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UNIVERSITY OF CALIFORNIA

ENERGY & ENVIRONMENT DIVISION

THE LAWRENCE BERKELEY LABORATORY/UNIVERSITY OF CALIFORNIA LIGHTING PROGRAM OVERVIEW

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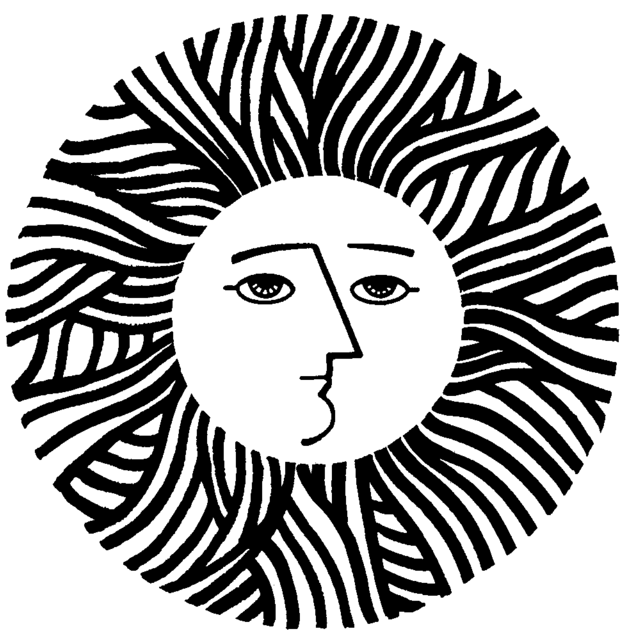

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THE LAWRENCE BERKELEY LABORATORY/UNIVERSITY OF CALIFORNIA

LIGHTING PROGRAM OVERVIEW

THE LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
LIGHTING PROGRAM

I. INTRODUCTION

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 a gradual replacement of existing lighting with energy-efficient lighting. This would amount to an annual savings of some 220 billion kilowatt-hours of electricity.

The objective of the Lawrence Berkeley Laboratory (LBL) Lighting Program is to assist and work in concert with the lighting community (composed of manufactureres, designers, and users) to achieve a more efficient lighting economy.

To implement its objectives, the LBL Lighting Program has been divided into three major categories: technical engineering, buildings applications, and human impacts (impacts on health and vision).

The technical program aims to undertake research and development projects that are both long-range and high-risk and which the lighting industry has little interest in pursuing on its own, but from which significant benefits could accrue to both the public and the industry.

The building applications program studies the effects that introducing daylighting in commercial buildings has on lighting and cooling electrical energy requirements as well as on peak demand. This program also examines optimization strategies for integrating energy-efficient design, lighting hardware, daylighting, and overall building energy requirements.

The impacts program at LBL examines relationships between the user and the physical lighting environment, in particular how new energy-efficient technologies relate to human productivity and health. These efforts are interdisciplinary, involving engineering, optometry, and medicine.

Since its inception in 1976, the LBL Lighting Program has produced more than 45 reports and publications documenting research on subjects such as solid-state ballasts, operation of gas-discharge lamps at high frequency, daylighting availability and computer programs, energy-efficient fixtures, lighting control systems, and visibility and human productivity. The internationally recognized interdisciplinary staff spans the fields of engineering, physics, architecture, optometry, and medicine and is involved in a variety of professional, technical, and in-government activities.

The Lighting Program combines the facilities and faculties of LBL with those of the University of California College of Environmental Design and the School of Optometry (at Berkeley) and the School of Medicine (at San Francisco). It is fully a unique program, not only in the U.S., but worldwide. The results of this program, made available to all, will enhance the capabilities and long-term viability of the lighting industry while providing the design profession and general public with needed information.

II. HISTORY

A. Technical Program

During the past few years, the technical program has supported development in two areas of application: operating gas-discharge lamps at high frequency, and substituting energy-efficient light sources for inefficient light sources.

The high-frequency application was concerned primarily with the solid-state ballast used for operating gas-discharge lamps. Two ballast developers were chosen to design, build, and submit to LBL for testing and evaluation several solid-state ballasts. A facility was built to measure the needed parameters: high frequency, power, and light output. LBL assessed the products to identify any design shortcomings that would limit their application. The products were then tested in a large-scale demonstration which the LBL staff designed and monitored in an operating office building. These efforts identified areas for improvement; once the improvments were made, another demonstration was designed and monitored by the LBL staff at a Veterans Administration Medical Center. In addition to measuring the energy savings and providing a thorough life-cycle cost analysis, LBL measured electromagnetic interference levels to determine if they would adversely affect equipment or personnel. LBL has established that system efficacies can be improved by 25% and that better quality illumination (flicker-free) can be obtained with gas-discharge lamps operated at high frequencies.

The most inefficient light source is the incandescent lamp. LBL has a program to explore new energy-efficient lamps that can replace this lamp in applications having high annual use. The LBL project has been subcontracted to the developers of several promising concepts. LBL's goal is to assess the potential and development status of these concepts and to provide technical evaluation and guidance. The approaches that have been studied include the adaptive circline, the electrodeless lamp, the compact fluorescent, the mini-metal halide, and the coated filament. LBL has the facilities to test and evaluate all of the essential parameters, including the capability of examining frequencies over 10 MHz and determining spectrum, color rendition index, and lumen depreciation.

Some of these new lamps have been received, and lamp efficacies as high 56 lumens per watt have been measured--more than three times more efficient than a 100-watt incandescent lamp.

B. Buildings Applications Program

Lighting System Integration: Understanding and appreciation of optimal dynamic control of lighting are lacking in the field of lighting design and application. In this program area LBL's goal has been to determine how much energy could be saved by employing a variety of control strategies and techniques. To this end, LBL designed two major demonstrations of automatic, centralized control systems in large areas of office buildings in San Francisco and New York City. Two manufacturers supplied and installed the systems, and LBL designed the monitoring and data acquistion systems. LBL designed various experiments to determine the effectiveness of the control strategies of scheduling, lumen depreciation, tuning, and daylighting. In conjunction with the demonstration, a computer program was developed to predict the energy savings for a building that employs one or more of the control strategies, as well as to produce an economic analysis based on system cost.

Daylighting: During the past five years the daylighting program has been assisting the building design community in developing techniques for daylighting application in an energy-conscious environment. The program encompasses a broad range of project activities. Detailed climatological data on characteristics of daylight as a resource have been collected and analyzed for use in design and energy analysis. This knowledge acquisition has been coupled with the development of new design techniques, especially graphic, analytical, and physical models, so that daylighting can be better applied to satisfying indoor lighting requirements. The combination of improved resource data and new calculation techniques has allowed us to develop procedures for estimating annual energy savings and peak load reductions. We have also been able to evaluate existing and novel daylighting strategies that are both cost-saving and user-beneficial when coupled with appropriate lighting control and window management systems. These models have been applied to examining optimal fenestration strategies for commercial buildings when both thermal efficiency and daylighting benefits are considered. Studies of discomfort glare from windows and other indirect features which affect real energy savings have also been undertaken.

All of this data, information, and experience has been made available to the lighting community and the public in general through the Daylighting Resource Center (DRC) at LBL. The primary purpose of the center is to provide up-to-date, accurate, and objective materials and data to assist design professionals in selecting the best and most cost-effective daylighting strategies.

C. Impacts Program

Lighting and Visual Performance: Luminance, contrast, and size are the three primary factors that affect visibility of print. We designed an experiment that was unique in that it studied how all three factors interact to affect reading performance.

In this experiment, normally sighted literate subjects 17 to 34 years old were tested on their reading performance in a variety of luminous environments. The reading material was black and white print presented at three contrast levels (0.97, 0.64, and 0.17) and with the background luminance ranging from 3 to 1600 candelas per square meter.

