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LIGHTING RESEARCH PROGRAM

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ABSTRACT

The aim of the U.S. Department of Energy (DOE), Lawrence Berkeley Laboratory (LBL) lighting program is to reduce the nation's lighting energy use by 50% through the introduction of more efficient and cost-effective systems and strategies. We work toward this goal in close partnership with the lighting industry to enhance its long-term viability.

To achieve this goal, the lighting program undertakes research in lamp science and technology, application of lighting to buildings, and the impacts of lighting on human health and productivity. The technical methodologies employed by LBL are described herein.

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PROGRAM OBJECTIVES

We estimate that approximately 50% of the electrical energy consumed by lighting, or about 12% of total national electrical energy sales, could be saved by gradually replacing existing lighting with energy-efficient lighting. This would amount to a yearly savings of some 220 billion kilowatt-hours of electricity.

The objective of the Department of Energy (DOE) Lighting Program is to assist the lighting community (manufacturers, designers, and users) to achieve a more efficient lighting economy. The program, carried out at Lawrence Berkeley Laboratory (LBL), exemplifies a unique partnership between a national laboratory/university complex and industry, facilitating technical advances, strengthening industry capabilities, and providing designers and the public with needed information.

PROGRAM SCOPE

To implement its objectives, the lighting program has been divided into three major categories: engineering science, electromagnetic compatibility, and impacts on human health and productivity.

The engineering science component of the program undertakes research and development projects in lamp technology that are both long-range and high-risk. These are projects in which the lighting industry has an interest but cannot pursue on its own, and from which significant benefits could accrue to both the public and industry if the technical barriers were surmounted.

The program also aims to understand the electromagnetic compatibility of high-frequency lighting with building functions including machinery, computers, and other electrical and electronic systems. The program's impacts component examines relationships between workers and the physical lighting environment to assure that energy-efficient technologies contribute to human productivity and health. These efforts are interdisciplinary, involving engineering, optometry, and medicine. To implement its Lighting Program, DOE combines the facilities and faculties of LBL with those of the University of California College of Environmental Design, School of Optometry, and School of Medicine.

TECHNICAL DESCRIPTION

Total annual costs of a lighting system are dominated by energy costs, close to 80% of the total, the remaining 20% going to lamps, fixtures, wiring, electrical components, and controls. Because lighting systems use so much energy and have much shorter lifetimes than furnaces, elevators, and other building systems, there are excellent opportunities to replace inefficient lighting systems with more efficient ones. Heightened energy concerns and consumer demands for more efficient products can hasten innovations. In this technically difficult and high-risk area, a cooperative effort between government and industry can achieve technological solutions and market penetration more quickly.

Three major components of lighting system are important for energy considerations: The lamp converts electricity into visible light and is the major user of energy in the lighting system. The electronics, switching, and controls generally use only a small fraction of the lamp energy but can have a major effect by regulating, scheduling, and switching the lamp. The fixture consumes no energy but can greatly affect illumination efficiency through illumination distribution and light capture within it.

Although in a typical residence lighting energy often represents less than 10% of net energy use, in a high-rise office building it can account for more than 50% of the building energy consumption. Table I shows how, on a national basis, lighting energy use compares with the total electrical energy use for the four main categories of consuming classes: residential, commercial, industrial, and street lighting. The category referred to as "other" includes outdoor lighting such as sports lighting, transportation lighting, or outdoor advertising. Thus lighting accounts for 25% of the national electrical energy consumption, approximately equally divided between incandescent and gas-discharge [fluorescent and high-intensity discharge (HID)] lamps.

