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FY 1986 Annual Report

WINDOWS AND LIGHTING PROGRAM

May 1987

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LBL-22156

APPLIED SCIENCE DIVISION ANNUAL REPORT

WINDOWS AND LIGHTING PROGRAM

FY 1986

Elton J. Cairns
Head, Applied Science Division
and
Associate Director, LBL

Stephen E. Selkowitz
Program Leader, Windows and Lighting Program

Applied Science Division
Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

Prepared for the U.S. Department of Energy under Contract No. DE-AC03-76SF00098

WINDOWS AND LIGHTING PROGRAM STAFF

Stephen Selkowitz, Program Leader

WINDOWS AND DAYLIGHTING

Dariush Arasteh
James Ashby
Erica Atkin
Charles Benton
Dennis DiBartolomeo
Patrice Dinhut
Dan Even-or
Ori Even-or
Ellen Gailing
Edward Gleason
John Hartman
Mary Lou Hinman
Nori Hudson
Arlon Hunt
Antonia Hutchinson
Richard Johnson
Kim Kara
Harry Keller
Guy Kelley
Jong Jin Kim
Joseph Klems
Carl Lampert
Theresa Lessard-Smith
Stephanie McDonald
Shirley Nozaki
Konstantinos Papamichael
Amy Rakley
Michael Rubin
Stephen Selkowitz*
Jonathan Spear
Mark Spitzglas
Robert Sullivan
Glenn Sweitzer
John Thornton
Michael Wilde
Ruth Williams
David Wruck
Mehrangiz Yazdanian
Phillip Yu

LIGHTING SYSTEMS RESEARCH

Erica Atkin
Samuel Berman*
Ted Clark
Robert Clear
Douglas Crawford
Charles Dumm†
Jean Ferrari
Ellen Gailing
Chuck Greene†
Donald Hollister
Donald Levy
Maynard Michel
Christopher Moll‡
Oliver Morse§
Francis Rubinstein
Robert Richardson‡
Michael Siminovitch
Rudy Verderber
Gregory Ward
Ruth Williams
Liang-Zhong Wang‡
Tai-Ming Zhou‡

*Group Leader, †Engineering Division,
‡Participating Guest, §Plant Engineering.

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WINDOWS AND LIGHTING PROGRAM

INTRODUCTION

Over 30% of all energy used in buildings is attributable to two building elements, windows and lighting. Together they account for annual consumer expenditures of over $50 billion. Each affects not only energy use by other major building systems but also comfort and productivity, factors that have a far greater influence on building economics than direct energy consumption alone. Windows play a unique role in the building envelope, physically separating the conditioned space from the world outside without sacrificing vital visual contact. Lighting systems make it possible to conduct any task of any visual difficulty anywhere in the indoor environment, and at the same time define the luminous qualities of the indoor environment. These two building elements are thus essential components to any comprehensive building science program.

Despite the important achievements in reducing building energy consumption over the last decade, significant additional savings are still possible. These will come from two complementary strategies: 1) better building designs that effectively apply existing technology and extend market penetration, and 2) new advanced technologies to increase the savings potentials with each application. Both the Windows and Daylighting and Lighting Systems Research groups have made substantial contributions in each of these areas. The ongoing research described in the annual summary aims to further advance achievement of these goals.

The Windows and Daylighting Group focuses on developing the technical basis for understanding the energy-related performance of windows. If the flow of heat and light through windows and skylights can be properly filtered and controlled, these building elements can outperform any insulated wall or roof component and provide net energy benefits to the building. The group's investigations are designed to develop the capability to accurately predict net fenestration performance in residential and commercial buildings. Simulation studies, field measurements in a mobile field test facility, and building monitoring studies help us to understand the complex tradeoffs in fenestration performance. The Group's three major project areas are optical materials, fenestration performance, and building applications and design tools.

In our studies of optical materials and advanced concepts, we develop and characterize thin-film coatings and other new optical materials that control radiant and thermal flows through glazings and study innovative concepts for large-area envelop enclosures. The program helped accelerate the development and market introduction of windows incorporating high-transmittance, low-emittance coatings for R3-R5 windows. If they sell as currently anticipated, they will save consumers over $3 billion annually in heating bills alone.

Our research of window performance aims to develop new analytical models and experimental procedures to predict the thermal and solar-optical properties of the complex assemblies of glazing materials and shading devices that comprise complete fenestration systems. Thermal performance models are being validated with the Mobile Window Thermal Test (MoWiTT) Facility, now collecting data at a field test site in Reno, Nevada. This unique facility combines the accuracy and control of lab testing with the realism and complexity of dynamic climatic effects. LBL daylighting studies employ a unique 24-foot-diameter sky simulator for testing scale models under carefully controlled conditions, and new experimental facilities for measuring the photometric and radiometric properties of complex fenestration systems.

Building applications studies and design tools help us to understand the complex tradeoffs in fenestration performance as a function of building type and climate. In nonresidential buildings major reductions in electric energy use and peak electric demand can be achieved if the tradeoffs between daylight savings and solar-induced cooling loads are understood. We are developing concepts for an Advanced Envelope Design Tool using new imaging techniques and expert systems.

The research of the Lighting Systems Group is divided into three major areas: advanced light sources, building applications, and impacts on health and visibility.

Our light source research is concerned primarily with developing new concepts for efficiency converting electrical energy into visible light. Areas of interest include mechanisms for reducing the ultraviolet self-absorption in gas-discharge lamps and

the excitation of plasma gas at ultrahigh frequency ranges (approximately 10^9 hertz). Both hold the promise of a more reliable and more efficient conversion of energy into light.

The building applications research concentrates on the design of lighting systems and the effective use of lighting controls, and their interaction with a building's HVAC system.

Research in visibility impacts is focused primarily on gaining basic information needed to define lighting conditions that enhance productivity in a cost-effective manner. It also seeks to determine any possible undesirable visual effects, such as excessive fatigue, associated with using modern office equipment such as visual display terminals in an advanced lighting environment.

Our studies of health impacts extend electric lighting research to a wider class of human activities. In specially designed experimental rooms, conditions can be varied, and nonsubjective responses to lighting variables can be measured by sensitive instrumentation.

The Lighting Group's successes include advancing the development of high-frequency solid-state ballasts for fluorescent lamps and the invention of a new high frequency surface wave lamp with 30% better efficiency than the common fluorescent lamp. A 2-year test of solid-state ballasts in a large office building showed an electricity savings of 40%. Scaled to the entire country, this represents an annual savings of $5 billion. The energy-efficient surface wave lamp promises major reductions in energy use with considerably longer lamp life.

Windows and Daylighting*

S.E. Selkowitz, D. Arasteh, D.L. DiBartolomeo, A.J. Hunt, R.L. Johnson, H. Keller, J.J. Kim, J.H. Klems, C.M. Lampert, K. Lofftus, K. Papamichael, M.D. Rubin, M. Spitzglas, R. Sullivan, P. Tewari, and G.M. Wilde

Approximately 20% of annual energy consumption in the United States is for space conditioning of residential and commercial buildings. About 25% of this amount is required to offset heat loss and gain through windows. In other words, 5% of U.S. energy consumption—the equivalent of 1.7 million barrels of oil per day—is tied to the performance of windows. Fenestration performance also directly affects peak electrical demand in buildings, sizing of the heating, ventilating, and air-conditioning (HVAC) system, and the thermal and visual comfort of building occupants.