We devised word charts on which the print size ranged from 20 points to 2 points in systematic progression. When each subject's data was normalized to his own maximum, a surprising general picture emerged: maximum reading efficiency was obtained when the print size was approximately three times larger than threshold size, independent of luminance and with contrast as low as 10 cd/m^2 and 17%, respectively. This result is directly applicable to lighting design, which has traditionally stressed lighting quantity rather than task attributes.

Visibility and Productivity: During the past 25 years, various attempts have been made to apply laboratory studies of visual performance to lighting requirements for real work environments. Attempts to apply research to cost/benefit decisions and to situations where the visual component is not fully delineated encountered numerous difficulties.

The problem is further exacerbated when new energy-efficient light sources are introduced, especially in environments where visual display terminals and other computer equipment are used and where there is a strong correlation between visual productivity and speed and accuracy.

During the past few years we have reviewed the validity of the works that purport to relate visual performance and productivity. The various models of how lighting affects vision and visual performance have been studied. Further research is necessary to produce a series of valid models useful for application, especially when decisions on cost-effectivness must be made.

This latter effort has been especially helpful in deciding what further laboratory experiments need to be undertaken. It has also been helpful in determining what kind of field measurements are needed to ensure that the laboratory studies will provide useful field applications. An example of a research direction suggested by our analysis program is a study underway at the U.C. School of Optometry which relates visual fatigue at visual display terminals to environmental lighting.

A further effort in analyzing visual performance and productivity was an in-depth critique of the work of the International Commission on Lighting (CIE), represented by the document CIE 19/2. The critque pointed out inadequacies, inconsistencies, areas where further research is needed, and possible applications for cost/benefit decisions.

III. SUMMARY OF THE 1981/1982 PROGRAMS

For the 1981/1982 fiscal year, the Technical Program is concerned primarily with developing an understanding of new concepts for converting electrical energy into visible light. Areas of interest include mechanisms for reducing the ultraviolet self-absorption in gas-discharge lamps, making use of processes such as mercury isotope enrichment, magnetic arc spreading, and enhanced gas mixtures. In addition, the search for high-frequency ranges of optimum excitation of the plasma gas holds the promise of more reliable and inexpensive electronics as well as more efficient conversion of energy into light.

The Buildings Applications Program during 1981/1982 will concentrate on research that will provide the lighting community with tools for assessing the benefits achievable through systematic application of daylighting strategies and overall building systems optimization. In particular, new computer models and a recently completed artificial sky will be used to determine the energy and load management potentials of daylighting strategies. Analysis of daylight availability data will be extended, and fenestration optimization studies will examine the effect of daylighting on overall thermal performance and peak loads. Field evaluation of daylighting savings in commercial buildings will be undertaken. Studies will also be carried out to show the effect of lighting controls on, energy savings, glare reduction, sun control, visibility, and aesthetics.

The Visual Impacts Program during 1981/1982 focuses primarily on establishing those lighting conditions that enhance productivity in a cost-effective manner. It will also ascertain any undersirable visual effects, such as excessive fatigue associated with the use of modern office equipment operating in an advanced lighting environment.

The Health Impacts Program extends the research on artificial lighting to a wider class of human activities. Here conditions can be varied, and nonsubjective responses to lighting can be measured by sensitive medical instruments.

IV. TECHNICAL PROGRAM

A. Energy-Efficient Light Sources

Objective: To improve the energy-efficiency of gas-discharge lamps by improving the conversion of electrical energy to visible light.

Background: Visible light from gas-discharge lamps (fluorescent, HID, HPS, etc.) requires that incoming electrical power be converted to UV radiation by the excitation of the enclosed mercury vapor. Visible light is produced when the UV excites the phosphors lining the glass envelope.

The lamp industry has concentrated its efforts to produce more efficient light sources on further confining phosphor emissions to the yellow-green spectral region where the human eye has its greatest luminous sensitivity. Technical improvements on the order of 5% have been obtained.

However, much greater improvements in energy efficiency could be achieved by increasing the UV radiation that impinges upon the phosphor. Realizing this possibility requires reducing the self-absorption or entrapment of the UV by the excited gas (plasma). Several mechanisms could decrease self-absorption by increasing the number of noninteracting energy levels that participate in the radiation and absorption process. Methods include varying the mercury isotope mixture, adding other excitable gases (halogens), and applying external magnetic fields or the electric field resonances with the plasma at high frequencies.

Efficiency could possibly be improved 10 to 15% with these mechanisms, but quantification requires an experimental program designed to directly measure these efficiency changes.

Because of the long-term and high-risk nature of this kind of research, the lamp industry has had little interest in pursuing it. Where industry showed some interest, the management of the company sought government funds to undertake the program with internal R&D programs.

General Approach: Similarities in measurement techniques and experimental setup allows LBL to investigate the four mechanisms described above in a series of closely related tasks.

The capability of controlling gas pressure, cathode voltage, and electrical wave shapes as well as performing accurate efficacy measurements with a monochrometer and integrating sphere permits a thorough and precise determination of the effects of proposed changes.

An important object of the isotope enrichment research is also to investigate possible cost-effective processes for separating the necessary isotope from naturally occurring mercury. Because of their long involvement in isotope chemistry, the LBL staff has the expertise necessary to contribute to the technical success of this effort.

B. Advanced Lighting Systems

Objective: To determine the optimum operating ranges of the new high-frequency lighting systems and determine the basis for their improved efficacy; also to address other technical issues that would affect their role in lighting applications (e.g., the EMI question).

Background: The DOE program fostered the development of the solid-state ballast that improved the efficacy of gas-discharge lamps by operating them at high frequencies (20 to 30 kHz). The choice of the range of frequencies is based upon early measurements on low-pressure gas-discharge lamps which indicated that most of the efficacy improvement was obtained by operating at 10 kHz and that little efficacy gain occurred above that. However, it was desirable to select a frequency above the human audible range, and 20 to 30 kHz was selected. Although further efficacy improvements are possible above 20 to 30 kHz, the present power-switching transistors become inefficient above this range, making it impractical to consider applications which take advantage of these higher frequencies.

LBL has been examining the starting characteristics and general performance of low- and high-pressure gas-discharge lamps operating at high frequency. Whereas previous work in this area has examined lamps only up to a frequency of 10 kHz, LBL will extend its measurements up to 100 kHz. We have found that starting voltages may decrease near 100 kHz and should be still less above 100 kHz. If the starting and operating voltages are reduced, the reliability and cost-effectiveness of the solid-state ballast will be greatly improved. Lamp life will be extended, lamp lumen depreciation will be decreased, and the blocking voltage requirements of the electronic components (e.g., the capacitors and switching transistors) will be reduced. This effect will reduce component cost while increasing transistor switching efficiency, since its forward resistive losses will be reduced. These improvements will increase ballast efficiency 5 to 10%. While the solid-state ballast is about 87% efficient in transforming input power to the high-frequency lamp power, it will be possible to achieve ballast efficiencies of 95%.

If the expected results are obtained, and the intrinsic high-frequency benefit is combined with reductions in starting voltage, significant overall increases in efficacy (10 to 15%) can be realized above 30 kHz. New high-frequency power supplies and core components will eventually be available to transform the 60-Hz power to the higher frequencies (above 30 kHz). Industry is developing the power-field effect transistor (FET) and amorphous magnetic core materials required for higher-frequency ballasts. We will consider this development work when determining how to select the optimum operating frequency for the lamp and ballast system.