Table I
National Lighting Energy Consumption (%)

Energy use	Res.	Comm.	Ind.	Street	Other	Total
Total (BkWh)	560	400	790	14	50	1,814
Lighting (BkWh)	90	200	90	14	24	418
(%)	16	50	11	100	48	23
Incandescent (BkWh)						200
Gas-discharge (BkWh)						218

Lamps

Table II shows the use of the three principal types of lamps (incandescent, fluorescent, and HID), their annual energy consumption, number of sockets, and total number of lumen hours they provide. Annual energy is indicated in lumen hours as well as kilowatt-hours because this indicates the efficacy of energy use. Table II shows that although the energy use of incandescents is comparable to that of fluorescents, incandescents produce almost five times less light. Clearly this represents a prime opportunity for improved efficiency. During the past few years several new lamps have appeared on the market as energy-efficient replacements for the incandescent lamp.

Table II
Use of Lamps

Lamps	Sockets	Ave. Power (W)	Ave. Light (l)	Annual Use (hr)	Annual Energy (kWh)	Annual (Lumen hr)
Incandescent	2.8×10^9	100	1,600	700	196×10^9	3.1×10^{15}
Fluorescent	1.4×10^9	50	3,300	3,000	216×10^9	14.0×10^{15}
HID	0.02×10^9	250	12,000	4,000	20×10^9	0.96×10^{15}

It is well-established that no single lamp will be the unique replacement for the ubiquitous incandescent filament lamp with its "Edison" socket, for reasons including the longevity, price, color quality, weight, size, location, and heat output of new lamps. Aside from using an infrared reflective coating to reduce heat loss on a standard filament lamp, all potential replacements are gas-discharge lamps. These lamps require more sophisticated controls than the typical on-off switch. Working with the lamp and electronics industry, DOE/LBL has proved the technical and economical feasibility of high-frequency solid-state ballasts, which, together with innovations in lamp design, have accelerated the availability of a variety of energy-efficient replacements for the incandescent lamp. But this is not the whole story because, although fluorescent and HID lamps are considerably more efficient than filament incandescent lamps, their efficiencies still are far below any physical limit. There are several technically feasible ideas for improving the efficiency of these lamps, but further scientific and engineering research is required before they produce marketable systems. Table III lists some promising possibilities and their target dates.

Controls

The revolution in micro-electronics coupled with the need to reduce operating costs of lighting systems spurred the development of dynamic controls for lighting systems operable by users.

Before the days of oil embargoes, lighting systems in most commercial and industrial establishments had only on-off switches for controls and, furthermore, a single switch quite commonly controlled large banks of lighting. More appropriate lighting controls make use of daylighting and provide various light levels through scheduling or lumen depreciation. Controls can also combine general with task lighting to moderate lighting energy use. Efforts are needed to understand how a control system should work to maximize energy savings and, at the same time, provide the desired lighting services. An important component of this research is understanding the degree and geometry of light-sensitive detection consistent with human needs and productivity. The potential

Table III
Targets of Opportunity

Technology		Total Efficacy (lumens/watt)	Year in Market
Fluorescent Lamps			
High-Frequency Operation		90	1980
Narrowband Phosphors		100	1983
Isotopically Enriched	LBL/DOE	110	1988
Magnetically Loaded	Technical	135	1990
Two-Photon Phosphor	Initiatives	200	1992
Gigahertz/Electrodeless		230	1994
HID Lamps			
Today with High-Freq. Ballast	130 lm/W (1000 W High-pressure Sodium)		
	90 lm/W (1000-W Metal Halide)		1984
	55 lm/W (1000-W Mercury Vapor)		
Electrodeless/High-Freq.	10 - 15% improvement, 1000 W lamps 30% improvement, low-wattage lamps		1989
New Gases	20 - 25% improvement		1990
Color Constant/Dimmable	20 - 25% improvement		1993

for energy savings is large and, using the new generation of microelectronics, can be cost-effective. A successful effort would develop ties with the controls industry so that innovations in technology and strategy can be passed on to the consumer.