The aim of the Windows and Daylighting Group is to develop a sound technical base for predicting the net thermal and daylighting performance of windows and skylights. The group's work will help generate guidelines for design and retrofit strategies in residential and commercial buildings and will help develop new high-performance materials and designs.

One of our program's strengths is its breadth and depth: at one extreme, we examine energy-related aspects of windows at the atomic and molecular level in our materials science studies, and at the other extreme, we perform field tests and *in-situ* experiments in large buildings. We have developed, validated, and use a unique, powerful set of computational tools and experimental facilities. Our scientists, engineers, and architects work in collaboration with researchers in industry and academia.

To be useful, the technical data developed by our program must be communicated to design professionals, industry, and other public and private interest groups. We publish our results and participate in industrial, professional, and scientific meetings and societies, national and international, to ensure that our research results are widely disseminated.

*This work was supported by the Assistant Secretary for Conservation and Renewable Energy, Office of Buildings and Community Systems, Building Systems Division and Office of Solar Heat Technologies, Solar Buildings Division of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

Our research is organized into three major areas:

- Optical Materials and Advanced Concepts
- Fenestration Performance
  - —Thermal analysis
  - —Daylighting analysis
  - —Field measurement facility
  - —Building monitoring
- Building Applications and Design Tools
  - —Nonresidential studies
  - —Residential studies
  - —Occupant impacts
  - —Design tools

OPTICAL MATERIALS STUDIES

Significant reductions in energy consumed by buildings will come not only from better building design, but also from the development and introduction of new glazing materials. Since the inception of our program in 1976, we have worked to identify, characterize and develop promising new fenestration materials to assist industry with developing the next generation of advanced fenestration systems. We also provide scientific coordination for DOE-funded research projects at universities, private-sector firms, and other national laboratories, and work to transfer our research results to the private sector.

In 1976, we made the development of low-emittance (low-E) coatings a major program objective. DOE-supported research has accelerated market introduction of new high-performance low-E window systems. Several small firms began offering commercial products in 1982, and in 1984 many of the largest glass and window manufacturers introduced low-E products. The use of low-E coatings in a conventional double-glazed window provides better thermal performance than triple glazing and makes a lighter and more compact window. In the long term this coating technology could produce windows having heat transfer values as low as those of insulating walls. On an annual basis such windows should outperform the best-insulated wall.

GLASS AND PLASTIC SUBSTRATES

To predict the performance of complex window systems, we must accurately know the optical properties of their coatings and glass and plastic substrates. Until recently, scientists did not fully understand these properties for even the most common varieties of glass used in windows. We have completed work on standard clear glasses, glasses having absorbing additives, and high-purity glasses. Our results were

summarized in a paper that includes a complete set of optical constants from the near ultraviolet through the little-studied far infrared for all common window glasses.[1] We also provided spectrally and directionally averaged bulk properties for calculating solar and thermal radiative heat transfer through windows.

Accomplishments During FY 1986

With the increasing marketing of low-E window systems, there is a concern that emittance be properly measured, calculated, and specified. Normal emittance can be measured in a spectrophotometer, but hemispherical values are required for thermal analysis. In FY 1986 we developed a procedure to determine the hemispherical emittance of a low-E coating if the normal emittance is known. This correlation, shown in Fig. 1, is now used by industry groups as standard procedure.

Planned Activities for FY 1987

We will continue measurement and analysis of coated glazings, seeking generalizable relationships between simple, measurable parameters and the more complex angle-dependent and spectrally dependent behavior of specific coatings. We will also continue collaborative work with an industry group developing voluntary standards for measurement of emittance.

DURABLE LOW-EMITTANCE COATINGS

Since 1976 we have contributed to the development of low-E window coatings that transmit sunlight but reflect thermal infrared, thus suppressing radiative heat transfer. Commercially available coatings based on vacuum-deposited metal-dielectric multilayer films have satisfactory optical properties and a low emittance value, 0.1-0.15, but are not sufficiently durable to be used in nonsealed glazings. Pyrolytic films deposited directly on glass in the float process are more durable but typically have a higher emittance, 0.35, and thus lower energy savings potential. We approach the problem by identifying materials with good intrinsic durability and then attempting to improve the emittance and solar-optical properties.

Accomplishments During FY 1986

We began by studying the titanium oxynitride (TiN_xO_y) system, producing these gradient-index coatings first by plasma-assisted chemical vapor deposition (PCVD) and later by sputtering. We installed a new reactive sputtering system with improved glass flow controls and successfully fabricated a series of gradient-index and multilayer films. The coatings were characterized by electron microscopy, Auger electron spectroscopy (AES), and Rutherford backscattering (RBS), in addition to complete optical characterization. A complete phase diagram of the Ti-O-N system was constructed. Multilayer TiO_2-TiN-TiO_2 coatings were successfully deposited with excellent optical and emittance properties, as shown in Fig. 2.

Planned Activities for FY 1987

We expect to optimize the properties of the multilayer TiN-based low-E coating. Detailed data on

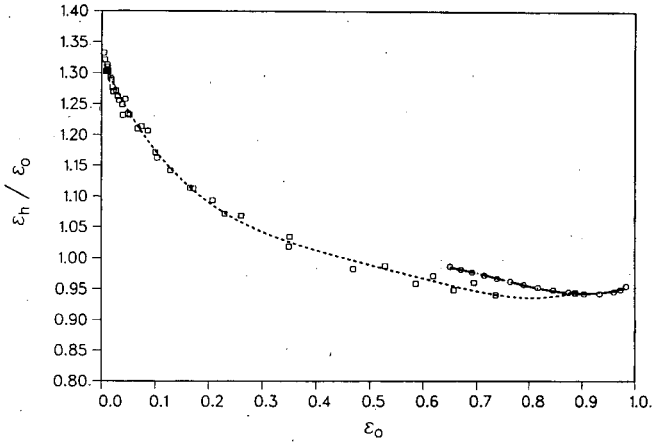

Figure 1. Normalized hemispherical total emissivity versus normal emissivity. Solid curves approximate (□) metals and coatings on glass, and (0), dielectric substrates. (XBL 876-2803)

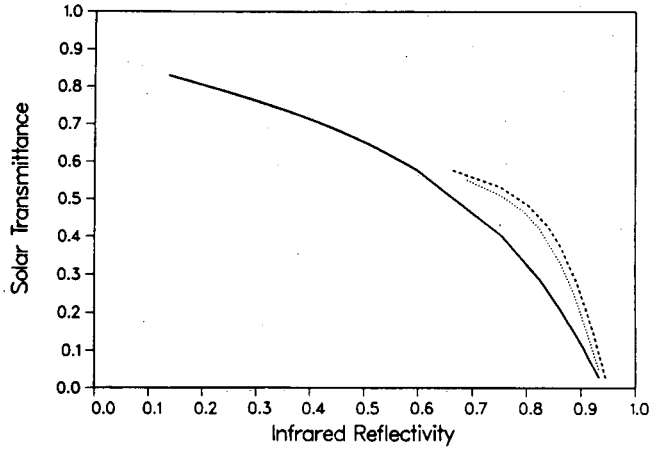

Figure 2. Solar transmittance versus infrared reflectivity of: ——TiN (experimental), ... composite TiN / TiO_2 and --- composite TiN / TiO_2 (theoretical).
(XBL 876-2805)

reduce light scattering, [4,5] initiated work to scale up the maximum size of the aerogel samples that could be dried, and studied the heat and light transfer properties of aerogel.[6] The time evolution of light scattering was used to follow the formation of the gel and understand and reduce the light scattering.

