act as a building energy educator by keeping co-workers up to date on campus energy problems.
- o Establish new patterns of use by personally turning off lights or equipment.

Even the ideal BEMs' interest and commitment can vary. It is the responsibility of the EMG to keep cooperation levels high.

To assist the BEM's the EMG issues an easy-to-read booklet describing basic energy saving techniques. Chapters include how the EMCS works, energy efficient lighting practices, and how energy costs vary from season to season and by time of day. Also included is a description of the type of support the BEM can expect from the EMG. A glossary is included to help readers get through some of the energy jargon that is often taken for granted.

One of the most common excuses for not conserving energy is lack of funds. Many departments have restricted budgets that make even small conservation fixes hard to carry out. To solve this problem the EMG set aside \$450 per BEM to be spent on projects that they identify. The only requirement was that the project save energy and have a two year or better payback. In most instances lighting projects were chosen. In any case, money that can be spent from a different budget (in this case the EMG's budget) is a positive encouragement for doing projects. If BEMs identify larger, more complex projects, the project is referred to the technical part of the EMG.

The ability to react quickly to a variety of problems is another benefit of having a Building Energy Managers Program. For example, last winter was particularly dry in northern California, causing a drought during the summer. Mandatory reductions have been placed on the University requiring prompt action. Since the BEM program is in place, distribution of water conservation materials has been made much easier. A great deal of time has been saved using established building contacts.

THE ENERGY EXCHANGE

To keep the BEMs current on campus energy issues and activities, a packet of information is sent out quarterly by the Energy Management Group. Included in this packet is a four-page newsletter called the *Energy Exchange*. The purpose of this is threefold. First, this is an informal way to promote achievements of the Energy Program and help to make BEMs feel they are a part of these accomplishments. Other developments such as grants or rebates successfully obtained are described. Second, in each issue a BEM profile describes how different BEMs tackle energy waste in their building or how others handle the problems of common interest. Last, it is a way to alert BEMs to seasonal steam shutdowns or other changes which might affect building occupants.

Included with each quarterly mailing of the *Energy Exchange* are energy consumption reports. Most of the buildings on campus have their own meter. Most of the larger buildings also have steam and chilled water meters that are tracked by the EMCS. These meters are read monthly for accounting purposes, and the data is passed on for analysis and summary. A spreadsheet

program (in our case, Lotus 1-2-3) makes data transfer to a format that the BEMs can read quickly and understand. Each BEM gets a readout for the building with a comparison with the same period one year earlier. An added benefit of this mailing is the opportunity to identify sudden increases that may be the result of HVAC or equipment schedule problems. The EMG encourages the BEMs to chart this data and leave it in a visible place for others to see.

The last component of the quarterly mailing is a packet of public awareness posters. Each quarter the EMG designs a poster to remind faculty, staff and students to save energy. Most campus members are receptive to a light, humorous approach. College campuses are a popular place for advertisers, so there is a challenge for the EMG to come up with unique slogans and ideas. Early ads focused on simple conservation ideas such as turning off lights. Several years ago some thought that turning on and off fluorescent lamps used more energy than leaving them on. One poster attempted to dispel this notion.

Don't Be Afraid to Conserve Energy

In order to provide a consistent approach, a theme is usually chosen for the public awareness posters. The current theme is *Don't be Afraid to Conserve Energy*. Monsters were selected from famous horror movies and used with energy-related slogans. For example, the Mummy is shown with the slogan "Sometimes you get all wrapped up in yourself and forget to save energy." Another poster has the Wolfman with the caption "Some things change every full moon, energy conservation is here to stay." Several other monsters, such as the Bride of Frankenstein and Dracula, have been used. In all cases the message is upbeat and positive.

To complement the monster posters campaign, a brochure was developed and given to all campus employees. Using the same monster theme, an explanation of how energy costs affect the university's operation, along with phone numbers of people who answer energy questions, is provided. To help develop good energy habits early, this brochure is also given to new employees. To make sure the brochure is more useful, it folds out into a large map of the campus. In Stanford's case, a map that is attractive can be hung in offices or on cubicle walls and help newcomers find their way amidst the unfamiliar buildings and roads. Others more familiar with the campus can use it as a reference or to give directions. For other companies or institutions a calendar with important dates might be as useful.

While the "monster" posters are visible to most full-time faculty and staff, students can be a difficult audience to reach. At Stanford, energy conservation is encouraged in the dormitories and other campus residences. Some students, however, live off campus and need to be reached in another way. Fortunately, there is a daily student paper where advertisements can be printed. To be effective, the ads

must be unique. Repeating ads more than two or three times diminishes impact. Using the same "monster" poster sent to the BEMs as an ad at the beginning of each quarter is enough to reach our target student group. Reinforcement is an additional benefit of advertising for those have already seen the posters.

RECOMMENDATIONS

- o Support from upper management is required to encourage BEM participation. Without solid support, participation will be uneven. A kickoff letter from a position of authority requesting support can do this effectively.
- o Building energy managers must be selected who can devote a least some time to the program. Fortunately, even a busy BEM who is enthusiastic will make time for energy conservation.
- o Find a way to acknowledge the active BEMs. For example, a short biography in the newsletter or a letter of thanks. Last year the EMG sent T-shirts to the BEMs as a thank you.
- o An energy fair or other display should be presented annually to gain a wider audience.
- o Most importantly, the public awareness effort must communicate that conservation is in the interest of each member of faculty, staff and student body. Explaining energy costs in terms that everyone can understand is vital.

BENEFIT ANALYSIS

Quantifying the energy savings of a public awareness program is a challenging task. Normally energy conservation paybacks are calculated by verifying engineering assumptions. As discussed, meter readings cannot be used to calculate savings unless weather conditions, occupant changes and technical improvements are factored. BEMs were interviewed to determine techniques used in conservation. Some of the techniques were delamping, controlling thermostats and updating scheduling on the EMCS. If the net energy saving coincides with changes in behavior suggested by the BEM, then this saving can be attributed to the BEM program. Savings varied from building to building, but overall program impact is estimated to be one percent of total campus usage, or \$120,000 per year. And \$120,000 is an energy term everyone can understand!

APPENDIX C

"Cautious Application of Electronic Ballasts"

CAUTIOUS APPLICATION OF SOLID STATE BALLASTS

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ABSTRACT

Manufacturer's claims of solid state ballast performance have been of interest to facility engineers for some time. Since these devices are relatively new to the market, little field data on performance exists. As a preliminary step to the installation of solid state ballasts in a large scale project, Stanford conducted independent bench testing of several solid state ballasts. Parameters such as input power, power factor, relative light output, voltage regulation, flicker, harmonic content, and conducted EMI were evaluated in the laboratory. Lamp life and ballast failure are currently being monitored in several small test installations.

The solid state ballasts tested performed 14% to 20% more efficiently than core and coil ballasts. Percent flicker is 33% with a core and coil ballast and between 2% and 26% with solid state ballasts. Harmonic content varied from ballast to ballast. These results are discussed in relation to the requirements of particular lighting applications.

Background

Visitors are almost always surprised to learn just how energy-intensive a place like Stanford University can be. This is by no means a sleepy college community! Stanford's annual energy bill is over \$12,500,000, and lighting represents approximately \$2,800,000 of this total. Since energy is an overhead cost, it competes directly for funds with Stanford's academic mission; hence there is a strong desire to control energy expenditures.

The use of electronic ballasts at Stanford must be seen in the context of the University's broader view of such devices. During the early 1980's large-scale delamping projects and incandescent conversions were completed on the Stanford campus. Many of the early energy management projects--such as delamping--were relatively easy to implement, had quick paybacks, and were easy to reverse if necessary. Because energy management remains a worthwhile investment, however, Stanford continually seeks new ways to conserve energy, often using sophisticated,

innovative products. Many new companies are formed quickly and introduce new products in an attempt to beat other manufacturers to the marketplace. As a result, products not completely perfected are sometimes introduced. Because of the lack of field experience with these new products, Stanford generally takes a cautious approach.