Fixtures

Fixtures help determine how much of the light flux emitted by a light source reaches a work surface. This metric is defined as the coefficient of utilization (CU) and is a function of the reflectivity of the material, transmissivity of the lens, geometric shape of the fixture and light source, the ambient temperature, and wall and ceiling reflectivities. Work has been completed on improving the reflectivity and transmissivity via multiple-coated films. The major problem has been in estimating the ballast factor and thermal effects of fluorescent lamp/ballast systems; mis-estimations have resulted in improper evaluation of the CU factor and, as a result, over-illumination of spaces by more than 50%. DOE, through LBL, is determining the functional dependence of the light output of fluorescent lamp/ballast systems, as well as measuring the thermal characteristics of fluorescent luminaires in environments where they typically are used. If these functional dependencies are disseminated, they can serve as design guides for meeting targeted illumination levels. This information could help designers approach the illumination target within 10%, in contrast to the +50% that is typical, and would reduce energy consumption by 20%.

ACCOMPLISHMENTS

High-Frequency Solid-State Ballasts

All gas-discharge lamps (e.g., fluorescent, mercury vapor, high- and low-pressure sodium, and metal halide) require ballasts to maintain stable electrical operation. The ballast provides the required starting voltage and limits the lamp current to a constant prescribed value. In normal operation, typical electromagnetic ballasts can undergo energy losses amounting to 25 to 35% of the overall lamp/ballast system. The advent of solid-state electronics provided the impetus for creating ballasts that experience much lower energy losses, and allowed lamps to be operated at high frequencies— in the 30,000-cycle range where the intrinsic efficiencies of the low-pressure lamps are 10 to 15% greater than at 60 cycles. The Department of Energy, through LBL, worked with two small engineering firms and developed a cost-effective, high-frequency, solid-state ballast that is 20 to 25% more efficient than the typical electromagnetic ballast. Demonstrations conducted by LBL in occupied buildings measured savings achieved by the new ballasts and convinced the lighting community of their viability and effectiveness.

After the small engineering firms successfully developed engineering prototypes, they were purchased separately by different major ballast manufacturers, who have introduced the ballasts to the market. The technical knowledge that DOE brought to the solid-state ballast field has stimulated the entire industry to examine the general usefulness of high-frequency lighting, and the solid-state ballast industry is now worth more than $10 million. Table IV lists the system efficacy improvements realized with solid-state fluorescent ballasts.

Table IV
Comparison of energy performances of standard magnetic ballasts, energy-efficient magnetic ballasts, and solid-state ballasts with a standard F40, cool-white fluorescent lamp and with two types of energy-efficient, "lite-white" phosphored lamps.

Ballast/Lamp System Efficacy			
Ballast/Lamp System	Input Power (watts)	Rated Light Output (lumens*)	Efficacy (lumens/watt)
St-F40	100	6300	63
St-Br	100	6900	69
St-35	91	6100	67
EC-F40	91	6300	69
EC-Br	82	6900	76
EC-35	79	6100	74
SS-F40	79	6300	80
SS-Br	79	6900	87
SS-35	71	6100	86

St Standard two-lamp, F40 magnetic ballast.
EC Efficient core two-lamp, F40 magnetic ballast.
SS Solid-state two-lamp, F40 ballast.

F40 F40 T-12, rapid-start, cool-white lamp (argon-filled).
Br F40 T-12, rapid-start, lite-white lamp (argon-filled).
35 35-watt F40 T-12, rapid-start, lite-white lamp (krypton-filled).
* Lumens measure the quantity of the luminous flux of light.

Energy-Efficient Replacements for the Incandescent Lamp

Nearly 90% of the energy applied to an incandescent filament lamp is dissipated as heat. An energy-efficient replacement for this kind of lamp is an acknowledged need and the focus of much research. Low cost, ease of use, and good color quality are all concerns that must be addressed in developing an efficient substitute.

Working with the lamp industry, DOE, through LBL, in 1979 began a program to accelerate development of a variety of energy-efficient replacements for incandescent lamps. One concept is a slimmed-down fluorescent (compact fluorescent) small enough to use in incandescent configurations. To satisfy individual preferences, the phosphor coating the lamp's inner wall can be tuned to provide a color indistinguishable from that provided by either an incandescent lamp or daylight.