We prepared aerogel samples with solar transmittance greater than 86% and thickness of 20 mm. Aerogel of this thickness has a thermal resistance of about 5.5, which can be tripled by partially evacuating the window system to 0.1 atmospheres.[6] Alternative vacuum window concepts require a high vacuum that is very difficult to maintain over window life. A reasonable commercial design for an aerogel window is a 12mm (1/2 in) evacuated configuration with a thermal resistance of R-10.

We undertook development to scale up the supercritical drying process to produce larger samples. An improved drying process, developed earlier at LBL, reduces the temperatures and pressures required for aerogel manufacturing processes. The new process substitutes liquid CO_2 for the alcohol in the alcogels prior to supercritical extraction. In FY 1986 a new larger autoclave based on this process was designed and fabricated. Development of instrumentation to monitor the conditions in the autoclave was initiated late in FY 1986.

Planned Activities for FY 1987

Our primary goal for FY 1987 is to further decrease the scattering of aerogel to improve its acceptability as a window material. We will further investigate the effects of temperature and catalyst during the gelling process. The large autoclave will be instrumented and then installed to prepare larger samples for thermal testing.

CHROMOGENIC MATERIALS RESEARCH

Optical switching materials or devices can be used to dynamically control transmission of solar radiation through windows by changing its optical properties in response to light, heat, or electrical field. Initial results of energy simulation studies of office buildings suggest that an automatically controlled optical shutter coating can provide substantial economic benefits by minimizing cooling and lighting energy use, reducing peak electrical demand and HVAC system size, and improving thermal and visual comfort. Thermochromic and photochromic systems may have less universal application than actively controlled electrochromic coatings, but may be simpler and cheaper to produce and perform equally well for specific building applications.

Electrochromic Materials

Electrochromism is exhibited by certain metal oxide and organic materials.[7] An anodic electrochromic material undergoes an intense color change when a colored compound is formed from both dual ion and electron extraction. We are studying hydrated nickel and manganese oxides as optical switching materials for electrochromic devices.

Accomplishments During FY 1986

Our emphasis is on developing a detailed understanding of the behavior of electrochromic films in order to improve their operating properties. We determined the spectral solar transmittance for hydrated nickel films switched in liquid cells containing a KOH electrolyte. The solar transmittance can be switched from 73 to 35% for a single 1-volt pulse for a film of 500 Å thickness. Even greater dynamic range, 74% to 25%, is achieved in the visible. Ion backscattering spectrometry, sputter-Auger, and x-ray photoelectron spectroscopies were used to chemically characterize hydrated nickel oxide films.[8] Cyclic voltammetry was used to characterize the switching reaction.[9] We also did initial analysis of hydrated manganese oxide as a potential ion-storing counter electrode material and developed potentially faster and lower-cost electrochemical processes to deposit nickel and manganese hydroxide directly on to doped tin-oxide-coated glass.

Planned Activities for FY 1987

We will continue our research on hydrated nickel and manganese oxides, especially on the molecular and structural transformation in hydrated nickel oxide during switching, and on cyclic stability. We will also begin to study devices using nickel oxide, a polymeric ion conductor and a suitable counter electrode material.

Thermochromic Materials

Simpler thermochromic coatings that switch in response to heat or light may also be useful, particularly if these coatings can be fabricated and installed less expensively than more complex electrochromic coatings. A thermochromic material might, for example, be used in sun-belt residential windows.

Accomplishments During FY 1986

In FY 86, we started work on a thermochromic vanadium oxide coating. Prior work by Honeywell suggested that VO_2 was a promising material,

although its transition temperature was too high for use in buildings. Jorgenson successfully demonstrated that the transition temperature could be reduced by doping the oxide. We studied the optical and long-wave IR properties of the coating to determine its suitability for a combined low-E/thermochromic coating for windows in sun-belt residences. Initial tests suggest that the emittance effect is not large enough to influence performance but the coating does switch over a moderate range.

Planned Activities for FY 1987

The objective in FY 87 will be to raise the overall transmittance of the film while maintaining a dynamic transmittance range of at least 2:1. Simulation studies will be used to quantify the performance of alternative coating and window designs.

MATERIALS FOR IMPROVED USE OF DAYLIGHT

Conventional methods of controlling the intensity and spatial distribution of daylight in buildings rely on architectural elements and interior or exterior shading devices. Greatly improved performance would result from materials or systems that could: (1) transmit maximum daylight with minimal cooling load impact (i.e., reject solar infrared radiation); (2) collect and distribute daylight beyond the perimeter zones in buildings; and (3) provide angular selectivity in accepting and redirecting incident light at the building envelope.

In earlier studies we evaluated the performance of a variety of devices for daylight acceptance and control on the basis of their reflective and refractive optics. In 1982 we reviewed the feasibility of innovative optical materials and devices such as fiber-optics systems, hollow light guides, holographic coatings, selective-reflectance materials, and scattering media.

Light Guide Systems

Daylighting can reduce electricity use and peak demand in buildings. However, its application is currently limited to work areas close to windows and skylights. There is sufficient usable flux on the exterior skin of a building, however, to provide adequate illumination throughout any building. The technical challenge is to collect, transmit, and distribute the light where it is needed. We believe that light transmission systems are the critical optical elements for successfully developing core daylighting systems. We are developing the performance data necessary to evaluate the economic feasibility of such systems.

Accomplishments During FY 1986

Previous simulation studies have shown that several types of solid and hollow light guides can transmit significant fractions of incident light. Performance is a function of materials, geometry, and incident sun conditions. Figure 4 illustrates the importance of surface reflectivity and the degree of collimation of the input light beam for a hollow, reflective light guide. A modest increase in reflectivity from 85 to 95% results in a large increase in net transmittance, particularly for a poorly collimated beam. We have determined that guide transmittance of greater than 50% appears possible over a distance of 50 ft for a 2-ft-square guide. Optical measurements on a scale-model guide have corroborated these findings. We have begun a mathematical study of total optical system performance including the coupling between collector and guide optics, and we simplified a technique for analyzing overall optical system performance.

Planned Activities for FY 1987

We will continue modeling studies to determine the overall performance of alternative optical system designs. The most promising systems will be tested in scale models. DOE-2 will be used to estimate the annual performance of different systems in different climates.