Nonetheless, electronic ballasts show great promise, and not only as energy saving devices. They also reduce flicker, a potential problem for those who work around video display terminals (VDT's). There is evidence that the interaction of fluorescent lamp flicker with display refresher rates affects people who work with VDT's. Since electronic ballasts operate in the 20 to 50, kHz range flicker can be significantly reduced.

We estimate that lighting costs could be reduced by as much as \$250,000 per year if all standard core and coil ballasts on campus were replaced with electronic ballasts. Many buildings are approaching the age where rebalasting is required. In addition, a major campus redevelopment effort that is now under way, with at least one large building planned for each of the next five years, holds further potential for savings. For these reasons the impact of an energy saving device such as the electronic ballast could be very large.

Ballasts are required to perform in different environments and fixture types. It is unlikely that one particular ballast will be optimal for every application. Because of this, we are not looking for one ballast to fit all uses, but rather several ballasts that can be applied where they fit best. The goal is eventually to have enough confidence to specify electronic ballasts for all new construction, remodels, and replacements.

Several considerations kept us from a quick entry into large ballast replacement projects. First, we were concerned that high frequency electronic ballasts might interfere with sensitive electronic equipment. Many buildings on campus have computer or lab testing equipment that is costly and delicate. Furthermore, it is imperative that this equipment operate uninterrupted. Second, standard core and coil ballasts are a stable and reliable product. Their technology is straightforward and has been refined over the last several

decades. Universally accepted data to compare specific electronic ballasts, however, is not available, although the American National Standards Institute (ANSI) is currently working on a revised version of Standard C82 to include electronic ballasts. Manufacturer's data can be quite helpful in explaining product features, but it is difficult to judge performance with this information alone. Direct comparisons become difficult when tests are done under different operating conditions. Each manufacturer uses different lamp fixtures and test equipment to measure performance.

Our final area of concern was Stanford's own acceptance of a new technology. Building occupants are justifiably protective of their work environment and suspicious of changes. Likewise, shop personnel are reluctant to risk repeated trips to a project site when they know a core and coil ballast will work fine. Products, like people, earn reputations that can be long lasting. With sufficient research and investigation a good track record can be established and acceptance will follow. The failure of one project might make it difficult to implement future projects.

Program Objectives

- Collection and Organization of Literature
- Bench Testing
- Field Testing

The purpose of the bench tests is not to uncover unique data but rather to satisfy ourselves 1) that the electronic ballasts will save energy while maintaining acceptable light output; 2) that the ballasts will maintain this performance through reasonable voltage variations; and 3) that flicker can be improved.

We felt the best way to satisfy our concerns was to do our own independent evaluation of electronic ballasts. The first part of this review was collecting and organizing information on electronic ballasts. Letters were sent out to seven manufacturers requesting product literature, technical reports, and in-house testing results. We also asked each manufacturer to contact our office. Some of this information was very useful. For example, we found that some manufacturers recommend using certain lamps. Independent sources such as the Illumination Engineering Society handbooks were consulted to determine the appropriate procedures and parameters for ballast testing. The Lawrence Berkeley Laboratory Lighting Systems Research Group has also written numerous technical articles on electronic ballast performance. Useful references are listed at the end of this paper.

After reviewing the above sources, we decided on a bench test procedure that could compare the operating costs and performance capabilities of the ballasts. The next step was to obtain test equipment and find a

suitable location for our tests. The tests are not complex and can be done by anyone familiar with basic electric circuits and test equipment such as oscilloscopes and ammeters. There are several companies that rent equipment if purchasing or borrowing is not practical. Equipment required would depend of course on the tests chosen. (See the Appendix for the model numbers of the test equipment used.)

Each parameter that we tested has an impact on either direct lamp operation cost, user comfort, or compatibility with other equipment as shown in the table below.

Testing Parameter	Area of Impact		
	Operation Cost	User Comfort	Compatibility
Input voltage	x		
Input line current	x		
Power factor	x		
Light output		x	
Voltage regulation		x	
Flicker factor		x	
System efficacy	x	x	
Harmonics			x
Conducted EMI			x

System efficacy and the voltage-output regulation parameters were derived, and the other parameters were measured directly.

Data Collection

Our interest was to compare only the relative performance of these electronic and core and coil ballasts. Absolute measurements would require additional equipment to calibrate the lamp test fixture. (This is usually accomplished in an integrating sphere.) The disadvantage of relative measurements is that they cannot be readily compared with measurements from other sources, but they were satisfactory for our purposes.

A comparison test requires a reference lamp and ballast. The Sylvania GTE Super Saver II LiteWhite F40/LW/RS/SS 34-watt lamp was used with the GE Maxi-Miser II (core and coil) ballast. This combination was selected because it is the most common on campus. Stanford has made an effort to standardize on one type of four-foot fluorescent. We found that stocking both warm whites and cool whites in 40-watt and 34-watt tubes became too unwieldy for our relampers. Burnt-out lamps will most likely be replaced by whatever is in the relamping truck. Therefore, we selected only those ballasts that did not require a special lamp to operate.

Our carpenter's shop constructed a wooden box to cover the lamps during the tests, to simulate an enclosed fixture with a stable operating temperature. The lamp temperature should be held relatively constant since temperature directly affects light output. To speed testing, a small wooden test board was also built with holes for lead connections. This made it easy to plug in the ballast for each test, rather than hand wire each time.

Prior to the active testing, four fluorescent lamps were burned in for 120 hours each. This was done to ensure stable operation during the experiments. Much of the initial lumen depreciation common in fluorescent lamps takes place in the first one hundred hours. Lamps were also warmed up for at least fifteen minutes before each ballast was tested. Two different ballasts from each manufacturer were used for each test. The ballast testing results are summarized in the Appendix.

Test Equipment and Analysis of Test Results

Input Voltage--This was measured with a digital power analyzer and held constant with a Variac. (A Variac is a variable transformer used to vary and control AC voltage.)

Input Line Current--The power analyzer was also used for measuring the input current in amperes.

Power--Since power consumption directly determines operating costs, it is best to use a power analyzer/wattmeter which will measure true RMS power. Power can also be calculated using the current, voltage, and either a measured or estimated power factor, but this method is not sufficiently accurate.

Power Factor--Power factor can be calculated when the voltage, current, and input power is known (P/VI =Power Factor). Most utilities charge customers for having a power factor under 85%. A high power factor is desirable in order to keep currents down and hence enable the use of smaller-sized conductors. Although performance varied from a power factor of 97.9% to 90.6%, we considered all values to be within an acceptable range.

Lumen Output--Lumen output was tested by taking footcandle measurements with a high quality hand-held digital light meter. First we measured our reference ballast's light output and compared that with the manufacturer's rated average output for that particular model lamp. From this information we determined a correction factor for the rest of the readings. This method, of course, gives only relative measurements, but is adequate for our purposes. Absolute measurements were beyond the scope of our test equipment.

Voltage Output Regulation--Voltage was adjusted with the Variac to ten percent above (132 v) and ten percent below (108 v) standard 120 service. Light readings were then taken to determine how each ballast performed under these conditions. Because small voltage variations can be expected from time to time, the ballast should be able to handle these with a minimum of change in light output. A large change in light output will disturb the building occupants. We also wanted to determine if there was anything in the circuitry to cause them to fail under these conditions. Our tests showed that electronic ballasts appear to be more sensitive to voltage fluctuations than core type ballasts. However, this additional

sensitivity does not appear to be significant enough to cause user discomfort. In no case did the ballasts fail to perform in the specified voltage range.

Percent Flicker--As mentioned earlier, one of the important selling points of an electronic ballast is the reduced flicker over standard core and coil ballasts. The IES 1984 Reference Manual describes flicker as a cyclic variation in instantaneous light output. Since this variation is twice the input frequency (120 Hz modulation when 60 Hz power is supplied), flicker can be virtually eliminated at the frequency range that electronic ballasts operate in (between 20 and 30 kHz). Using a Tektronix light probe with a small amplifier and an oscilloscope, a single cycle light variation was read and the maximum and minimum values recorded. The formula for percent flicker is then $100(\text{max}-\text{min})/(\text{max}+\text{min})$. Although percent flicker varied from ballast to ballast, the results were lower than core and coil ballasts in all cases.