Electromagnetic interference radiation is of concern to end-users. Most of these concerns arise from lack of experimental information. LBL can lead the effort to obtain this information for industry as well as for concerned government agencies due to its established experience with the high-frequency operation of lamps. The major technical problem is establishing reliable near-field EMI measurements and relating them to the far-field FCC requirements. Furthermore, a methodology must be developed to determine near-field effects upon electronic equipment and far-field effects when many EMI-generating systems are in use. This work will be the basis for establishing the potential collective effects of the very high-frequency systems if they become commonplace.

The lighting industry has not made high-frequency measurements available even though the DOE program has shown the viability of the high-frequency solid-state ballast. Without knowing the level of EMI, designers are restricted to the frequencies in the lower kHz region, and the more rewarding areas will remain undeveloped. This especially impacts the smaller development groups that do not have the expertise, equipment, or finances to study these potential negative impacts.

With regard to EMI, the Federal Communications Commission and National Electrical Manufacturers Association have strongly recommended that LBL participate in collecting data on the EMI generated by solid-state ballasted systems. While the larger firms, if they are interested in supplying solid-state ballasts, have the in-house expertise to address these problems, a rush to market may well prevail, allowing poorly designed solid-state ballasts to be introduced, thereby adversely affecting their acceptance. Because LBL has knowledge of many circuit designs, it is in a unique position to offer prescriptions for reducing the EMI levels in the circuit, which is the preferred method, since it is usually the most effective and least costly. To date, LBL, through the DOE programs, is the only group that has reported its measured EMI levels for existing high-frequency systems to the general public. If industry collected the information, many believe it would most likely not be released unless it was favorable, and then its credibility would be open to question.

<u>General Approach (High-Frequency Lamps)</u>: Initial experiments will collect and assess data on the performance of gas-discharge lamps at high frequencies. The study will include measurements of the lamps with solid-state ballast systems developed under the DOE program. In addition, LBL has a power supply that can be used to start and operate gas-discharge lamps at frequencies of up to 100 kHz. Additional equipment must be designed to extend the range of test frequencies up to 500 kHz, which initial results indicate may be of interest.

A controversy now exists over whether HPS and HID lamps are more efficacious when operated at high frequency. In addition to establishing a basis for operating the lamps at high frequency, the data will determine the conditions that lead to optimum lamp operation. A full report will be presented to the lighting community.

General Approach (Electromagnetic Interference): One issue that has recently arisen is that of the generation of EMI which could interfere with external communications and other equipment within a building. This project will be concerned with measuring EMI (radiated and conducted) from all types of lighting equipment. From this data, computer models will be developed to determine the stray radiation that will occur from various types and sizes of buildings and communities. In addition, models will be developed for assessing the extent and effects of stray EMI inside buildings.

V. BUILDINGS APPLICATIONS PROGRAM

A. Lighting Systems Integration

Objective: To determine the optimum energy-efficient, cost-effective lighting designs that can be achieved by using the advanced lighting technologies and control systems which should be available in 1990.

Background: Lighting designers develop their system concepts based upon traditional component parts. Thus, it requires many years after initial market introduction for new lighting products, especially for new buildings (e.g., energy-efficient systems), to achieve widespread use. The new elements are often incorporated in a manner that reduces performance because they must fit older components or systems. Thus, new additions cannot usually be designed for maximum performance. In order to efficiently meet our future lighting needs, it is essential to examine lighting designs that will optimally incorporate the energy-efficient products that should be available in 1990. This study will determine the detailed interdependence among lighting components. The results will give industry a guide to performance changes that could improve some standard components as well as indicate which energy-efficient lighting components will have an extended market life. More importantly, it will give designers a target for the power and energy densities. It will assist federal, state, and local agencies in planning future (1990) lighting expectations for retrofit and new construction.

Optimum use of energy-efficient design, technologies, and controls should provide desired lighting levels at considerably reduced lighting power levels. We should be able to reduce the current national average in office buildings of 3.5 watts per square foot to 1.5 watts per square foot--a savings of two watts per square foot. If one-half of the 40 billion square feet of all commercial space shifted to energy-efficient lighting systems and were saving two watts per square foot by 1990, approximately 40 gigawatts of power, or 10% of the national generating capacity, would be saved.

General Approach: In order to achieve the program's goal, initial projects will be collecting and compiling data on the performance of current and developmental lighting products and concepts. The four major areas are controls, ballasts, lamps, and fixtures. By studying the details of their performance and characteristics, we will determine their potential as components in an optimally conceived system. A report will be prepared for each area of interest and for the system in which it would be used. All the information will be stored in a computer file.

Following the above study, an idealized, generalized lighting design will be developed based upon several "typical" designs for offices, plants, warehouses, and schools for ambient, task, and ambiet-task systems. The design concepts will adhere to the lighting practices recommended by IES to provide the necessary quantity and quality of illumination. Typical designs will be programmed to permit both optimizing performance and minimizing connected load and energy consumption. The program will incorporate an economic analysis for the lighting system as well as for the operation of the building as whole.

The program should be flexible enough to apply to other lighting sectors such as outdoor and residential sites.

B. Daylighting

Objective: To provide the technical basis for determining potential daylight energy and load management savings, consistent with reductions in HVAC requirements, while maintaining or improving productivity and visual quality.

Background: Effective use of daylighting in commercial buildings promises substantial electrical energy savings as well as reductions in peak electrical demand while maintaining or improving visual performance. Unfortunately, daylighting design skills are largely unknown or unpracticed by today's professional designers, who were educated and trained in a period in which cheap electricity was the dominant light source. This lack of professional training, the lack of client interest, and other technical and nontechnical evolutionary forces in building design combined to remove daylighting as a significant design concern during the past forty years. Several major related efforts are required to reverse these trends. First, climatological studies are necessary to establish the availability of the daylight resource. Second, improved daylight illuminance models must be developed to predict interior daylight illuminance for state-of-the-art architectural designs under clear sky and sunlit conditions. Third, improved building energy analysis models are needed to predict energy and load management potentials in commercial buildings. Fourth, experimental validation of 2) and 3) above are necessary to verify that the models properly predict operating characteristics and all of the significant energy interrelationships. Finally, results must be communicated to the appropriate design professionals.

General Approach: During the 1981/1982 period, daylighting efforts will be directed toward:

1. Continuing the development of a national daylight availability data base that provides information for design and energy analysis. Radiation and illumination data have been collected for three years in San Francisco and are being used to validate models that can generate a daylight availability data base.

2. Continuing the development of methods for determining the impact of daylighting on interior illumination requirements. These methods include graphic, computational, and physical models. Two new computational models have been developed and are being tested. QUICK-LITE is a simple model for use by architects, engineers, and lighting designers with a programmable calculator. SUPERLITE is a powerful new main-frame computer model that can predict daylight illuminance in geometrically complex rooms, even accounting for the effects of sunlit shading devices.

3. Developing analytic procedures for determining the electrical energy savings in daylit buildings. DOE-2 has been modified to include both a simplified and detailed daylighting model. These models will be validated and used for parametric performance studies.

4. Assessing the potential of coupling daylighting with controls of artificial lighting for load management and assessing the impact on peak loads of both buildings and utilities. In many buildings, load management opportunities may prove more significant than energy savings. However, the thermal impact of fenestration must be considered along with the lighting energy savings.

5. Examining the relationship between daylighting strategies and requirements for glare control and solar control, using both laboratory and field techniques. These studies are essential since improper window management can increase energy consumption for lighting and cooling. See additional discussion in Section VI C.

6. Searching for the optimal fenestration area that combines the requirements of thermal efficiency with the benefits of daylighting. This subject is addressed more completely in Section C which follows.

7. Validating computer and other analytical tools for field measurements of daylit environments. This is being accomplished using outdoor test cells, the artificial sky, and measurements in real buildings.

8. Continuing LBL's operation as a national resource center that makes available technical data, design tools, and other information that is useful to the lighting community for design, cost analysis, and aesthetics. A variety of resource materials and computerized data bases have been developed.