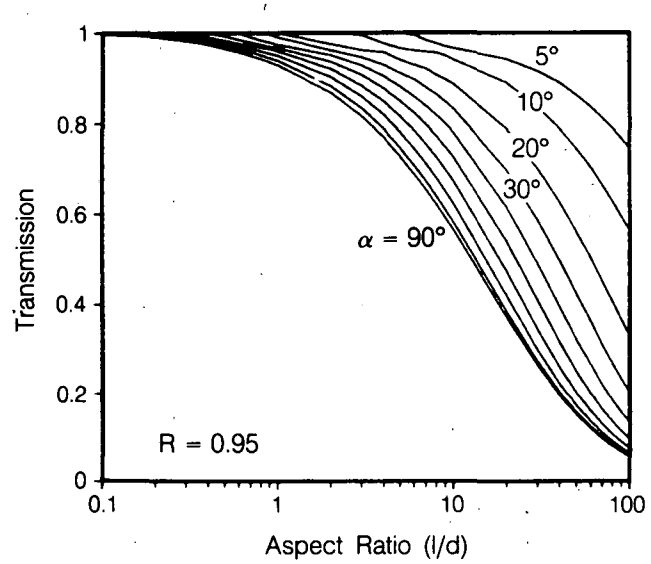

Figure 4. Transmission efficiency of a tubular light guide vs. aspect ratio (length/diameter). The parameter α is the half-angle of the concentrated sunlight. The inner surface reflectivity R is 0.95. (XBL 854-9798)

ADVANCED GLAZINGS FOR AUTOMOBILES

We have begun investigating new advanced glazing for automobiles. Automobile aerodynamics and styling trends dictate greater glass areas, which burden downsized air conditioners and reduce thermal and visual comfort. Our objective is to determine which properties can best meet the optical performance needs in the automobile industry and to investigate appropriate materials to fill these needs. Our initial task is to develop a better understanding of the technical performance issues through optical and thermal modeling studies.

Accomplishments During FY 1986

One initial task was to lay groundwork for cooperative studies between LBL and automobile and glass manufacturers, who have provided data for our modeling studies.

For our thermal analysis simulation tool, we selected the Environmental Systems Performance program (ESP), developed by the Architecture and Building Aids Computer Unit (ABACUS) at the University of Strathclyde in Glasgow, Scotland. This program has the flexibility of a user-friendly yet rigorous analytical methodology and predicts loads, cooling system response, surface temperatures and comfort conditions. We simulated hot-day soak conditions for two typical automobile sedans and compared several glazing systems (Fig. 5).

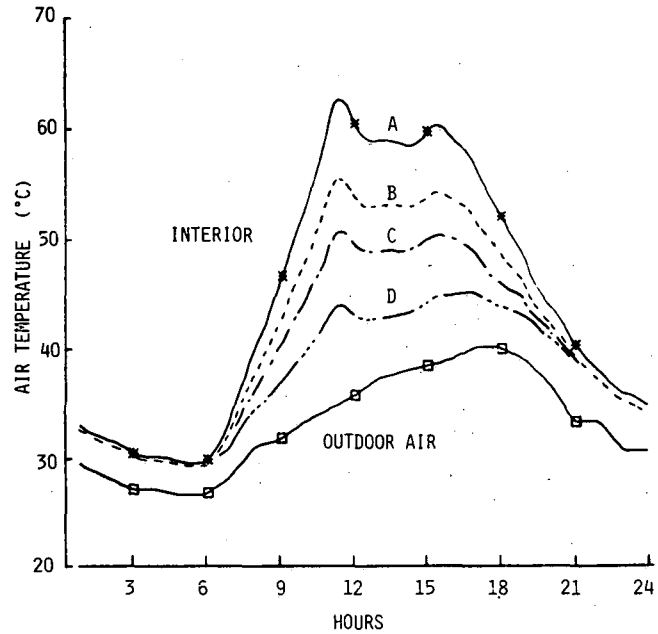

Figure 5. Interior air temperature versus time of day for a sports model automobile under static soak conditions in Phoenix, AZ on a clear day on a typical June 30th. Curves are shown for glazings with varying solar transmittances. Direct solar transmittance at normal incidence (%):

Glazings	Front	Rear	Side
A	83	83	83
B	43	43	43
C	43	23	23
D	43	3	3

(XBL 876-2800)

Planned Activities for FY 1987

We plan extensive parametric simulations using ESP to analyze variables including automobile model, window placement and sizing, and glazing optical properties and orientation. Static soak conditions and the cool-down characteristics of air conditioners will also be examined, as well as possible changes in the interior characteristics of the automobile to reduce the effects of extreme solar loads. We hope to begin a modest measurement program to verify our simulation results. We plan to document interior surface temperature effects using an infrared thermography system.

FENESTRATION PERFORMANCE

Research activities in this area are intended to characterize the performance of fenestration components and complete systems over the entire range of operating conditions in any climate or building type. The research will develop and refine experimental techniques and analytical models for accurately determining heat transfer and solar optical properties of fenestration components and systems and will validate these models in field test facilities and occupied buildings. Many of the new algorithms and data sets are designed to be incorporated into hour-by-hour building energy simulation programs such as DOE-2.1. These data will not only improve the accuracy of our predictions but will also allow us to predict the performance of new fenestration systems and novel architectural designs. Our plan for developing and implementing these new analysis capabilities in energy simulation models is shown schematically in Fig. 6.

THERMAL ANALYSIS

Most design and engineering estimates of the energy impacts of windows rely primarily on calculated values of heat transfer. In the past when comparisons were usually between single and double glazing, accuracy and consistency in calculating rela-