System Efficacy--Efficacy, in lumens per watt, is the best cost performance measure of the lamp and ballast system performance. Electronic ballasts were 14% to 20% more efficacious than our reference core and coil ballast. In all cases the electronic ballasts used less power (watts) than the reference core and coil. In some cases part of this efficacy improvement is at the expense of light output. This can be a problem where light levels are close to or below minimum recommended levels.

Harmonics and Conducted Electromagnetic Energy (EMI)--Harmonic content can be measured using a spectrum analyzer. In simple terms, harmonics are high frequency variations of the fundamental 60 Hz sinusoidal wave form. The electronic switching in the ballasts can produce harmonics that are transmitted back into the power supply. If there is enough disturbance in the power line, other sensitive equipment (such as personal computers) could be disrupted. In a three-phase power system the neutral can become overloaded with a large third harmonic. EMI effects are potentially higher with the electronic ballasts. However, in some cases they were the same or lower than our reference core and coil. Therefore, EMI readings should only be of concern where sensitive equipment is operated at the same fundamental frequency as the electronic ballast (20-30 kHz).

Field Testing

Field testing is the last part of ballast evaluation. There are several key parameters that cannot be bench analyzed. One is the effect that electronic ballasts have on fluorescent lamp life. The best way to test this is to install the ballasts into typical work environments and monitor their performance. An hour meter can be installed at the circuit panel to measure lamp life. Another concern is audible noise problems. In one field test, electronic ballasts were

installed with a manual dimmer. Several ballasts had a noticeable hum that increased as the light level decreased. Some people seem to be more sensitive to this than others. The problem was solved by installing a different brand of ballast.

In one of the field tests we found that additional labor costs for installing new lamp ballast combinations should be considered. For example, some ballast manufacturers offer three-lamp and four-lamp models. Though these can lead to a more efficient lamp ballast system, our relampers were not familiar with these products, and it took repeated trips to the site before they were acquainted with the new wiring requirements. In some cases this doubled the installation time for a normal two-lamp or one-lamp ballast (also part of three-lamp and four-lamp fixtures). Probably this time will be reduced once the relamper has installed a number of units, but it may be a continuing concern.

An interesting side benefit of electronic ballasts came to our attention recently while completing a lighting project in one of our music buildings. For many years the Dinkelspiel Auditorium recital hall had been lit by 22 300-watt incandescent lamps. When it became necessary to renovate the room and install a drop ceiling it was appropriate to install fluorescent fixtures. The musicians were pleased with the renovation aesthetically but claimed that the hum from the fluorescent ballasts was annoying. When visiting this site it was difficult for the untrained ear to determine the origin of this complaint. Nothing appeared out of the ordinary. When the musicians insisted that something be done we called the Lighting Systems Research group at Lawrence Berkeley Labs to see if they had had similar experiences. As it turns out, a standard core and coil ballast operates at a frequency between the musical notes B and B-flat. Because of this, the musicians using this room had difficulty tuning their instruments. Electronic ballasts were then installed, and because of their higher frequency operation they alleviated the problem.

Further Considerations

Other considerations not yet discussed include ballast cost and manufacturer reliability. Costs are continually changing and can vary with quantities purchased and vendor competition. When contacting vendors we found large variances in cost, availability, and delivery time. As with any large purchase, recommendations from other users should be solicited.

Dimming capability is a feature available with some electronic ballasts. We did test one of the electronic ballasts that had an external dimming feature. Input power, power factor, and voltage regulation tests were repeated at one-third and two-thirds of 100% light output. As expected, power input and light output are nearly proportional. At lower light levels this relationship appears to fall off. This

is apparently due to the power requirements of the lamp filament to preserve lamp life. Power factor decreased by 7% to below 85% at one-third light output. Besides the additional energy savings, dimming offers a convenient method of adjusting light levels without the expensive control hardware required for dimming core and coil ballasts. Dimmable ballasts can also work in combination with daylight design strategies. Ballast performance under dimmed conditions is worth further investigation. Our dimming tests were done with only one manufacturer, who has since gone out of business. For this reason the results of the dimming tests are not included in the Appendix Summary.

Conclusions

- Electronic ballasts result in energy savings at the expense of some light output relative to core and coil ballasts.
- Efficacy of electronic ballast systems is 14% to 20% higher than core and coil ballast systems.
- Electronic ballast systems appear to be more sensitive to voltage fluctuations than core ballast systems. However, the observed variations are not considered significant.
- EMI effects, as expected, were generally more pronounced in electronic ballasts. However, except for environments where equipment is operated in certain frequency ranges (coinciding with 20-30 kHz fundamental), EMI effects were secondary.
- No one ballast exhibited across-the-board superiority in performance (with respect to measured parameters).
- Electronic ballasts performed well in the power factor tests and in all cases had flicker levels below core and coil ballasts.

Acknowledgment

Our energy management group is in the unique position of being able to hire highly qualified part time help from our student body. Thomas Ikuenobe, a part time employee of Stanford's Energy Management Group and a doctoral candidate in the school of Electrical Engineering, conducted the bench tests for us.

Ballast Test Summary

BALLAST MODEL	# OF LAMPS	VOLTAGE (VOLT)	CURRENT (AMP)	POWER (WATT)	EFFICACY (LUM/WATT)	OUTPUT @120V (LUMEN)	REGULATION	
							@108V	@132V
Electronic "A"	2	120	0.51	55.8	82.3	4592	-9.69	6.99
Electronic "B"	4	120	0.94	106.7	81.5	8700	-5.31	-0.83
Electronic "C"	3	120	0.76	85.2	79.4	6764	-6.61	9.36
Electronic "D"	2	120	0.48	53.3	78.6	4187	-9.03	7.88
Electronic "E"	2	120	0.50	56.5	78.1	4414	-8.02	8.84
Electronic "F"	2	120	0.46	54.0	77.5	4183	-9.71	11.04
Electronic "G"	2	120	0.49	54.7	75.7	4139	-9.23	8.48
Core and Coil "1"	2	120	0.48	55.9	71.5	3996	-4.38	3.88
Core and Coil "2"	2	120	0.63	68.5	65.5	4490	-4.99	3.01
Core and Coil "3"	2	120	0.62	72.8	65.1	4740	-1.60	2.62

BALLAST MODEL	FLICKER (%)	PF (%)	Harmonic as %age of the fundamental			CONDUCTED EMI (dbuv)
			(3rd)	(5th)	(7th)	
Electronic "A"	3	90.6	25.0	3.2	1.3	93
Electronic "B"	2	94.7	6.3	6.3	4.0	118
Electronic "C"	8	93.5	32.0	1.0	0.8	113
Electronic "D"	11	93.3	16.0	3.2	1.0	113
Electronic "E"	10	93.6	32.0	1.0	0.8	110
Electronic "F"	26	97.2	10.0	2.0	1.0	115
Electronic "G"	5	93.2	25.0	2.0	1.0	93
Core and Coil "1"	33	97.9	16.0	4.0	0.3	55
Core and Coil "2"	33	90.8	16.0	4.5	0.0	55
Core and Coil "3"	33	97.8	16.0	5.0	0.1	55

Equipment List

1. Two 2 lamp Fluorescent fixtures
2. Variac (0-230V)
3. Fluke 77 Multimeter
4. Fluke Digital Thermometer 2176A
5. Valhalla Scientific Digital Power Analyzer 2101.
6. Litemate III Photometer (Photo Research)
7. Tektronix Light Probe J6502
8. Power Supply 0-40VDC 0-5A (Holtek Electronics HR40-5B)
9. Hitachi Oscilloscope
10. Beckmann Industrial Oscilloscope Granit Mate 9020 (20 mhz)
11. HP 3580A Spectrum Analyzer 0-300khz
12. Triplet Current Transformer
13. Polaroid CR-9 Land Camera
14. Wooden Lamp Fixture

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APPENDIX D

"Lighting and Energy Conservation: A Review of Current Technologies"

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In This Issue...