C. Building Energy Optimization

Objective: To improve understanding of the net energy performance and load management potentials in daylit buildings, this understanding to serve as the basis for guidelines for optimizing overall building energy utilization.

Background: Any study of energy utilizaton in commercial buildings must address the interrelationships among various energy end-uses. An understanding of the net energy performance of daylighting strategies and efficient electric lighting systems must include not only direct lighting energy savings but also the impact on overall building energy consumption and peak load characteristics, including heating and cooling system performance. Although daylighting offers opportunities to significantly improve the energy efficiency of buildings, inadequate design analysis may increase heating and cooling loads to the point that they exceed lighting energy savings. We therefore need to completely understand all energy-related aspcts of fenestration performance in order to properly predict real energy savings. Computer models of building energy performamce are required to study all of the parametric variations of energy use with climate, orientation, building type, glazing type, glazing area, conductance, shading coeffient, and visible transmittance. The use of geometrically complex sun-control systems and operable shading systems further complicates the problem. Due to the complexity and interrelationships of the energy flows it is necessary to provide field validation of analytical results at several different levels.

General Approach: We study this optimization problem from three perspectives. Large building-energy analysis models are powerful tools for systematically studying the energy and load implications of changes in building design and operation. We utilize DOE-2.1 as the primary analysis model for our optimization studies. During the last three years we have made a number of modifications to the standard operating version to incorporate new fenestration algorithms that allow us to better model the thermal and daylighting aspects of glazing performance. A simplified daylighting model for DOE-2 was developed in 1980 and has been used extensively in optimization studies. A second-generation model has been developed and is undergoing validation. The performance of a broad range of glazing materials has been systematically studied in three diverse climates, with additional studies now in progress. These studies will help us understand the complex energy-related functions of windows as well as identifying optimal strategies for each climate, orientation, and building type.

A second, and complementary, approach to analytical modeling is to collect detailed experimental data to verify model predictions. We have

A second, and complementary, approach to analytical modeling is to collect detailed experimental data to verify model predictions. We have designed and are constructing a unique fenestration test facility which will allow, for the first time, direct measurement of the net energy performance (thermal and daylighting) of fenestration systems. The Mobile Window Thermal Test (MoWiTT) facility consists of two side-by-side, highly instrumented test chambers and is designed to test windows and skylights outdoors under varying environmental conditions. The facility can be used to measure net energy flows across a glazing system, or, more significantly, the net energy consumption of the chamber as it simulates a room in a building. The thermal effects of lighting energy consumption and daylighting savings can be measured in this facility.

The final perspective on optimal energy performance is that of the actual building, including not only design and construction, but also operation. Many design decisions hinge upon assumptions about the manner in which real buildings are utilized, assumptions which frequently turn out to be inaccurate. For this reason, although it is costly and time-consuming, it is important to measure actual building performance to learn more about energy use and load profiles. Limited data on several buildings have been collected during the past five years. We will enlarge this limited data base with new data from our own field evaluation programs as well as those of other research groups.

VI. IMPACTS PROGRAM

A. Lighting and Visual Performance

Objective: To determine the relationship between environmental lighting and visual fatigue for operators of visual display terminals (VDTs).

Background: Users of video display terminals (VDTs) commonly complain of a variety of symptoms which can be grouped under the heading of "eyestrain" or "visual fatigue." Discomfort may be accompanied by a temporarily impaired ability to perform the VDT task, and the symptoms may continue for hours after VDT use. Users, employers, and equipment manufacturers could benefit from eliminating this problem.

In an experimental approach to this problem, one could, ideally, measure "fatigue" during performance of a VDT task, and vary display parameters and lighting conditions in an attempt to minimize the fatigue. This approach is impractical, however, because fatigue is not readily quantified and measured, or even defined. Thus researchers must make assumptions about which measurable visual functions may be correlated to subjective visual fatigue, and then construct an operational definition of fatigue in terms of these parameters. Through experimentation, one might then be able to identify certain temporary sensory or motor deficits or abnormalities which correlate with subjective fatigue and/or reduced performance. It can then be determined which properties of the stimulus produce these changes in visual function. Ideally, one could then make appropriate changes in the display hardware or task lighting and thereby reduce or eliminate subjective fatigue, at which point the ultimate goal of this type of research will have been served.

General Approach: First we will obtain measures of performance, measures of the parameters of visual function, and subjective reports of visual fatigue for sessions in which a task is performed on a video display unit and compare these to data for sessions in which the same task is performed with a typewritten or printed display. Any statistically significant differences we may then associate with properties of the video display, or with interactions between the display and the lighting environment. The sensory tests (of spatial and temporal contrast sensitivity) will give us insight into specific parameters of the display which are associated with visual fatigue and/or reduced levels of task performance.

Variables of interest include specific video display terminal units (with their associated spatial, temporal, and chromatic parameters), environmental lighting (luminance level, glare level, spectral distribution, temporal characteristics), reverse field vs. normal field, viewing distance, and transient adaptation effects.

An experimental session will be devoted to a single set of experimental conditions (one video monitor or printed stimulus, one set of lighting conditions, etc.). A session will begin with visual function tests (spatial and temporal contrast sensitivity measurements and color vision tests) followed by a one- or two-hour period of task performance, and concluding with repeat sensory visual function tests.

B. Human Responses to Artificial Lighting

Objective: To determine the human responses to artificial lighting and lighting systems through quantitative, objective experiments.

Background: The possiblity that environmental factors will have adverse effects on health has become more prominent in the lay press in the past few years. These reports are principally subjective, unconfirmed, and anecdotal. Many environmental factors have been implicated, but scientifically obtained data are lacking. One implicated factor which is amenable to control is that of artificial lighting. Preliminary scientific reports have occasionally appeared.

Lighting factors that may influence performance and productivity can be attributed to the lamp, the electronics and associated controls, and the fixture, as well as to the geometry and location of the lighting system. These factors produce conditions such as color variations; glare; intensity fluctuations; spectrum variations including within the ultraviolet region; electromagnetic field generated by the lamp, ballast, or controls; and flicker, all of which could evoke a variety of human responses. These responses can be behavioral, phsychophysical, physiological, or biochemical.

Present knowledge does not adequately explain the effects of lighting parameters on performance or productivity. Furthermore, there are no generally agreed-upon field tests for ascertaining any possible negative impacts on workers, taking into account the wide variety of tasks and lighting systems in use or proposed.

The purposes of this research are thus twofold: (1) to determine direct connections (if any) between human responses and lighting factors, and (2) if there is such a connection, to provide information about quality and impact of a given lighting environment. Although subjective responses by verbal and written communication with workers can provide some of the needed information, these are generally muddied by a mix of sociological and motivational factors.

General Approach: These investigations make intensive use of nonsubjective responses in order to obtain a higher degree of cause-and-effect as well as repeatability.

We will test whether acute changes in ambient lighting in a blinded paired-comparison test can produce detectable changes in any of a number of behavioral, psychophysical, physiological, or biochemical parameters. The paired comparison is between incandescent lighting and a test lighting. By studying multiple parameters and organ systems we will increase the likelihood of detecting an objective measure of a physiological effect.

Since most physiological functions are under strong homeostatic (feedback) control, in order to increase the sensitivity of our measures we will study changes not only in mean responses but also in the variance of those responses, particularly under conditions that additionally perturb ("load") the system. In this way we can determine not only absolute changes in responses but also any effect that lighting changes have on the "dynamic range" over which the homeostatic mechanisms compensate. In such an approach the measured end-point is the amount of load required to significantly alter a controlled quantity or its variances. This experiment will require on-line analysis of the results with a microcomputer that is running the experiment. The time spent with each subject is also minimized by using sequential statistical analysis (terminating a trial as soon as statistical significance is reached).