Also considered as a possible replacement is an electrodeless fluorescent lamp in which the discharge is excited magnetically at very high frequencies (13.56 megacycles). Still another possibility is to cover the inside of the incandescent lamp with a very thin selective coating that transmits visible light but reflects infrared radiation. The radiation reflected back to the filament reduces its power requirement and increases efficacy. Another concept is a small metal halide lamp operated at high pressure, but with a very small arc length to provide the light output characteristic of an incandescent lamp rather than the high lumen output typical of metal halide lamps. These lamps have efficacies ranging from two to four times that of the incandescent lamp. Some can last longer than 10 years (10,000 hours), compared to less than one year (750 hours) for the incandescent. Although first costs may be higher, the longer lifetime and lower operating costs provide a lower life-cycle cost than that of an incandescent lamp.

Lighting Controls Demonstration at the World Trade Center

Many approaches have been considered for saving lighting energy in commercial buildings. Techniques such as having the lights turn off and on according to predetermined schedules, removing overhead bulbs in little-used areas, and taking advantage of available daylight have been discussed theoretically. To quantify the energy saved by introducing an energy-saving lighting management system in a real environment, LBL conducted a demonstration on the 58th floor of the World Trade Center in New York City. The tests were designed to determine:

1. which control functions have the greatest impact and why,
2. what the economic tradeoffs are between control cost and savings,
3. how acceptable controls are to occupants, and
4. how reliable control systems are.

To provide the monitoring to evaluate a range of strategies, a relay was attached to every ballast on the 58th floor of the building. By selectively switching relays, it was possible to make each 6-lamp, 3-ballast fixture go to 1/3, 2/3, full "ON," or "OFF." The 1350 relays were operated by a computer-programmed system that allowed independent scheduling of each relay, monitoring of daylighting thresholds to provide a constant level of illumination, and manual override by occupants via their desk phones. All relay activity was stored on tape to record consumption in response to various strategies.

A series of one- to two-week tests focused on finding the most effective ways to schedule lighting levels to match tasks, take advantage of daylight, and provide occupancy-based control. Variables were manipulated to determine their impacts on the use of that strategy. The most significant conclusions of this demonstration were:

1. Lighting controls can have a significant and positive impact on energy consumption: a maximum reduction of 52% was achieved.
2. The payback on relay-based lighting control for new construction is extremely attractive.
3. Relay-based automatic lighting controls are acceptable to occupants, are very reliable, and provide significant energy savings, but continuous dimming is preferable.

The value of the tests was not only the 52% savings achieved, but also the insight gained into why certain strategies were successful, how strategies interact, the relationship of a strategy to the purpose of a space, occupants' responses to techniques, and the importance of providing individual overrides to ensure positive reactions to a system.

PROJECT AREAS AND CURRENT PROJECTS

The LBL lighting research program is divided into three major areas: Advanced Lamp Technology; Electromagnetic Compatibility of High-frequency Lighting; and Impacts of New Lighting Technologies on Productivity and Health.

Advanced Lamp Technology

Today's fluorescent lamp has a luminous efficacy of approximately 80 lumens of light output per watt of electrical power input. Although this is nearly four times as efficient as an incandescent lamp, greater efficacies are possible. White light can, theoretically, be produced at almost 350 lumens per watt. The technology program is working to reach an efficiency of 200 lumens per watt within the next few years.

Two loss mechanisms must be changed to allow for more efficient fluorescent lamps. First, we must reduce the self-absorption of the ultraviolet (UV) radiation within the lamp plasma before it strikes the phosphor-covered inner wall, and second, we must develop a more efficient phosphor that will convert one energetic UV photon into two visible photons. Reductions in self-absorption could provide a 30% improvement, while a two-photon phosphor could double lamp efficacy.