<i>F. William Payne, Strategic Planning for Energy and the Environment, Editorial</i>	5
<i>Christopher Flavin, The Shape of a New Energy Future</i>	8
<i>Anne L. Lyons, Abating Global Warming—At a Profit</i>	21
<i>Dr. Hameed G. Nezhad, World Energy Scenarios for the Year 2010</i>	26
<i>He Athaj Rikvanu Lukman, OPEC and the Environment</i>	50
<i>Scott Gould, Lighting and Energy Conservation: A Review of Current Technologies</i>	52
<i>Michael B. Whaley, Energy Management in New Construction</i> ...	67
<i>John S. Hies, Energy Forecast: Houston Will Revive</i> ...	72
<i>Philip C. Craver, The Emerging Trillion-Dollar Electric Energy Market</i>	74
<i>New "Energy from Biofuels" Study</i>	78

Strategic Planning for Energy and the Environment

J. William Payne, Editor-in-Chief

Lighting and Energy Conservation: A Review of Current Technologies

SCOTT GOULD
Stanford University

PRODUCTS DESIGNED TO REDUCE LIGHTING ENERGY CONSUMPTION ARE OF constant interest to facility engineers, lighting designers and energy management professionals. Data supplied by manufacturers can be helpful in explaining features of these products, but it is difficult to judge their performance with this information alone. Products such as electronic ballasts, occupancy sensors, and dimming systems are continually developed and refined, yet insufficient field data are made available to the end user. Sparse data exists on the effects that these products have on the building occupants and building systems.

This article will define lighting product parameters such as input power, power factor, relative light output, voltage regulation, flicker, harmonic content, and conducted EMI and briefly explain the relevance of these parameters to the end users of these products. Recommended (or tolerable) values for these parameters will be given, followed by an evaluation of lighting products in the view of these characteristics and recommended values.

Despite the recent stabilization of energy prices at unrealistically low values, many companies continue to view energy management as a worthwhile investment. Lighting continues to consume forty percent of the electrical power load of most commercial buildings. In specialized applications such as retail or display lighting, that figure is often higher.

Most companies have implemented the simplest of energy manage-

ment measures. Projects such as delamping or converting incandescents to fluorescents were completed during the early 1980s. Projects that require more engineering and coordination are necessary to secure additional lighting savings.

Many products are being introduced and new companies are being formed to supply energy reducing equipment. As a result, some products not completely perfected are introduced. Sometimes products are marketed that neglect important productivity or ergonomic factors such as eye strain or glare.

Since these products can require a large capital investment—and therefore compete with investment or growth funds—project risk must be minimized. Current building regulations mandate that energy efficient features be included as part of new building and retrofit design, adding to the number of energy products purchased annually.

A gap exists in the information available to lighting professionals. Although energy conservation lighting products are tested, the results are often not in a format useful to the end user. Product research most often comes from three sectors: manufacturers, utility-sponsored research firms, and manufacturer-sponsored testing laboratories. Each sector has its own justifiable, separate bias.

1. Manufacturers of lighting products often make available product specifications and performance claims as part of their advertisements or technical catalogs. Often their data highlight only the positive aspects of a product's performance. This is not usually an attempt at fraud, but rather an effort to put the product in the most favorable light.

Another potential problem with manufacturer's data is the lack of a reference standard against which results can be compared. In addition, critical evaluation factors that affect performance are often not standardized, making a comparison of similar products from different manufacturers difficult. These factors combine to make the evaluation of product literature difficult for the end user.

2. Another source of information on the performance of lighting products is utility-sponsored research firms such as the Electric Power Research Institute (E.P.R.I.). Utility-sponsored research firms collect data and organize research in areas that affect the operation of utilities.

In the case of lighting products, the utilities are interested in learning the effect a particular product or class of products will have on their electric distribution system. For example, several utility-

sponsored studies have focused on the electromagnetic interference or other power quality issues that new lighting technologies may present. These studies are not usually intended to be used as end-user product evaluations.

3. The third group involved in the evaluating of lighting product testing is independent testing laboratories. This group authors authoritative papers on all aspects of lighting product performance. Unfortunately, as in many research areas, specific evaluations are only completed when a sponsor is interested in funding a specific research project. The research may also be too technical for many end users.

This analysis which follows is broken down into three areas that affect purchasers: **impact analysis, savings calculation methods, and recent product advances.**

The impact analysis section describes aesthetic, safety, and comfort issues as well as maintenance considerations.

The savings calculation portion points out some of the variables that must be considered when determining cost feasibility.

Recent product developments, described in the preceding two areas, are reviewed.

Due to space limitations, only three indoor lighting products are discussed. These are occupancy sensors, electronic ballasts, and compact fluorescent lamps. All installations mentioned have been completed on the Stanford University campus by the university's in-house Energy Management Group. There are many other lighting technologies that warrant further investigation. These three products, however, have been widely used on the Stanford University campus so more background material on these conservation technologies is available to the author.

Occupancy Sensors

Manual Control vs. Occupancy Sensors

One of the most frustrating tasks for the energy manager is convincing building occupants to turn off the lights. Light switches are simple to operate, yet even a short stroll through any school or office building reveals lights left on unnecessarily. People either forget to turn off lights or, in larger areas, are reluctant to turn the light off on someone who might be in another part of the building.

Manual control, where possible, is the preferred method of on/off lighting control and should be considered before any discussion of occupancy sensors. The advantages of manual control are obvious: no additional installation or engineering costs, no nuisance shutoff or "ghost" detection, very little training. Users also get in the habit of thinking about energy and may turn off computers, printers and other office equipment.

Despite these advantages, experience shows us that manual lighting control can only be used effectively in controlled areas. These might include laboratories or libraries where a single person is responsible for watching an area. Public areas such as classrooms, conference rooms, hallways, and open office areas are not usually good candidates for manually controlled lighting.

Types of Occupancy Sensors

Occupancy sensor operation is simple. When no movement is detected in a controlled space for a given period of time the sensor will operate a relay to shut the lights off. The two most popular methods of doing this are with either ultrasonic or infrared sensing. Although limited, microwave and audio sensors are also available. *Energy User News* has listed fourteen manufacturers. About two-thirds of the companies make infrared units, and the remaining third specialize in ultrasonic. At least two companies manufacture both types.

Although the specific method of operation varies, ultrasonic type sensors detect movement by responding to frequency changes produced by interference with a moving object (Doppler shift). Infrared sensors respond to movement of heat sources within the unit's range.

Most sensors have two adjustable controls. The first is a time delay that allows the operator to set the interval between the last time the sensor detects motion and the time the lights switch off. The second adjustment allows the user to set the unit's sensitivity, or more specifically, how much movement is required to activate the sensor.

Even though different models of sensors are constructed for use in specific room shapes and sizes, the sensitivity adjustment allows for more precise coverage. For example, cubicle walls, carpeting, movement outside windows or doors, and air movement from HVAC ducts can all affect the sensor's operation.

In addition, rooms are occupied differently. Active areas such as cafeterias require a different sensitivity level than a quiet office with someone working on a personal computer. Potential problems can be moderated by the sensitivity adjustment.

Neither type of sensor is intrinsically "better" than the other. Because they are not directional, ultrasonic sensors work better in areas with obstacles such as cubicle walls or partitions. This can also be a disadvantage when the coverage area spills into areas such as corridors or adjacent rooms. Infrared sensors are cheaper to manufacture and somewhat simpler in design, so they are generally less expensive.

Savings Calculation Methods

Although the equation for determining energy savings from occupancy sensors is straightforward, obtaining accurate assumptions for the calculation can be difficult. The most accurate method is to set up a simple field test. All that is required are two inexpensive hour meters and an occupancy sensor.

One hour meter is used to determine how much time the lights are on during a given period of time. The second hour meter records only the amount of time the sensor would operate if it was controlling the lights instead of just the hour meter (actually, this is sensing the hours the space is occupied).