C. Occupant Response to Natural Lighting

Objective: To develop an improved understanding of occupant response to the fenestration controls necessary for maximizing daylight utilization.

Background: Energy and load reductions will be achieved with daylighting strategies only if discomfort glare from windows and the undesired heat losses and gains through fenestration can be controlled. Limited experience in daylit environments suggests that the added thermal "cost" of fenestration can outweigh the daylighting benefits if fenestration is not properly designed and managed. Direct glare from sunlight and discomfort glare from an unobstructed view of the sky can force office occupants to increase indoor electric light levels in order to lessen brightness gradients. Thus, control of fenestration 1) to minimize heat loss and heat gain, 2) to control direct sunlight penetration, and 3) to reduce the luminance of occupant views of the sky are all prerequisites to achieving significant savings. Since interior daylight illuminance will be modified by most strategies which control thermal and optical properties of glazing, it is important to link the operation of lighting controls to fenestration controls.

Technically, the best way to arrive at an optimum daylight/energy management system is to simultaneously control the luminous and thermal properties of indoor environments using automatic insulating and shading systems coupled with proportional dimming of electric lighting. Conceptually, such an approach appears to be straightforward. In practice, problems arise in four areas:

1) Development of necessary hardware and controls.

2) Incorporation of controls into the architectural design of a building.

3) Cost-effectiveness of the control systems.

4) Occupant acceptance of the controlled environment and response to the control functions.

We possess limited data on the first three issues but a poor understanding of the fourth. Yet decisions concerning automatic vs. manual control may have significant cost implications. In addition, major investments in sophisticated control technologies may be wasted if occupant response is not considered.

General Approach: This research project builds upon prior studies of occupant preference for window size, shape, and location and related work on view. Specific planned tasks include:

1. Conducting a site survey to identify the range of characteristic existing conditions related to fenestration and lighting controls.

2. Interviewing occupants to determine preferences for control strategies and hardware and for general interior environmental conditions.

3. Studying occupant response under a variety of building conditions with a full range of manual and automatic fenestration and lighting control systems.

4. Determining the relative energy savings and load management potentials of the systems studied in task 3.

5. Based upon initial field results, modifying control systems to improve the fit with occupant preferences.

6. Developing a model of occupant response to thermal and luminous factors which can be used to determine optimal control strategies for maximizing energy/load savings consistent with occupant satisfaction.

7. Extending results to several building types and to a range of climate types.

D. Visibility and Productivity

Objective: To develop analytic tools necessary to determine the effect of lighting systems on the performance of visual tasks and to test the application of models such as the ESI and CIE model.

Background: Two empirical methods for assessing the quality of a lighting environment and its effect upon productivity have been developed, one by the Illuminating Engineering Society (IES) of the United States and one by the International Commission on Illumination (CIE).

The IES has recommended the use of Equivalent Spherical Illumination (ESI) as a figure of merit for the comparison of lighting systems. The CIE is developing a more complex model which attempts to predict visual performance as a function of lighting. This model includes the concept of ESI. However, there is disagreement over some of the qualitative trends in ESI between different lighting systems (e.g., the advantages of polarizing systems or even the desirability of lighting levels above 50 or 100 ESI footcandles. Furthermore, the visual model has not been characterized sufficiently to be usable in a complete economic model for optimizing lighting levels or establishing lighting standards.

General Approach: The following specific analytical tasks will be undertaken:

1) Identifying what additional information is needed to make the CIE model directly applicable to field situations.

2) Identifying and analyzing the visual and nonvisual factors that contribute to job performance.

3) Analyzing common visual tasks to identify the visual stimulus parameters they encompass.

4) Analyzing the way changes in stimulus parameters affect visual performance.

5) Determining whether changes in visual performance resulting from manipulation of stimulus parameters are consistent with predictions from the ESI model.

6) Evaluating the effects of changes in luminaire design and placement on parameters of the visual stimulus.

7) Establishing a protocol for evaluating the effect of luminaire and placement on visual performance and comparing innovations in lighting design.

8) Evaluating the effect that changes in lighting hardware and luminaire arrangement have on the performance of common work tasks in the field.

VII. PROGRAM FACILITIES

A. Lawrence Berkeley Laboratory

Physical Lighting Laboratory

Facility Location: Building 46, Room 159
Lawrence Berkeley Laboratory

General Description: The Physical Lighting Laboratory is a newly constructed laboratory specifically designed to measure light and lighting systems. The space measures 1200 square feet and is divided into three sections: a lighting measurement area, a lamp and lamp system life test area, and a general laboratory area.

The lighting measurement room is 600 square feet and is equipped to measure all of the characteristics of light sources and lighting systems in a standard controlled environment of 25°C. A heat pump is used to maintain a temperature of 25 ± 1°C so that absolute light flux can be accurately measured and referenced to the standards set by the National Bureau of Standards and the American National Standards Institute (ANSI).

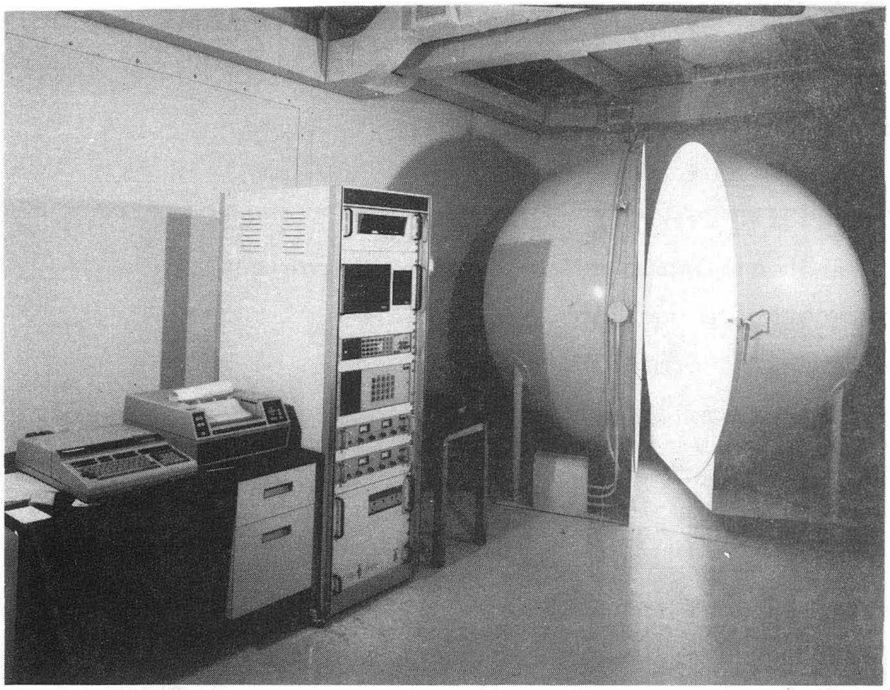
The lamp-life test area is 300 square feet and contains lamp test racks which permit the long-term operation of all types of light sources and systems. The power is furnished by two stablized, regulated power supplies that can furnish either 120 or 277 volts. The total capacity of the supply is 20 kw. The power supply can be programmed to provide a wide range of on/off cycles to conform to the standard ANSI test procedure for each type of light source. A mechanical ventilation system removes the heat given off by the lamps in test and minimizes drafts.

The third room houses a small office and a general laboratory with running water and sink. The construction of test equipment and the needed chemical preparations are conducted in this laboratory.