LBL is studying two principal ways of reducing the UV self-absorption. The first method uses the naturally occurring isotopes of mercury. There are seven stable isotopes that differ according to their UV emission spectra. A small subgroup of isotopes will emit and absorb UV radiation with such a small spread in energy that a nearby subgroup of isotopes is not involved in its radiative transfer. Altering the natural isotope composition can increase the amount of UV radiation reaching the phosphor, thereby improving lamp efficiency. One possibility for isotope alteration, enrichment with mercury 196, is being pursued in a joint effort by LBL and GTE Lighting. Should isotope alterations prove economical, modified lamps could enter the market quickly, as lamps could simply be loaded with isotopically enriched rather than natural mercury, while other components would remain the same.

Another method for reducing UV self-absorption, recently discovered at LBL, involves an applied magnetic field having a direction parallel to the main current. Axial magnetic field strengths of about 600 gauss can increase light emission by 12% to 15%. LBL and major lamp industries are studying practical ways to apply this technique.

The second loss mechanism is that a lamp's phosphor converts each UV photon into at most one visible photon. Improving this conversion rate could increase the efficacy of low-pressure discharge lamps. Although the energetics are sufficient to permit the cascade conversion of a UV photon into two visible photons, this process must occur quickly and the intermediate level in the cascade tuned carefully to ensure that both emitted photons are in the visible spectrum. Studies on phosphor chemistry are ongoing at LBL to discover whether the two-photon phosphor is feasible. The lamp industry, long aware of this problem but not in a position to make these investigations, awaits the results.

Based on work at LBL, future fluorescent lamps should operate at high frequency and be isotopically enriched, magnetically loaded, and coated with a two-photon phosphor. Such lamps would have an efficacy of more than 200 lumens per watt, three times that of today's 60-cycle fluorescent. Other research concentrates on high-intensity discharge lamps, which can be made both more efficient and dimmable if operated without electrodes. High-frequency operation is required to excite the lamp plasma in an electrodeless mode. Operation at high frequency may permit lamps to function with just one or two metal halides and without any mercury or sodium. Electrodeless operation would also enable the use of compounds in the discharge that have desirable light output and color, but are not used today because they harm the electrodes. An electrodeless lamp, dimmable without a spectral change, would appeal to lighting designers. It would be an efficient, dimmable point source that could produce any color.

Electromagnetic Compatibility of High-Frequency Lighting

The successful development of high-frequency, solid-state ballasts provided the impetus for adopting high-frequency lighting and control systems in commercial and industrial buildings. Many benefits can be realized by operating at high frequencies: lower starting voltages, increased efficacy, ease of dimming, etc. The electronics industry is making rapid progress in developing less expensive high-power transistors and amorphous magnetic materials needed to ensure that high-frequency ballasts will be cost-effective and enter the market rapidly.

High-frequency lighting, however, can produce electromagnetic energy, which could affect sensitive machinery, computers, and electronic systems. The widespread use of these lighting systems requires studying possible effects of electromagnetic interference (EMI) on other building operations. LBL leads the effort to obtain information needed for industry and government agencies. The major technical problem is establishing reliable near-field EMI measurements for lighting systems and relating them to what the Federal Communications Commission requires for far-field radio interference. Also, a methodology must be developed to determine near-field effects on electronic equipment and far-field effects when many EMI-generating systems are used.

The Federal Communications Commission and National Electrical Manufacturers Association have recommended that LBL assist in collecting data on the EMI generated by high-frequency lighting systems. The development at LBL of a standard source and measuring method for determining radiated near fields is essential to make convenient and reliable procedures available to industry. Computer models for stray EMI are being developed at LBL to further study the physical characteristics of external electromagnetic fields generated by high-frequency lighting.

Impacts of New Lighting Techniques on Productivity and Health

The idea that lighting might negatively affect health has become prevalent in the lay press in the past few years. Many factors have been implicated, but scientific data are lacking, especially to ascertain whether new energy-efficient technologies have adverse effects on human health and productivity.

Factors that may influence performance and productivity (as well as energy efficiency) may be associated with the lamp, the electronics and associated controls, the fixture, or the geometry and location of the lighting system. These lighting factors are: color variations; glare; intensity fluctuations; spectrum variations, including in the ultraviolet region; electromagnetic fields generated by the lamp, ballast, or controls; and flicker, all of which could evoke a variety of human responses (behavioral, psychophysical, physiological, or biochemical).