The difference in these two readings gives an accurate idea of potential energy savings. Of course, the longer the test the more accurate the results. Take caution to select a site that represents the potential project.

At Stanford we performed such a test on seven classrooms. The number of hours saved on an annualized basis ranged from 600 hours to 2730 hours. The average number of hours saved was 1,300. Because the amount of "off" time used in the equation really drives the savings calculation, care should be taken to determine this number accurately.

Impact Analyses

The following analyses should be considered part of any occupancy sensor installation. Each particular item should be weighted according to the type of occupants, type of space and economic priorities of the company or institution.

System Operation: Aside from the time and sensitivity adjustments, most occupancy sensors include a combination of the following features: A L.E.D. to indicate sensor operation and range, a bypass to remove the sensor from the lighting circuit, and an override used to switch off the lights for showing slides or movies. Several manufacturers offer "slave sensors" to work in combination with a "master sensor" to extend coverage range.

Adding features to a sensor usually only requires additional circuitry. Absence of a certain feature may reflect the manufacturer's design philosophy. For example, not all sensors include a bypass switch. Some claim that the occupant will use the bypass to defeat the sensor, and thus impede energy savings. Others claim that making a bypass available is preferable to having someone not familiar with sensor operation or lighting circuits attempt to adjust or repair it. Ideally, the bypass can be used to reduce the inconvenience to the building occupant. Sensor adjustments or repairs can be made later by competent personnel.

Maintenance: The success of any sensor installation is largely dependent on the amount of maintenance required to keep them operating properly. Several things must be done early in the engineering and installation phase to avoid problems.

- Enough sensors must be used to cover the space properly. Although this seems obvious, competitive bidders often reduce the number of sensors used to gain the low bid. This can result in nuisance shutoff.
- Sensors should not be used to the limits of their coverage capabilities. If a room is 1000 square feet, select a sensor that can cover a larger area or use two 600 sq ft sensors.
- In-house personnel must be trained in sensor operation. Unfortunately, the newest or most unfamiliar item will be the suspect in any lighting problem. If the electricians know how the sensors operate and how they were installed, the chances increase that they will be adjusted correctly.
- If a large project is completed with many different types of rooms and wiring schemes, a single line sketch of the room should be required of the installer to show the location of new relays or transformers. This is especially critical in areas that have complicated switching layouts. Troubleshooting time can be reduced with simple, organized installation details.

- Two features make testing and troubleshooting easy: the first is the L.E.D. indicator and the second is the short time test mode. The L.E.D. is illuminated when the sensor detects motion. This is necessary to check the sensor's range. The short-time test-mode bypass sets the sensor timer to shut off the lights after only 15 seconds. Both of these features decrease the amount of time needed to troubleshoot the sensors.

- Although the cost of energy is much greater than the cost of lamps, the time delay and sensitivity should be set to avoid excessive lamp cycling. This will help prevent early lamp burnout.

Aesthetics, Safety, and Comfort Issues: Unlike electronic ballasts or optical reflectors, occupancy sensors are a high visibility product. Building occupants are quickly aware of sensor problems. For this reason the importance of proper installation is emphasized. Although many people will put up with early tuning adjustments, few will put up with continuing problems.

In 1983, the health impact of ultrasonic occupancy sensors was considered by the California Energy Commission. Ultrasonic sensors are "active" by nature: that is, they emit high frequency sound. This tone is above the levels audible to the human ear (25 kHz). Several groups (American National Standards Institute, Department of Health Services) have concluded that the sound pressure levels (dB) emitted by ultrasonic sensors do not adversely affect the health of workers. A high quality sensor will also be free of any subharmonics and emit only a "pure" tone. Infrared sensors, by virtue of their passive operation nature, have no potential adverse effects.

Recent Sensor Advances

Although recent changes in occupancy design are subtle, they warrant discussion. Manufacturers have been working to increase coverage areas, to improve the transmitting and receiving electronics in the ultrasonic sensors, and to improve the lens optics in the infrared sensors. Wall switch sensors have become increasingly popular, and sensor installers have improved their application techniques.

The increasing popularity of wall switch sensors is due to their low cost and easy installation. Sensor installations can now be completed cost-effectively in smaller rooms with fewer fixtures. Although some wall sensors will cover areas as large as 800 sq ft,

perhaps their best application is in single offices or conference rooms with few obstructions. Both ultrasonic and infrared wall switches are available.

One manufacturer is preparing to introduce a wall switch sensor with a photocell control. Not only will the sensor turn off the lights when no one is in the room, but it will also turn off the lights when a preset amount of sunlight is available making the fluorescent lights unnecessary. Since traditional indoor photocell control is rarely cost effective in small areas, this sensor will be particularly useful in peripheral offices and other sunlit rooms.

In an effort to reduce nuisance shutoff, one manufacturer has increased the time delay from 10 minutes to 15 minutes. The amount of energy saving lost is minimal, yet complaints due to accidental shutoffs are reduced.

One way to improve the coverage area of infrared sensors is to improve the optical quality of the lens. The larger the number of facets the more complete the coverage the sensor will provide.

The ability to identify the most appropriate application for occupancy sensors is perhaps the most important recent achievement in the sensor industry. Although technical features have improved, the experience gained from innumerable sensor installations has increased the success rate of new installations.

Electronic Ballasts

Electronic ballasts have shown great promise as energy-saving devices. Manufacturers claim a 10 to 20 percent energy reduction when compared with core-and-coil ballasts. Electronic ballasts perform the same function as standard core-and-coil ballasts (i.e., regulate current flow and voltage to the fluorescent lamps), but use solid state technology to operate at a much higher frequency. This high frequency operation allows the ballast to operate with lower losses, making them more efficient than core-and-coil ballasts.

Aside from energy savings, electronic ballasts offer several other advantages over core-and-coil ballasts. One advantage is the potential for reduced flicker, a problem for those who work around video display terminals (VDTs). In addition, some electronic ballasts offer a dimming control feature that can increase energy savings and flexibility.

Three factors have made energy managers cautious about purchas-

ing electronic ballasts: a high premature failure rate with early electronic ballasts; a potential for excessive harmonics and conducted electromagnetic interference (EMI); and a higher cost per unit. Many manufacturers have improved internal ballast circuitry and quality testing techniques to diminish these problems.

Savings Calculation Methods

Accurately calculating the energy savings for electronic ballasts is difficult. Ballast manufacturers claim 14 to 20 percent energy savings, but several factors influence the actual energy savings: the existing ballast/lamp combination energy consumption; the proposed ballast/lamp combination energy consumption; and the hours of operation.

To complicate the evaluation further, there are no universally accepted standards to compare electronic ballasts. (To remedy this problem, the American National Standards Institute is now working on an update of Standard C82 to include electronic ballasts.) As mentioned above, input watt measurements only tell part of the story.

Impact Analysis

Since most ballasts are not visible, building occupants are unaware of ballast changes or retrofits. Unless there is an unusually high number of early ballast failures, occupants should not be negatively affected by any ballast project. The following factors should be studied before a ballast installation is considered:

System Operation:

- *Ballast Factor:* Ballast factor is a comparison of the lumen output from a reference ballast with that of the subject ballast. In a retrofit, the new ballast factor should be at least equal to the ballast factor of the ballast being replaced (unless the light level is too high). In new construction, the ballast factor should be considered as a part of the lighting design.
- *Voltage Regulation:* Because small voltage changes occur from time to time, the ballast should be able to accommodate these with a minimum of change in light output. A large change in light output will disturb building occupants. An electronic

ballast should be expected to handle a ten percent voltage fluctuation without affecting user comfort.