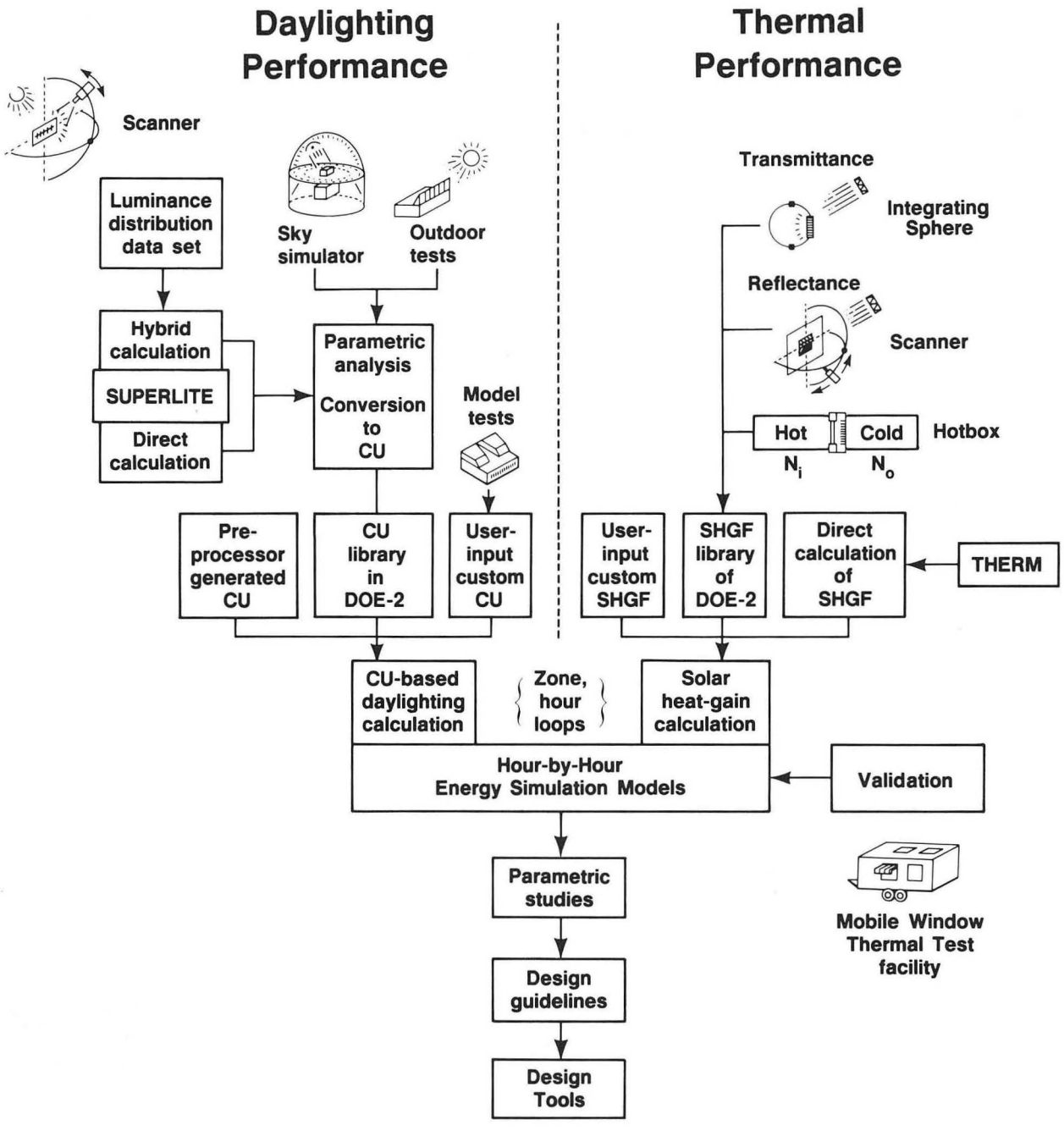

Figure 6. Schematic diagram of DOE-2.1 fenestration modeling capabilities under development. The new solar heat-gain model is shown on the right, the new illuminance model on the left. (XBL 8212-4972A)

tive heat transfer rates was not essential. Today a proliferation of new window designs makes it possible to find windows with U-values over a continuous range of 0.2 - 0.9 Btu/hr°F ft^2. Small differences in U-values (because of differences in calculation techniques) can now make a large difference in marketing and purchasing decisions.

The objective of our work is to develop a calculation method to predict the thermal and optical properties of windows from materials properties and dimensions. New window concepts can be compared to conventional windows without expensive laboratory or field testing. The method we develop can also be the basis for an industry-wide standard.

Accomplishments During FY 1986

Initial objectives were to develop a model to predict thermal properties (e.g., U-values and shading coefficient) of glazing systems incorporating varying substrate types, coatings, gas fills, etc. The calculation procedure is described in detail in an earlier paper [10] and has been used as an in-house computer program for several years. In December 1985 we released a PC version of this program, WINDOW 1.0. By July 1986, major changes had been made to the program to make it more user-friendly and a simple one-dimensional frame-effects model was added. This version and an accompanying user and reference manual were released as WINDOW 2.0 [11]. More than 100 copies have been distributed throughout the fenestration industry. WINDOW 2.0 was validated by comparing predictions to U-value data from five manufacturers and researchers [12].

Planned Activities For FY 1987

In response to industry requests, in FY 87 we will enhance the frame model, add new algorithms for solar optical properties, and provide data bases of optical properties. By providing the calculation procedure in an easy-to-use microcomputer program, we have encouraged the acceptance of this calculation method as a de-facto standard.

DAYLIGHTING STUDIES

Providing daylight to building interiors is one of fenestration's most important functions, both from an energy perspective and from an occupant's point of view. We conduct a wide range of activities to establish the facilities, tools and data to address these perspectives.

Daylighting Optics of Complex Glazing and Shading Systems

A quantitative understanding of the solar-optical properties of fenestration systems is essential for us to accurately calculate daylight illuminance levels, glare potential, solar heat gain, and thermal comfort. Our existing models are adequate for determining the properties of simple, but not complex, fenestration systems. We want to develop a methodology to analyze the luminous and solar heat gain performance of any complex fenestration system. We determine daylight performance by treating fenestration systems as light sources of varying candlepower distribution that can be calculated from bidirectional solar-optical properties. This information can be used in a daylighting model to predict interior illuminance distribution. We derive solar heat gain by processing the directional-hemispherical solar-optical properties to get the total transmitted and absorbed radiation. For these purposes, we have developed two new experimental facilities, a scanning photometer radiometer and an integrating sphere.

The scanning photometer/radiometer is used to determine the bidirectional transmittance and reflectance of fenestration components and systems, i.e., the fraction of the incoming radiation from any single direction that is transmitted or reflected toward any single outgoing direction (Fig. 7).

We use the integrating sphere to determine the directional hemispherical transmittance of fenestration components and systems, i.e the fraction of the incoming radiation from any single direction that is transmitted toward all outgoing directions (Fig. 8). These two facilities are part of a Daylighting Laboratory that includes a roof-top station for measuring daylight availability, outdoor scale-model test facilities, and a 24-ft-diameter sky simulator for making scale model building measurements under controlled conditions.

Accomplishments During FY 1986

We concentrated on developing methodology, experimental facilities, and software for the manipulation of the measured directional-hemispherical and bidirectional solar-optical properties. We have automated the movements and the data acquisition system of our scanning radiometer.

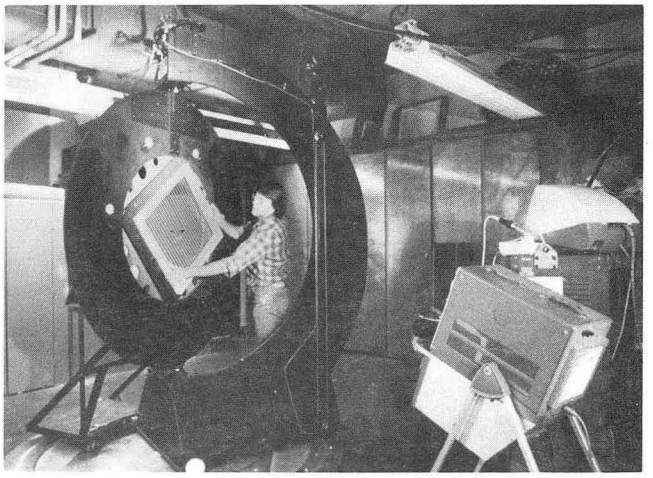

Figure 7. Venetian blind being tested in the scanning photometer/radiometer. (CBB 867-5656)