Equipment List:

- Eight-foot integrating sphere

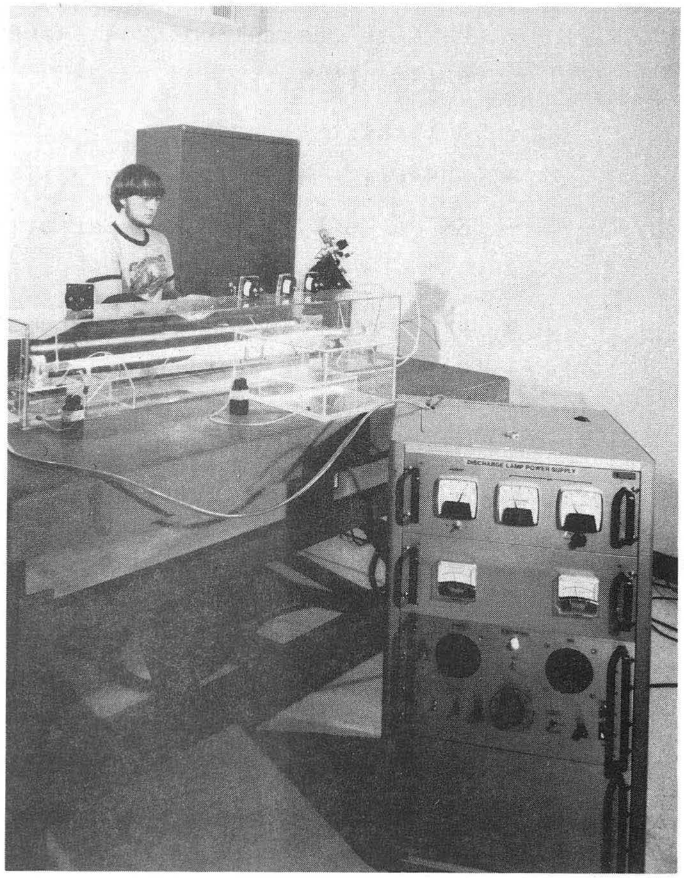
- EG&G Model 550-1 digital radiometer/photometer
  - Calibrated photometer probe
  - Calibrated spectro-radiometer (280 nm - 100 nm)
- Hewlett-Packard 9825T desk-top calculator
- Hewlett-Packard 358A signal analyzer with antenna set
- Tektronix 7623A storage oscilloscope
  - 7A13 differential comparitor
  - 7A18 dual trace amplifier
  - 7B53A dual time base
  - 7A22 differential amplifier
- Function generator
- Hewlett-Packard 3456A digital voltmeter
- Hewlett-Packard 3497A data acquistion system
- 20-channel multiplexer
- Clark Hess 255 high-frequency volt-amp-watt meter
- two-pen recorder
- Vecco diffusion pump system
- Peltier thermal control system
- Reference ballast
- Ballast test system
- NBS calibrated light sources
- EMT 4106CR 120-volt superior power supply (6.6 kw)
- EMT 10432 277-volt superior power supply (12.4 kw)
- Fluke data acquistion system (60-channel)
- Voltage, current, power transducers
- Tektronix J-16 photometer with luminance probe
- 0-36 VDC power supply (6-8 amp)
- 0-150 VDC power supply (0-2.6 amp)
- 20´ x 30´ screen room



Eight-foot integrating sphere with data acquisition system.

CBB 819-8734

Equipment for fundamental plasma research.



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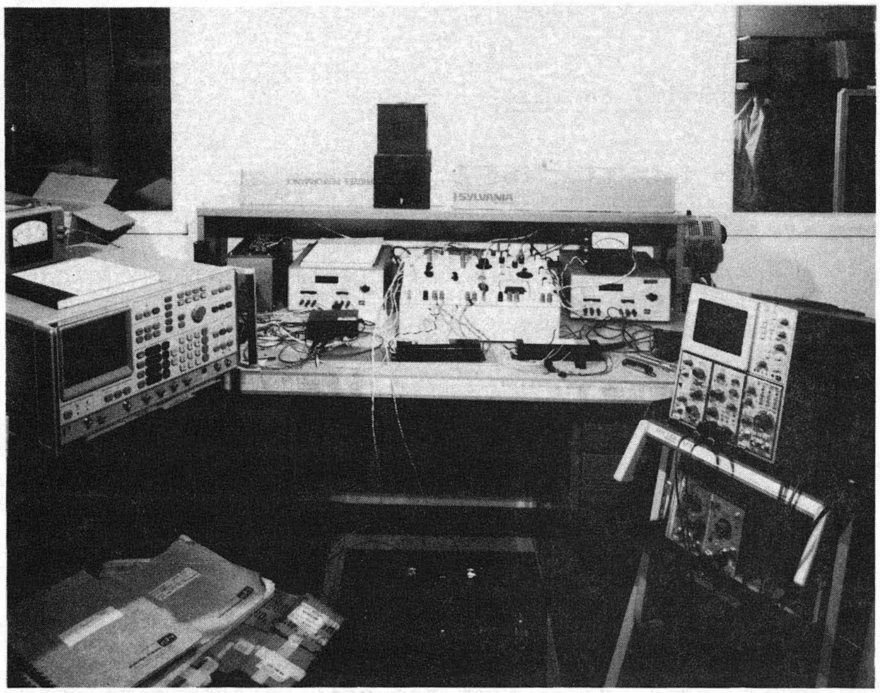
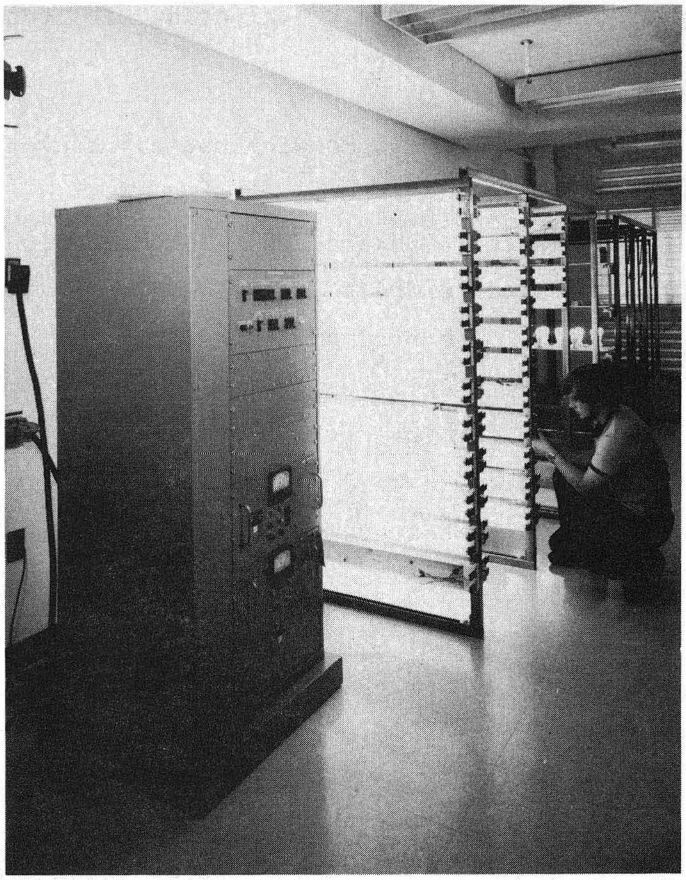


High-frequency ballast test station.

CBB 819-8740



Lamp-life test racks for long-term testing.

CBB 819-8738

Mobile Window Thermal Test (MoWiTT) Facility

General Description: Energy optimization for daylighting cannot be properly determined unless the thermal impacts associated with lighting and daylight utilization are assessed. Although these effects are modeled by DOE-2 and other large energy-analysis computer programs, there has been no experimental validation of the net energy flows through window systems. We are building a field test facility which for the first time will provide accurate measurements of net energy performance.