- *System Efficacy:* Efficacy, in lumens per watt, is the best cost performance measure of the lamp and ballast system performance. Electronic ballasts have been shown to be more efficacious than core-and-coil ballasts. Sometimes this efficacy improvement is at the expense of light output! This is a problem when light levels are already close to or below minimum recommended levels. The total amount of light output should be considered in every electronic ballast installation.
- *Harmonics and Conducted EMI:* In simple terms, harmonics are high frequency variations of the fundamental 60 Hz sinusoidal waveform. The electronic switching in the ballast can introduce harmonics that are transmitted back into the power supply. A small percentage of harmonics will go unnoticed, but larger amounts can disturb sensitive electronic equipment. Many electronic ballasts now manufactured have acceptable harmonics and EMI levels.
- *Power Factor:* Most utilities charge a penalty to customers with a total power factor under 85 percent. A high power factor is desirable to keep currents down and enable the use of smaller sized conductors. According to the IES, a high power factor is above 90 percent.

Aesthetics, Safety and Comfort Issues:

- *Percent Flicker:* One of the important advantages of electronic ballasts is the potential to reduce or eliminate flicker. The IES 1984 Reference Manual describes flicker as a cyclic variation in instantaneous light output. Since this variation is twice the input frequency (120 Hz modulation when 60 Hz power is supplied), flicker can be virtually eliminated at the frequency range that electronic ballasts operate in (between 20 and 30 kHz). Magnetic ballasts operate at 33 percent flicker. A reduction in percent flicker can improve lighting conditions especially for those who work around VDTs.
- *Audible Noise:* Ballast noise or hum is the result of vibrations caused by the magnetic elements in a core-and-coil ballast. Because electronic ballasts are solid state, manufacturers claim audible noise is reduced. Each company publishes sound ratings

that indicate a relative sound output. The highest rating "A" is used for most indoor applications.

Maintenance Considerations:

- **Lamp Life:** Some manufacturers claim that electronic ballasts extend the life of fluorescent lamps. In most cases this claim is based on accelerated life tests. Most of the electronic ballasts available today have not been on the market long enough for longevity field test data to be complete. Since lamp life is a function of many factors, it may be difficult to extrapolate even good test data to other sites. In addition, there are many possible combinations of lamps and ballasts, further complicating the issue. Although some buyers complained of reduced lamp life when electronic ballasts were first introduced, the installations at Stanford have been free of this problem.

There are two strategies for controlling fluorescent lamp burnouts. Sometimes the electronic ballasts will only operate if the circuit is complete (e.g., if one lamp burns out the ballast will shut itself off along with any other lamps powered by that ballast). This strategy is intended to protect the ballast circuitry.

The second strategy is to let the good lamps operate even with a burnt out lamp. There are several advantages to this second strategy. When new ballasts are installed, it makes sense to use new lamps even in retrofit applications. If one of the new lamps happens to be defective, it will be unclear to the installer if it is the lamp or ballast that isn't working.

This can waste time, especially if the ballast supplies three or more lamps. In areas where few fixtures are present, if the whole fixture goes out there may not be enough light available for safe egress. This can be a problem particularly in areas with dispersed fixtures.

Not all of the companies that have marketed electronic ballasts are still in business. Warranty and service should therefore be part of the product evaluation. Most companies offer at least a two-year warranty. Some warranties include a labor allowance of up to ten dollars per ballast. Service is managed either factory-direct or through the distributor.

Recent Ballast Advances

An important recent advance in electronic ballasts is the use of

integrated chip technology. By using microchips, manufacturers will be able to sell electronic ballasts at a lower price, making them more competitive with core-and-coil ballasts. In addition, these microchips can be designed to improve dimming capabilities.

Electronic ballasts have also become available for a wider range of indoor lighting applications. Initially, ballasts could only be found to operate four-foot lamps. Now electronic ballasts can be purchased to operate eight-foot lamps, and high-output lamps. In addition, one, two, three, and four lamp models are available. Manufacturers are also stocking electronic ballasts to operate T10 and T8 lamps. Most of these combinations can be found in either 120 or 277 volt.

Compact Fluorescent Lamps

Compact fluorescent lamps are available as energy saving alternatives to standard incandescent lamps. Although these lamps can initially cost as much as ten times more than incandescent lamps, compact fluorescents are often cost effective. While specifications vary from manufacturer to manufacturer, an 18-watt compact fluorescent usually replaces a 60- to 70-watt incandescent. In addition, compact fluorescents have an operating life of 10,000 hours compared with 750 hours for a standard incandescent.

Compact fluorescent lamps generally can be used as replacements for incandescent "A" or "T" lamps. But because most compact fluorescents are larger, heavier and shaped slightly differently than incandescent, they cannot be used to replace incandescent in all situations.

Two different types of compact fluorescents are available, an integral type and a modular type. Integral compact fluorescents are sold as a single lamp and ballast unit. An integral lamp looks like a slightly oversized incandescent bulb. Modular compact fluorescents, often referred to as "PL" lamps have a separate plug-in lamp and ballast. The advantage of the modular approach is the ballast can be reused when the lamps burn out. A typical modular compact fluorescent can be found with lamp wattages ranging from 5 to 13 watts. Most integral models are between 15 and 20 watts.

Savings Calculation Methods

Calculating the energy savings for installing compact fluorescents is straightforward and without the pitfalls that make some energy

calculations difficult. The only variables needed are the hours of operation, the wattage of the existing lamps, and the wattage of the proposed lamps. A more rigorous estimate of the total savings as a result of a compact fluorescent project will include other economic factors such as maintenance and relamping savings.

Impact Analysis

System Operation: Although this type of project may appear simple, several factors should be considered as a part of every compact fluorescent project.

- **Compatibility:** When compact fluorescents first became available, there was an incentive for manufacturers to design and produce lamps quickly. Because of this, there are many different sizes and shapes of lamps and bases on the market. Stocking replacement lamps for a variety of models and manufacturers is cumbersome. Versatility should be considered when selecting lamp models. Standardization of lamp sizes and bases will alleviate this problem.
- **Power Factor:** Power factor can be calculated when the voltage, current, and input power is known (P/VI =power factor). A high power factor is desirable to keep currents down and hence enable the use of smaller-sized conductors. Compact fluorescents often have a low power factor unless power factor correction is included in the circuit design. Unfortunately, not all compact fluorescent lamps have built-in power factor correction. Although installing a small number of compact fluorescent with low power factor will have only a limited effect, a large number can overload the electrical distribution system.
- **Flicker:** Some compact fluorescent lamps have electronic ballasts that reduce or eliminate flicker. Flicker may be noticeable in some task lighting applications but is generally not a problem in most compact fluorescent installations. (There is a more detailed discussion of flicker in the electronic ballast section.)
- **Heat Buildup:** There is evidence that the light output of compact fluorescents decreases as the temperature of the lamps increases. A 1989 Advance Lighting Technologies report drafted prepared for the California Energy Commission points out that rated lumens are measured at 77°F, a condition that is likely

only to occur in an open fixture. At 95°F the light output of compact fluorescents decreases by 7 percent, at 113°F the light output decreases by 17 percent, and so on. Since a common application of compact fluorescents includes recessed can fixtures and other reduced air circulation fixtures, some light loss should be expected.

Maintenance: Relamping costs can be significantly reduced with compact fluorescent lamps when compared to incandescent lamps. Most compact fluorescents have an operating life from between 9,000 and 10,000 hours. In many cases, the reduced replacement costs are greater than the energy savings!

For example, a compact fluorescent rated at a 10,000 hours life will last for just over three years in a typical nine-hour-per-day, 360-day-per-year environment. Under these same conditions, a 750-hour incandescent will need to be changed over four times per year (or thirteen times for every time a compact fluorescent is changed).

Using costs at Stanford to continue the example, energy at \$.06/kWh and labor rates at \$30 per hour, the energy savings would be \$8.16 per year whereas the maintenance savings would be \$21.60. Even with long-life incandescent lamps (2500 hours rated life) there still is a \$6.50 annual maintenance savings. This simple example points out an important side benefit of compact fluorescents.

Aesthetics, Safety, and Comfort Issues

Aesthetics: The color "quality" of compact fluorescent lamps varies. Many of these lamps have a color rendering index over 80 and up to 85. There is also a wide range of color temperatures available from 2700K to 5000K. Caution should be taken to avoid mixing lamps of different color temperatures in the same area. The slightly larger size and heavier weight of compact fluorescents makes some applications, such as desk lamps with swinging arms, impractical.