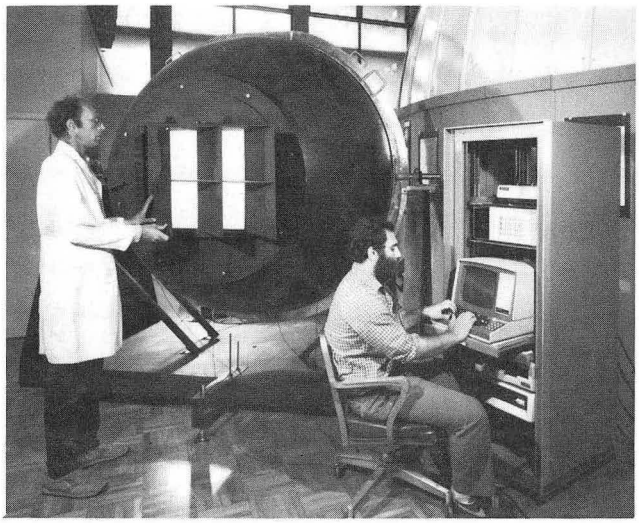

Figure 8. The integrating sphere for measuring hemispherical transmittance of glazing materials and fenestration systems. (CBB 837-6399)

We developed a new computer program, TRA (Transmittance Reflectance Absorptance), which calculates the bidirectional solar-optical properties of complex fenestration systems given the bidirectional solar-optical properties of their component layers. Additional software was partly implemented for determining the hemispherical-hemispherical and the hemispherical-directional solar-optical properties of fenestration systems for the CIE overcast and clear sky luminance distributions, given their directional-hemispherical and bidirectional solar-optical properties. These data will serve as input to the SUPERLITE and the WINDOW computer programs for determining daylight and thermal performance, respectively.

Planned Activities for FY 1987

We will continue developing and documenting the methodology, concentrating on new detectors and a more versatile computerized data collection system for the scanning radiometer and the required software for the manipulation of bidirectional solar-optical properties. Our goal is to entirely automate the procedures for data collection and manipulation to generate a data base for a large number of fenestration systems. This data base will be input to energy analysis programs such as DOE-2.

We also intend to intervalidate our experimental facilities and analytical routines, as illustrated in Fig. 6.

The Sky Simulator and Daylight Photometric Laboratory

A 24-ft-diameter hemispherical sky simulator (Fig. 9) was designed and built on the University of California's Berkeley campus in 1979. In operation since 1980, it can simulate uniform, overcast, and clear-sky luminance distributions. Sky luminance distributions are reproduced on the underside of the hemisphere; light levels are then measured in a scale-model building at the center of the simulator. From these measurements we can accurately and reproducibly predict daylighting illuminance patterns in real buildings and thereby facilitate the design of energy-efficient buildings. The facility is used for research (Fig. 10), for educational purposes, and on a limited basis by architects working on innovative daylighting designs.

Accomplishments During FY 1986

Sky simulator research was limited in FY 86 because of funding reductions. However, it continued in its role as an educational facility and was used by a number of architects and lighting designers to evaluate the effectiveness of daylighting designs.

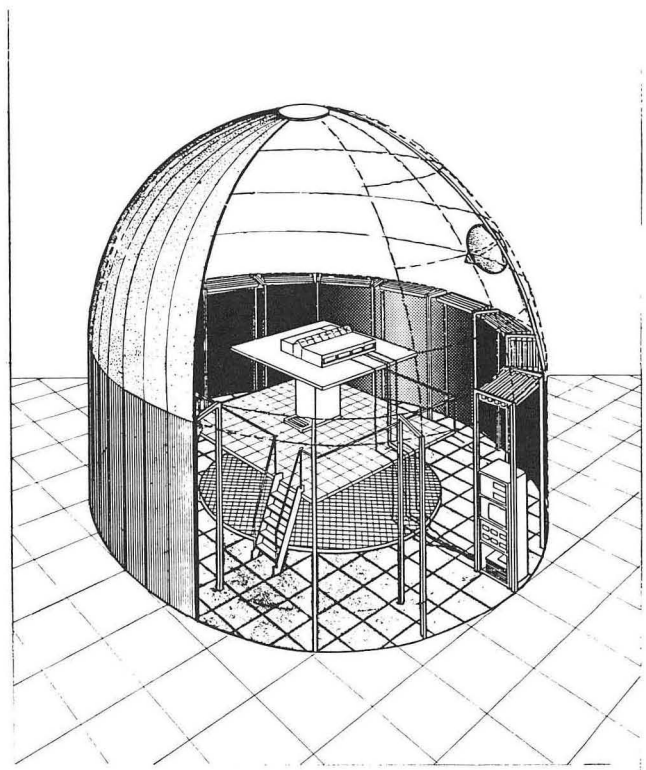

Figure 9. Schematic of 24-ft diameter sky simulator with model on platform. (XBL 8412-5328)

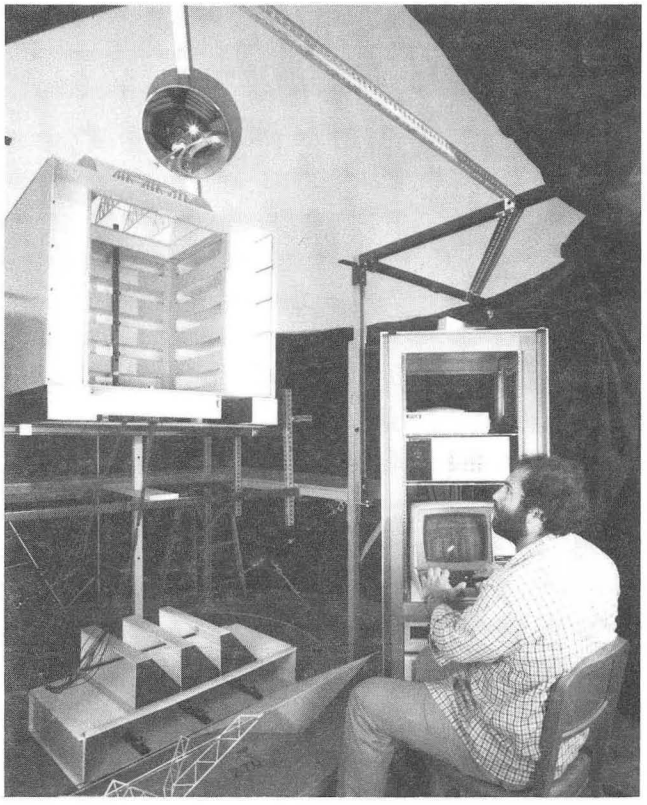

Figure 10. Interior of sky simulator showing reconfigurable scale model of a five-story atrium (with one side removed). (CBB 848-5926)

Planned Activities for FY 1987

Research, educational and professional activities will continue in the sky simulator.

Daylighting Analysis

In previous years we developed several simplified daylighting design tools (such as the QUICKLITE program), that are now widely used in the architectural and lighting design communities. Last year we expanded the range of modeling capabilities and improved computational accuracy in SUPERLITE, our advanced program. A collaborative effort to develop a new lighting/daylighting model was also initiated.