The mobile trailer contains two instrumented cells in which comparative tests of window systems will be made. The cells can be used in a calorimetric mode, in which basic fenestration properties are measured. It can also be used in a simulation mode, when the cell is configured to thermally behave like a residential or commercial building. In this mode, the net heating and/or cooling loads experienced by HVAC systems are measured. Measurements of the effects of lighting and daylighting on internal heat gain can be made with greater accuracy and at lower cost than through field evaluation of actual buildings.

Equipment List:

- 2 Calendar clocks with battery back-up
- 2 LSI-11 computers
- 1 Hewlett-Packard 3054A/280 data acquisition system
- 1 Fixed-head disc drive
- 2 Dual floppy disc drives
- 2 Zenith Z/19 terminals
- 1 ADM terminal
- 1 Hewlet-Packard plotter
- 3 Staefa temperature control systems:
  2 heating/cooling/humidity; 1 heating/cooling
- 1 Chiller, large capacity
- 2 Air/liquid heat exchangers
- 2 Humidifiers
- 2 Precision electric heaters
- 2 Power metering systems
- 2 Liquid flow/temperature metering systems

2 Multipoint temperature sensor systems

2 Multipoint anemometer systems

1 Weather station, measuring

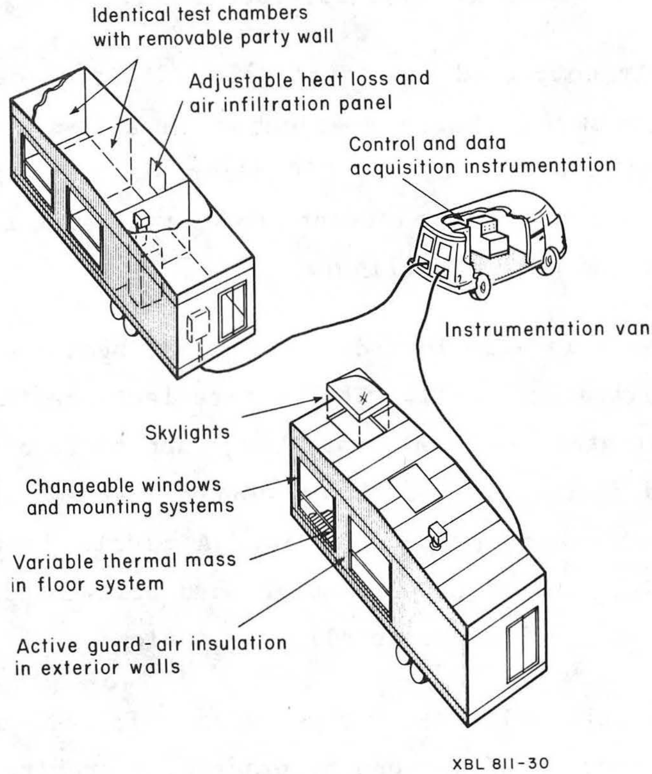
Dry bulb temperature

Wind speed and direction

Wet bulb temperature

2 Eppley PSP pyranometers

2 Large-area heat flux sensor systems



Schematic view of Mobile Window Thermal Test (MoWiTT) facility.

B. UCB College of Environmental Design, School of Architecture

Artificial Sky - Daylighting Simulator

Facility Location: Room 275, Wurster Hall
College of Environmental Design
University of California, Berkeley

General Description: Scale models allow quantitative and qualitative assessments of daylighting illumination levels and distribution patterns to be made without the time and expense of constructing full-scale room interiors. Although useful measurements can be made out-of-doors, highly accurate measurements can only be made under an artificial sky with reproducible luminance distributions.

We have recently completed construction and initial calibration of the only artificial sky in North America which allows model measurements under uniform, CIE overcast, and CIE clear sky conditions. Additional capabilities are under development to permit simulation of ground-reflected light and direct sunlight.

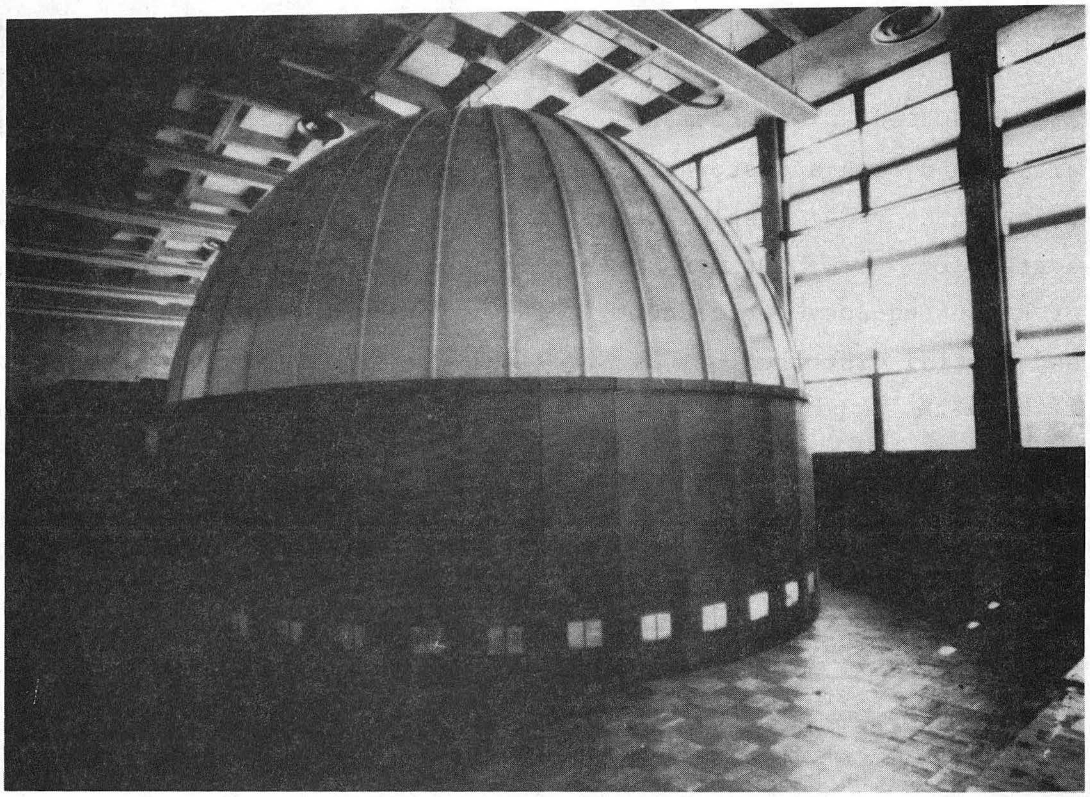
The artificial sky is a 24-foot-diameter metal hemisphere which rests on a seven-foot cylindrical wall. The high-reflectance interior white surface is illuminated by banks of high-output fluorescent lamps in custom-designed fixtures. A lighting control system allows easy conversion from one standard sky to another. A model platform accommodates large-scale models and adjusts in height and orientation to permit testing of a range of model sizes in all orientations.

The facility is currently used for research. It will also be available for teaching purposes and for use by practicing architects and engineers to facilitate the design of energy-efficient buildings.

Equipment List:

1. Tektronix option 1 and 2 j16 digital photometer
2. Tektronix option 1 and 2 j6511 illuminance probe
3. Tektronix option 1 and 2 j6523 one degree angle luminance probe (option 1 English scale, option 2 metric scale)

4. Megatron architectural model luxmeter (12 sensors)
5. Spectra Model 1980A photometer
6. Li-cor illuminance probes (60 sensors)
7. Litemate/Spotmate System 500 photometer
8. Photoelectric cells



XBB 804-5182

Exterior view of 24-foot-diameter hemispherical sky simulator for daylighting studies.