Safety: Some of the integral compact fluorescents are not recommended for use in enclosed unvented fixtures.

Recent Compact Fluorescent Advances

Compact fluorescent lamps have improved significantly since they were originally introduced. Some of the first models were shoddily constructed. New compact fluorescent lamps are well constructed and reliable. In addition, fixture manufacturers are designing fixtures

and reflectors to take advantage of the size and shape of compact fluorescents to improve light output.

High power factor compact fluorescents are now available with a power factor of 95 percent for magnetic ballasts and 105 percent for the electronic ballasts. These lamps offer the same color temperature and color rendering indices as the other compact fluorescents.

Higher wattage compact fluorescents with greater light output are also now available. Some can be used in traditional applications such as replacements for incandescent lamps. Other compact fluorescents will be used for more innovative fixture designs or to replace standard fluorescent fixtures.

About the Author

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APPENDIX E

"Using Submetering and Computer Modeling to Verify Energy Savings in New Construction"

USING SUBMETERING AND COMPUTER MODELING
TO VERIFY ENERGY SAVINGS
IN NEW CONSTRUCTION

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Abstract

Once building construction is complete, as-built drawings, computer simulation models and pre-construction energy calculations are often neglected by energy managers. These documents are an invaluable aid in evaluating building performance. This paper compares the energy consumption predicted in a mixed-use academic building with the actual energy consumption measured during the first three years of operation. This paper also recommends a report format that can be used by energy managers in future performance studies. Although each performance study will depend on the available information, the methods used in this report can easily be applied to future studies of other buildings. Perhaps the biggest advantage to doing such a report is that these methods can alert energy managers to consumption problems that could otherwise have gone undetected.

Introduction

Energy managers continually look for innovative ways to save energy. This paper will attempt to tie together three common energy management practices and at the same time reemphasize the importance of each. In doing so, this paper will discuss a method of alerting energy managers to excessive energy consumption in their newer buildings.

Often, new buildings are not considered good candidates for large energy retrofit projects. There may be an assumption that new buildings are designed to operate more efficiently or that energy dollars are better spent on older buildings. In some cases this is true; new buildings are designed more efficiently. But they may at the same time use more energy because of higher cooling loads brought on by the more compact, energy-intensive office and computer equipment. New buildings also may have more complex control schemes that offer the opportunity to save energy but also risk using much more energy if not adjusted or maintained properly.

Energy management projects involve more than theory and calculations. Some experience and skill are required to make the proper assumptions and the appropriate deductions in all phases of these analyses.

Step 1. Establishing a Reference Baseline

There are several ways to estimate an energy consumption reference baseline (how much energy a building should be using).

These range from building-specific, sophisticated modeling programs to more general nationwide consumption data. Not surprisingly, the trade-off is one of accuracy versus cost, since computer building models require an investment of time and start-up costs. A discussion of the trade-offs follows:

There are many good computer programs available to the energy engineer. In the 1990 ASHRAE Journal's "HVAC&R Software Directory" there were 75 software packages directly related to energy analysis simulation. The central theme of these programs is the ability to maintain some values constant (such as climate) while at the same time comparing the effect of design alternatives. For example, different types of glass could be compared and the benefits of each type could be weighed. Since weather, building schedules, solar loads, etc. are all compared on an hourly or daily basis, the accuracy is much closer than could be performed by hand calculations using broad assumptions.

The simplest programs display limited flexibility and may only allow for a few zones or certain types of equipment. More complex modeling programs, however, offer several advantages. The single greatest advantage is increased accuracy. Programs such as the Department of Energy (D.O.E.) II can typically estimate total energy usage within fifteen percent for a well modeled building. Another advantage is increased flexibility. Increased flexibility means the opportunity to specify a level of detail that is appropriate for the particular run. For example, if the specific construction materials are known, the precise thermal values can be used. If not, a representative "U" value can be assigned.

The cost for increased accuracy is both time and money. Sophisticated programs require training to operate them and time to gather data accurately. There are methods to control these costs, however. In California, energy calculations are required for new construction and large retrofits. Programs such as D.O.E. II are approved techniques for complying with Title 24 Standards. Two methods of compliance are available. The first is the "prescriptive" method, where the building must comply with specific design requirements such as walls and ceilings with a certain "U" value. The second method, specifically intended to allow for more innovative designs, is called the

"performance" method. For this method, the building can comply if it uses less than a set amount of energy per square foot. In some cases the energy manager can specify the computer building model at the design stage and take advantage of both the design and analytical capabilities.

Computer modeling can either be done in-house or by a consultant. For large companies or institutions where many building simulations will be performed, it may be worthwhile to develop this expertise in-house. Many of the simulation programs are available for use with microcomputers. On the other hand, if personnel resources are limited, finding an experienced consultant may be a better option.

If computer simulations are not feasible, there are other ways to establish a reference baseline. One way is to extrapolate the building energy consumption from similar buildings in a similar climate. The Department of Energy/Energy Information Agency publishes two helpful reports in this connection: Commercial Buildings Consumption and Expenditures 1986 (1990); and Characteristics of Commercial Buildings 1986 (1988). Consumption data are listed according to building type, building size, and climate. Although these are averaged values, the figures can be used as a starting point for establishing a reference baseline.

Step 2. Metering Energy Consumption

Documenting energy consumption is a fundamental part of any successful energy management program. For utility-owned meters this is a simple process. The consumption amounts can be read directly from the monthly energy bill. Typically, large companies and institutions have many buildings connected to a single utility-owned meter. Therefore, it can be difficult to estimate each building's share of energy use, and if the buildings are of dissimilar ages or occupancy, the estimates are less accurate. Where this is true submetering is a prerequisite to accurate data. Three key points:

- o Discovering where the energy is going in your facility by submetering or other means is the first step in determining retrofit priorities.
- o Consumption histories are needed in order to compare actual energy savings with predicted savings.
- o Large swings in energy consumption can alert the energy manager to H.V.A.C. or lighting control problems.

Different types of energy are measure in different ways. Metering electricity is straightforward; the meters tend to be reliable and the numbers can be used with confidence. Natural gas consumption is similarly straightforward. Metering chilled water and steam, however, involve more variables. Therefore, chilled water and steam data must be interpreted with care.

Step 3. Energy Balance

An energy balance is a convenient method of determining where energy is consumed in a particular building or group of buildings. The most common energy balance is a breakdown of percentages for lighting, heating, cooling, motors, hot water, and miscellaneous. When converted into common units, an energy balance fits well in the pie-graph format.

Using Weather Data

Since energy consumption is directly related to outside temperatures, local weather data is a necessary part of any energy study. A common method of comparing energy use data and weather data is the degree-day method. A heating degree-day is the average of the maximum and minimum temperatures for one day compared to a standard temperature (usually 65°F). For example, if the average temperature for one day is 40°F then 25 degree-days have accumulated. Thus, the total number of heating degree-days added together gives the annual heating degree-day value. There are 2,900 heating degree-days in an average year in the Stanford University area. Cooling degree-days are similarly computed. Degree-days are added when the average temperature is over 65°F. A normal cooling season for Stanford University has 275 annual cooling degree-days. By comparing annual degree-day information we can easily compare the intensity of a particular heating or cooling season with other years.

Actual weather data should be compared with the weather data used in the building model. Building models use averaged weather information which may be different from the actual weather at the building site. This data can be compared as in table 1. Weather variances should also be considered when analyzing monthly and annual energy meter readings.

Once an energy reference baseline is established, energy consumption data collected and an energy balance performed, this information can then be compiled for analysis.

Sweet Hall Energy Study

The following section is an example of an energy study using submetering and computer modeling to determine energy savings in a new building at Stanford University. Sweet Hall, built in 1986, is a five story, 49,376 square foot building. An outline of the types of topics that should be covered in a report is followed by an example of the report itself. Some parts of the original study have been removed for clarity and brevity.