Accomplishments During FY 1986

We continued to test and evaluate SUPERLITE, concentrating on its ability to model complex shading systems. Our approach is to define the daylight transmittance properties of the window and shading system as a candlepower distribution function that varies with sky conditions and/or the incidence angle of sunlight. We initially used theoretical distributions that could be compared to results generated by other computational techniques. This comparison showed good agreement.

We continued tests of a version of SUPERLITE with an electric lighting modeling capability. This new capability will allow us to study the combined effects of daylight and electric light in a room.

We also worked jointly with the ABACUS group, University of Strathclyde, Scotland, to develop an improved lighting/daylighting model for their building simulation program, ESP. This model, still under development, calculates spectral data so that illuminance results can be accurately reproduced on a color computer monitor. It can also model specular surfaces. Linked to a graphics package, which displays 3-D room views, it should provide a significant advance in our ability to accurately represent illuminated interior spaces.

Planned Activities for FY 1987

We will continue testing and validation of SUPERLITE's modeling of shading devices, using candlepower data sets measured by the luminance scanner. Collaboration on development of the new ESP lighting model will continue.

Coefficient-of-Utilization Model for Energy Simulation Models

Building energy analysis computer models must be able to predict the daylighting performance of complex design strategies commonly used by innovative architects. The models should either internally calculate the daylight illumination or be supplied with data precalculated by other illumination models or measured in scale models. The first approach, internal calculation of daylight illumination, is generally impractical for complex designs because of the significant computational cost and complexity required to obtain reasonably accurate answers. We are therefore developing a coefficient-of-utilization (CU) model that will be compatible with an hour-by-hour simulation model but still retain the flexibility and accuracy of more complex computational models.

Accomplishments During FY 1986

Our approach is to derive the CU model from regression analysis of a parametric series of daylighting analyses using SUPERLITE. We previously modified SUPERLITE to generate these parametric series and also modified the output to report the

indoor illuminance level due to each external light source—sun, sky, or ground.

We used a statistical computer software package to generate test regression equations for the sun, sky, and ground with a limited number of generalized variables (e.g., location of window, window dimensions). Initial results suggest that good fits can be obtained with relatively simple regression expressions. However, more extensive analysis is required to extend this to a wide range of room and fenestration conditions.

Planned Activities for FY 1987

We will expand the effort to develop new CU models that can handle greater variation in room geometry and surface reflectance. After we generate all equations, they will be thoroughly tested and validated. The final model will be incorporated into future versions of DOE-2 and may also be a stand-alone illuminance model.

Daylight Availability Studies

Accurate daylight availability models are necessary for many design and energy analysis simulations. In 1978 we began an availability measurement project, as data were lacking for most U.S. locations. However, a widely accepted generalized model of availability in the U.S. has yet to be developed.

Accomplishments During FY 1986

We previously published three papers analyzing daylight availability data for San Francisco.[13–15] Analysis focused on the relationship of measured illuminance and irradiance to atmospheric parameters such as turbidity. A new functional relationship was developed to determine an illuminance turbidity for visible radiation analogous to the conventional turbidity terms used with solar radiation. We also developed new functional relationships for zenith luminance as a function of turbidity and found that our clear-sky luminance distribution data agree well with data from currently accepted European models. These results were published in the Technical Proceedings of the International Daylighting Conference.[16]

In FY 86 our focus shifted to developing a better understanding of the nature of partly cloudy skies. Using a trailer-mounted sky luminance mapper developed by the Pacific Northwest Laboratories (PNL) (Fig. 11) we measured sky luminance profiles every few minutes throughout the day on the roof of the Space Sciences Laboratory in the Berkeley hills. Analysis of the data is being completed at Florida Solar Energy Center (FSEC).

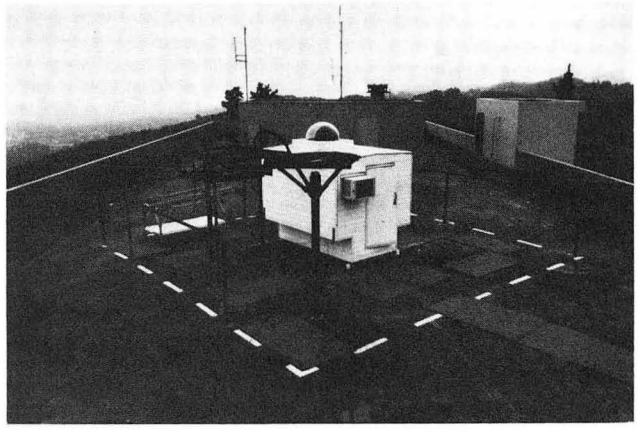

Figure 11. The sky luminance mapper on the roof of the Space Sciences Laboratory. (CBB 876-4910)

Planned Activities for FY 1987

We will continue to analyze our existing data base and complete a study of the luminous efficacy of daylight and sunlight. Data collection with the sky luminance scanner will be completed. We will collaborate with FSEC researchers on analysis of the availability data but will reduce the overall activity in this area at LBL.

MOBILE WINDOW THERMAL TEST (MoWiTT) FACILITY

We have known for some time that wintertime solar heat gain through south-facing windows in conventional buildings is a significant source of "free" energy. Calculations have indicated that it is technically possible, for any orientations in any U.S. climate, to use windows so that they help a building meet its own energy needs.

This claim is not likely to be widely accepted without firm experimental verification. However, measuring the performance of highly optimized window systems in a realistic way is a formidable task, requiring specialized non-steady-state calorimetry on a scale never previously attempted.

To perform these measurements, a unique facility, the Mobile Window Thermal Test (MoWiTT) facility, was designed, built, and calibrated. In developing this facility we had to solve the problem of doing calorimetry on a room-sized enclosure (which would normally require careful maintenance

of constant equilibrium conditions) in the presence of the solar fluxes and changing outdoor temperatures that control the behavior of a fenestration system. We solved this problem with a large-area heat flux sensor and a very sophisticated measurement of the heat extracted from the calorimeter by its cooling system. The MoWiTT, shown in Fig. 12, began operation in 1986 at a field test site in Reno, Nevada.

Accomplishments During FY 1986

One of our first tasks was a study of newly commercialized low-emissivity insulating glazings, which are now offered by nearly every major U.S. glass and window supplier. There has been, however, no convincing demonstration that the expected energy improvements occur in actual use, and the existence of products with different emissivities (hence, different U-values) had caused considerable confusion in the marketplace.

A definitive study using the MoWiTT is ending this uncertainty. A direct measurement of heat loss coefficient, or U-value, under realistic outdoor conditions (Fig. 13) showed that the improvement expected with low-E glazings indeed occurs. The measured average U-value reduction of ($30 \pm 5\%$) agrees well with theoretical calculations using the WINDOW 2.0 program. Further measurements of the net heat flow through the window (Fig. 14) demonstrated the effects of solar absorption in the low-emissivity coating. Because of this absorption, the overall effect of adding a low-emissivity coating to double glazing is not simply the difference in nighttime heat loss: daytime solar heat gain is also reduced. The net effect of the fenestration on a building's energy balance will depend on how beneficial or detrimental solar gain is, and this depends on the climate, the orientation of the fenestration, and on the building's heating or cooling demand and thermal capacity. Thus, we must know the true heat transfer through the window as a function of time in order to take full advantage of new window products.