Our research aims to assure that new energy-efficient lighting technologies do not adversely affect human health and productivity. We are investigating whether any aspect of the new technologies can produce responses in humans. If so, the effects will be characterized and necessary changes to lighting technologies identified. Although subjective responses of workers provide some information, such responses are generally muddied by a mix of sociological factors and motivations; the investigations carried out by DOE/LBL use non-subjective responses to establish cause and effect and assure repeatability.

In this first phase of the program, lamps to be evaluated include incandescent, cool-white fluorescent, full-spectrum fluorescent, high-pressure sodium, and metal halide. Effects of exposure to various lighting conditions will be assessed by monitoring autonomic responses. Parameters to be monitored include heart rate, respiration rate, galvanic skin response, muscle strength, exercise tolerance, facial expressions, and pupillary responses. Behavioral measures to be used include memory (Wechsler Memory Scale and Sternberg's Memory Scanning Time), cognitive function (Mental Arithmetic), time estimation, and simple reaction time. Other behavioral tasks probably will be implemented.

Data-gathering and subject control are supervised by trained medical personnel. A national technical advisory committee oversees and reviews the project. First results of this effort surround the effects of visible spectrum and low-frequency radiation on human muscle strength. Results, described below, indicate that subjective psychological factors are the likely cause of reported effects.

Study I: Ten subjects who stated they were bothered by fluorescent lighting were studied using maximal strength of shoulder forward flexion. Fifty trials, each a randomized sequence of paired exposures to 400-footcandle incandescent and cool-white fluorescent light, were measured in each subject to counter-balance effects of fatigue. Over all subjects the mean difference in maximal muscle strength for the two lighting conditions was less than 0.2% of the usual strength. The standard distribution was 13 times the mean difference. A paired-t test showed that our results were likely due to chance ($p = 0.85$). Similarly, there was no statistical difference in the responses under the two lighting conditions ($p = 0.39$). Power analysis showed that 90% of the time we would have detected a difference in muscle strength of 4%. Since the effects of suggestion on maximal muscle strength have been reported to be about 10%, the effects of the lighting, as tested, are likely to be obscured by psychological effects.

Study II: The results of Study I are not in agreement with the popular writings of John Ott, who used "kinesiology testing" to support his claim that muscle weakness was caused by both cool-white fluorescent light and lack of electric field shielding. Mr. Ott agreed to test the effect of shielding, double-blind, using his kinesiological evaluation of subjects' strength. On the unblinded tests the reported strength agreed with Mr. Ott's knowledge of grounding in 97% of the trials, but in the blinded condition the reported strengths agreed with grounding only 53% overall (range 31-75%). The likelihood of obtaining such a difference by chance was less than one in 100,000. We conclude that blinding the kinesiology testing significantly alters the result, which in the unblinded case is susceptible to suggestion; any claims based on this methodology, unblinded, are suspect. Efforts are now under way using infrared pupillometry to investigate visual reactions to high-pressure sodium and other HID lamps.

Besides direct effects of lamps on humans, LBL is examining how lamp characteristics— in particular compound flicker— can affect workers using visual display terminals. Compound flicker occurs in the work-place when there are two independent sources flickering at different rates that, when combined, produce a "beat." For example, light from a video display terminal whose refresh rate differs slightly from its nominal 60 Hz will combine with standard fluorescent lighting flickering at 120 Hz to form a low-frequency beat. Experiments are being performed to ascertain the effect of beats in general, and the beat between VDTs and ambient lighting in particular, on the visual system.

Present results show that beats formed by independently modulated fluorescent luminaires cause subjects to exhibit frequency-specific declines in temporal contrast sensitivity and entrained pupillary oscillations when the flicker rates of the luminaires are below critical fusion frequency (CFF). No evidence is found of these effects when the flicker rates are above CFF, or when a VDT is viewed under flickering ambient illumination. High-frequency operation of the ambient lighting would eliminate human response to those beats.

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