(Note to reader: An interesting result was that the steam consumption was some 1,000 percent higher than predicted in the original energy simulation model. We have since then resolved most of the discrepancy. Part of the problem was that the original computer estimates were too low. We can verify this by comparing data with other campus buildings. More importantly, however, there

actually was a problem with the control of the steam system. Since the month-to-month steam meter readings were consistent and the occupants comfortable it is likely that we would not have noticed the problem for some time. This result confirms the value of this type of study.)

Report Outline

Introduction

Building Description

- General
- H.V.A.C. System
- Lighting Systems
- Building Use
- Building Schedule
- Occupant Comfort
- Temperature control
 - o Warm-up
 - o Economizer mode
 - o Cooling mode
 - o Air Flow Control

Previous Energy Conservation Efforts

Energy Consumption History

- Measurement Techniques
- Analysis of Weather Data
- Comparing Weather Data with Energy Consumption Data
- Consumption Trends

Energy Consumption Costs

Comparison With Energy Predictions

- Background
- Electricity
- Steam
- Chilled Water
- Natural Gas

Conclusions and Recommendations

Energy Study Introduction

Purpose: This report compares the energy consumption predicted in Sweet Hall with the actual energy consumption measured during the three years following construction. Although energy conservation measures in new buildings have been mandated by California Title 24 for over a decade, no formal evaluation of building performance has been compared with pre-construction estimates for any Stanford University building.

Project Goal: To evaluate the effectiveness of energy conservation features designed into Sweet Hall, and to assess building performance.

Sweet Hall was chosen for this study for several reasons:

- o The energy consumption of this building was modeled prior to construction. This model was in the form of a Department of Energy II (D.O.E. II) computer energy analysis by an outside consulting firm. One reason for doing this model, was to evaluate design options available to architects and planners from an energy and life-cycle cost perspective.

- o Steam, chilled water, and electricity measurements are available for every month since the building was built three-and-a-half years ago.
- o Many of the "outside" parameters that can influence energy consumption, such as occupant schedules and equipment types used in the building, have remained relatively stable. No major retrofits or additions have been done since the building was completed.

Building Description

H.V.A.C. System: Sweet Hall has a variable air volume (VAV) air distribution system. One 75-hp supply fan and one 30-hp return fan, both located in the ground floor mechanical room, provide all the air circulation. A single vertical shaft distributes the supply air between zones. Each of the five floors in Sweet Hall is a separate heating and cooling zone. The heating, ventilation, and cooling of Sweet Hall are controlled by the central on-campus Energy Management and Control System (E.M.&C.S.). Under full-load conditions, the Sweet Hall supply fan generates 70,000 cfm of air.

Building use: The first floor is occupied by a number of different student service groups. There are enclosed offices around the perimeter and an open office plan with cubicles in the floor's center. The second floor houses the Low Overhead Time Share (LOTS) computer network. The entire floor is devoted to desks with individual computers. The third and fourth floors are occupied by the Academic Information Resource (AIR) group. The basement has several computer labs, but most of the basement is devoted to mechanical or electrical utility spaces.

Building Schedule: The building mechanical system operates 24 hours a day, seven days a week. The first floor and basement are shutoff from 9:00 PM until 4:30 AM weekdays and all day on weekends and holidays.

Temperature control: There are several modes of temperature control in Sweet Hall.

- o Warm-up: When the return air temperature is below 70.5°F the mixed air controller is closed to allow the building to "warm up." Once the return temperature has reached at least 71°F, the system returns to a normal mode.
- o Economizer mode: The economizer allows the use of a mixture of cool outside air and warm return air to reach the desired supply air temperature setpoint without the use of chilled water.

- o Cooling mode: If the outside air is over 60°F and is warmer than the discharge air, and the return air is over 72 °F, chilled water is used to maintain the desired setpoint.

Air Flow Control: Variable speed drives are used to control the supply and return air in Sweet Hall. The supply air system is designed to heat or cool the building during extreme temperature conditions. Most of the time it is not necessary to operate the fans at these peak levels. Fan speed is adjusted to meet the internal loads of the building. Under normal or low load conditions, the fan speed can be reduced and energy saved.

The E.M.&C.S. system controls the operation of these variable speed drives. In the monitoring phase of this project, we found that the supply fan operated on the average at 64 percent of capacity and the return fan operated at 43 percent. These averages are typical for the mild weather we had during the monitoring.

Energy Consumption History

Comparing Weather Data with Actual Energy Consumption Data: Both steam and chilled water consumption in Sweet Hall are clearly driven by the seasons. Chilled water usage peaks during the summer and fall, and steam usage peaks from November through February. As table 1 shows, chilled water consumption correlates directly with the degree-day weather information. The highest consumption was during the 1987-88 year when the weather was warmest. The lowest consumption was in 1986-87 when the weather was less warm.

Steam consumption also correlates with the weather data with one exception. As expected, the mildest winter (1987-88) had the lowest consumption. However, more steam was consumed in 1986-87 than in 1988-89 despite fewer degree days. Although it is difficult to be certain, this high first year consumption could be related to factors other than weather, such as inefficient H.V.A.C. operation or simple first year "fine tuning" of building systems.

Electrical Consumption Trends: To a certain extent, electrical consumption can be a function of weather conditions but more likely is a function of building use and occupancy schedules.

Comparison With Energy Predictions

Electricity: As shown in table 1, electrical consumption is approximately 55 percent higher than predicted. This difference is the result of several factors working together. Sweet Hall is used somewhat differently than was anticipated in the computer model. For example, occupants are using more equipment for longer periods of time. In fact, we know that many of the one-half amp local-area-network computers have been replaced with six amp units. This is a common occurrence in buildings where the occupants become increasingly dependent on more sophisticated and energy intensive electronic equipment.

Steam: In the same table, steam consumption is seen to be over one-thousand percent higher than predicted. This is clearly too large a difference to be a result of weather or occupant changes. Possibly the model was unrealistic in its assumptions or something is wrong with the building steam system, or both. A third possibility was an improperly calibrated steam meter was giving faulty data. After checking the meter, we found it to be calibrated properly.

Chilled Water: Chilled water consumption was close to the level predicted in the D.O.E. II study. Weather accounts for the small variances. During the first year, the weather was cooler than normal and chilled water consumption was below the estimate. The second year, chilled water consumption was higher than the estimate but the weather was also warmer than average. The third and final year's weather was close to average and the predicted consumption and the actual consumption were nearly the same. The chilled water consumption of Sweet Hall compares well with similar campus buildings.

Conclusions and Recommendations

The primary conclusion is that the steam consumption in Sweet Hall is unaccountably high and warrants further investigation. Electric consumption is higher than predicted but may be accounted for by changes made after the computer model was performed. Finally, chilled water consumption is reasonable and close to the prediction.

As anticipated, the consumption of chilled water and steam does correlate with seasonal and annual outdoor temperature changes.

Table 1.
Sweet Hall Energy Consumption Summary

Actual		Units	1986-87	1987-88	1988-89
Electricity	kWh		1,509,835	1,614,867	1,662,546
Steam	lbs		3,852,723	3,027,267	3,301,552
Chilled Water	ton-hr		128,107	191,397	177,185
Btu/sqft	btu		213,526	219,450	224,847
cdd 65 *			195	350	296
hdd 65 **			2,745	2,538	2,886

Predicted (Computer Model)		Units	1986-89	per year
Electricity	kWh		1,042,535	
Steam	lbs		258,000	
Chilled Water	ton-hr		171,750	
Btu/sqft	btu		119,029	
cdd 65			275	
hdd 65			2,891	

Variance (Actual v. Predicted)		Units	1986-87	1987-88	1988-89
Electricity	kWh		44.82%	54.90%	59.47%
Steam	lbs		1393.30%	1073.36%	1179.67%
Chilled Water	ton-hr		-25.41%	11.44%	3.16%
Btu/sqft	btu		79.39%	84.37%	88.90%
cdd 65			-29.09%	27.27%	7.64%
hdd 65			-5.05%	-12.21%	-0.17%

* cdd 65 is a cooling degree day measured at 65 F.

** hdd 65 is a heating degree day measured at 65 F.

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