C. UCB School of Optometry

Lighting and Visual Performance Laboratory

Facility Location: Rooms 389B,C
Miner Hall, School of Optometry
University of California, Berkeley

General Decription: There are two adjacent rooms, each approximately 11'x14'x10'. From one (the Control Room), psychophysical experiments are conducted. This room houses computer equipment, project development areas, and desk and storage areas. The second room (Subject Room) contains three video display terminals, each on a separate desk, a flexible system for room lighting (choice of incandescent, standard fluorescent, or high-frequency fluorescent, each with separate controls for luminance and spatial distribution), a Xerox daisy-wheel printer with table, and a rack which supports a Tektronix monitor (used for spatial and temporal vision tests), a Sanyo color monitor (for color vision testing), and an illuminated background screen. This room is newly painted and carpeted (neutral gray) and is without windows, but with a ventilation system. A portable Spectra Pritchard photometer with tripod and accessories is also in the laboratory.

Equipment List:

Control Room -

2 Apple II computers (48K), with accessory plug-in boards (clock, serial interface, parallel interface, communications, Videx Videoterm, PASCAL language APPLEPLOT printer interface)
4 disk-drive units
Centronics 737 printer
Centronics 739 printer
2 Sanyo DM5112CX B&W monitors

Computer bench
Electronics technician's bench and miscellaneous equipment
Desk, file cabinet, shelves

Subject Room -

ADM-3A video terminal (green phosphor)
ADM-3A video terminal (white phosphor)
Zenith Z-19 video terminal (white phosphor)
Xerox 1740 daisy-wheel printer
Tektronix 606 monitor
Sanyo DMC6013 color video monitor

Overhead lighting system containing four twin-lamp fluorescent fixtures, 28 incandescent lamps, and diffuser, with control panel allowing separate powering and dimming for different lamp arrays, and allowing choice of standard or high-frequency operation of fluorescent lamps

3 desks for video display terminals
table for Xerox printer
rack for Tektronix and Sanyo monitors, with system for background lighting
ventilation system
carpet

Portable Equipment -
Spectra-Pritchard photometer and accessories

D. UCSF Medical Center

Health and Environment Laboratory

Facility Location: Room U-471, Department of Medicine
School of Medicine
University of California at San Francisco

General Description: The laboratory space is a partitioned area approximately 11′x 11′ x 12′. Within this space is the experimental test chamber (7′ x 7′ x 8′), a digital PDP 8/A computer, an 05/8 operating system, two VT100 video terminals, and an ILA line printer. Inside the test chamber is the subject chair and an Orthotron, iso-kinetic exerciser.

The lighting system in the RF-shielded room consists of an overhead movable lighting panel, an adjustable glare source mounted on the front wall, and a photometer for measuring the light level in the room.

The lighting panel has space for eight lamp rods. An experiment may use two sets of four lamp rods each from any of the available types: incandescent, cool-white fluorescent, daylight fluorescent, or high-pressure sodium. A computer-controlled solid-state relay chassis allows the PDP-8 computer to turn on the lamp rods in a programmed combination. The computer can also turn on two colored lamps on each of the incandescent lamp rods. The light output from the different types of lamp rods will be matched to each other to within a few percentage points by varying input voltage to the fluorescent and high-pressure sodium lamps.

The adjustable glare source mounted in front of the subject houses two lamp rods, with one of each of the two types mounted in the overhead lighting panel. The computer, via the solid-state relay chassis, also controls these lamp rods. The front panel of the glare source is opaque except for 1/4-inch slits directly in front of the lamp rods inside.

A Tektronix J-16 digitial photometer is mounted inside the room. It is connected directly to the computer which can thereby measure the light level inside the room in real time.

Equipment List:

- Isolation chamber
- Digital PDP 8/A computer
- 05/8 operating system
- SKED software system
- 2 RL01 disk drives
- 2 VT100 video terminals
- ILA 120 line printer
- 2 Digitalker DT-1000 speech synthesizer boards
- 4 OPTEL LCD sets
- Typewriter stand and desk

VIII. PERSONNEL

Principal Investigator: Samuel Berman, Ph.D.

A. Lawrence Berkeley Laboratory Staff

Technical Program:

Rudolph R. Verderber, Ph.D., Program Manager
Solid-state device physicist with expertise in technology transfer and the application of electronics to lighting systems.

Francis Rubinstein, B.S.
Physicist with expertise in the design and measurement of lighting sources and systems.

Rai-Ko Sun, Ph.D.
Physicist with expertise in plasma physics and electronic systems.

Oliver Morse, Ph.D.
Electrical engineer with a background in designing lighting systems and electrical layouts for commerical and industrial buildings.

Buildings Applications Program:

Stephen Selkowitz, M.S., Principal Investigator for the Windows and Daylighting Program.
Expertise in daylighting modeling and analytical methods, net energy performance of fenestration, daylight resource assessment, evaluation of commercial building performance.

Eliyahu Ne`eman, Ph.D., Visiting Scientist
Electrical engineer with expertise in all aspects of illuminating engineering and daylighting. Dr. Ne`eman is Chairman of the CIE Daylighting Committee and Professor in the School of Architecture, Technion, Israel.

Richard Johnson, B.S.
Architect with expertise in performance of innovative window systems and commercial building modeling, including daylighting performance, and glazing optimization studies.

Michael Wilde, M.A.
Architect with expertise in technology transfer and education issues relating to daylighting,responsible for daylighting data base activities and compilation of Daylighting Resource Package.

Mojtaba Navvab, M.S.
Architect with expertise in instrumentation design and the measurement and design of daylighting systems.

Michael Rubin, Ph.D.
Physicist with expertise in all aspects of window thermal modeling and in building-energy analysis models and daylighting analytical models.

Joseph Klems, Ph.D.
Physicist with expertise in thermal modeling and laboratory and field testing of glazing materials and window systems.

Impacts Program:

Samuel Berman, Ph.D.
Physicist with expertise in lighting technology, the fundamental aspects of visibility, and environment effects of artificial lighting.

Robert Clear, Ph.D.
Theoretical chemist and visual psychophysicist with expertise in the fundamental aspects of illumination, visibility, and performance.

Allen Arthur, B.S.
Electrical engineer with expertise in electronic systems and the measurement and analysis of electromagnetic interference.

Michael Harms, M.S.
Computer scientist with expertise in the development of computer programs and systems.

Jerry Stoker
Technician, electronic specialist.

David Gumz
Technican, mechanical specialist.

B. University of California School of Optometry Staff

Daniel Greenhouse, Ph.D.

Vision scientist with engineering background specializing in psychophysical experimentation.

Terry Benzschawel, Ph.D.

Vision scientist specializing in color vision and psychophysics.

Ian Bailey, Ph.D.

Professor on the faculty of the School of Optometry.

Arthur Bradley, B.S.

Graduate student of physiological optics specializing in psychophysics and spatial and temporal aspects of the human visual system.

William Baird

Electronics technician.

C. University of California Medical School Staff

Don L. Jewett, M.D., D.Phil.
Orthopedic surgeon and neurophysiologist with expertise in environmental hypersensitivity.

Russell M. Jaffe, M.D., Ph.D.
Laboratory medicine and biochemistry, with expertise in environmental factors related to health.

Martin R. Greenberg, Ph.D.
Research psychologist with expertise in environmental determinants of behavior.

Richard Nahass, B.S.
Research technician with expertise in biobehavioral research and computer programming.

Burt Rutkin, B.S.
Engineer with extensive expertise in design and implementation of computer systems.

John Morris, M.S.
Computer programmer and system analyst.

IX. LIST OF PUBLICATIONS

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Energy Efficiency and Performance of Solid State Ballasts. R. Verderber, S. Selkowitz, S. Berman. LBL-7828, June 1978. Published in LD&A 9(4),pp. 23-28, April 1979.

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