Figure 12. The MoWiTT facility at its field test location in Reno, Nevada. The portable building at left contains the computer which controls the facility and records data, including data from the on-site weather tower. (CBB 860-10756)

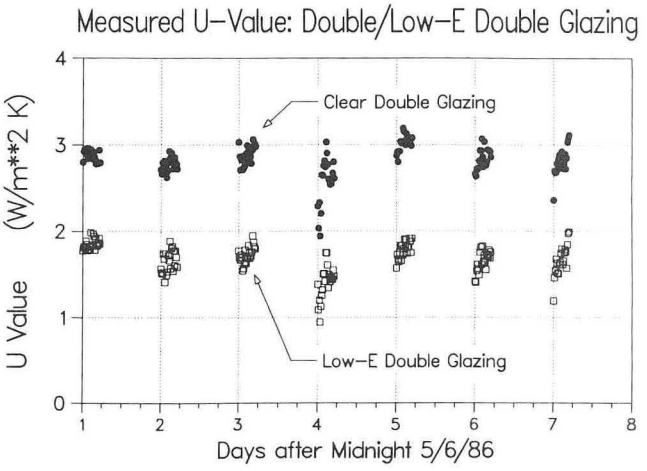

Figure 13. Measured nighttime U-values for clear and low-E double-glazed sealed-insulating-glass units. A measurement is made each 15 minutes. U-value fluctuates as a result of changing weather conditions, but, the difference between the two units remains relatively constant. (XBL 876-2797)

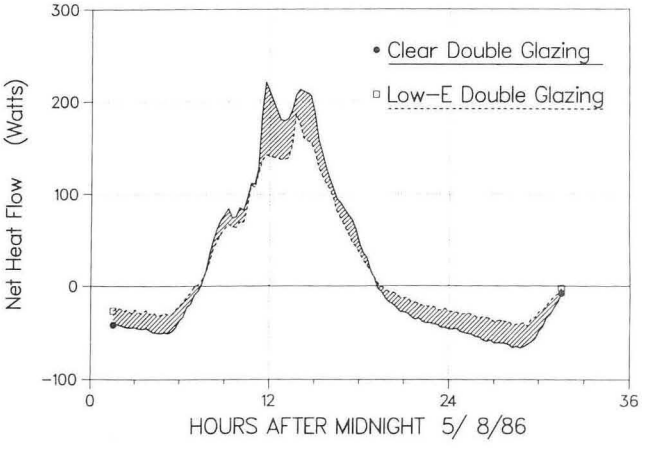

Figure 14. The measured heat flow through clear and low-E double-glazed sealed-insulating-glass units over a single diurnal cycle. The low-E unit reduces heat gain during the day and heat loss at night. (XBL 876-2795)

Planned Activities for FY 1987

During 1987 we will measure low-emissivity/low-shading-coefficient glazings, and "high-R" windows that combine low-E coatings with special gas fillings to produce the thermal equivalent of four or more glass layers (R-6 to R-10).

A systematic field study of the thermal performance of conventional glazing systems is also under way. Because window characteristics such as U-value are to some extent dependent on ambient conditions, there is controversy about how laboratory tests of window properties should be used to predict the heating or cooling energy use attributable to the windows. Beginning with simple frameless windows and working toward increasingly complex systems, our study will test current methods (e.g., DOE-2) of calculating window performance in detail, and will delineate the extent to which simplified models can be used.

We have made summer tests of single, double, reflective and absorbing glazings. During 1987 we will perform winter tests and study windows with frames (a cooperative project with support from the Bonneville Power Administration). The effect of frames and spacers in possibly degrading thermal performance, especially for low-E glazings, is currently the subject of disagreement within the fenestration industry. Exploratory studies of air infiltration fenestration performance will also be done. For reasonably well-constructed single- or double-glazed windows, fenestration-associated air infiltration is 10-20% of the nighttime heat loss. As glazings become more thermally insulating, the significance of air infiltration increases rapidly, making concommittant improvements in frame and sash design essential. MoWiTT measurements may help to focus attention on this need.

These and future measurements with the MoWiTT have the potential for removing uncertainties about window performance that have slowed progress in energy conservation during the past decade.

MONITORED BUILDINGS

Buildings are rarely built as designed and even less frequently operated as planned. In addition, occupants can significantly alter energy consumption patterns. Thus, for energy performance to be accurately quantified, it is essential to monitor fenestration performance in occupied buildings. In 1984, with support from Pacific Gas and Electric Company, we began a project to monitor an award-winning 500,000-ft^2 office building that incorporates a number of innovative daylighting and fenestration systems. The objective was not only to better understand how the fenestration systems perform but also to develop a building monitoring approach that collects better data, useful for quantifying fenestration performance, at lower cost than has been possible before.

Accomplishments During FY 1986

The data collection and analysis begun in FY 85 was successfully completed in FY 86. This included short-term, multi-point monitoring of selected areas and lighting circuits, well as more limited longer-term measurements of light levels and electrical requirements. The data indicate that the architectural design is admitting adequate daylight to achieve the desired ambient light levels but the lighting control system is not responding properly to the available daylight. Measured savings are in the range of 20-30%; daylighting should produce lighting energy savings of 50-70% in a properly "tuned" space.

Planned Activities for FY 1987

We hope to have the opportunity to retrofit a section of the building to correct some of the problems uncovered in Phase I. We are confident that relatively simple fixes will increase the energy savings to the levels originally predicted.

BUILDING APPLICATIONS AND DESIGN TOOLS

Research to develop new glazing materials and to better understand fenestration performance will provide real energy savings only if the technology is effectively applied in buildings. Using the technology requires that we have detailed understanding of how a wide range of fenestration systems can be optimally used in different building types and climates, and that we pass this understanding, through design tools, to building design professionals.

SIMULATION STUDIES: NONRESIDENTIAL BUILDINGS

While most building energy simulation studies have focused on minimizing total energy consumption, other issues are equally important. Peak electrical demand affects both user costs and the utilities' required generating capacity. A complete study of the cost effectiveness of fenestration systems, partic-

ularly those incorporating daylighting strategies, must include their impact on peak electrical demand as well as on energy savings. In addition, issues such as comfort and convenience affect the user acceptance and, consequently, effectiveness of these systems. Our studies explore the interactions of these issues.

Accomplishments During FY 1986

During the past several years the effects of a wide range of glazing properties, window sizes, lighting loads, orientations, and climates on the energy performance of a prototypical office building have been simulated with DOE-2.1B. Initially we examined the impact of fenestration properties, including the effects of daylighting strategies, on office building energy performance and peak electrical demand. Lighting energy savings resulting from daylighting were examined for a range of fenestration properties and lighting control systems. Annual energy consumption of an office module was found to be sensitive to variations in U-value, shading coefficient, and visible transmittance, as well as glazing area, orientation, climate, and operating strategy. Sample results from our simulation studies are shown in Fig. 15.

We conclude that, in almost all instances, it is possible to find a fenestration design strategy that outperforms a solid insulating wall or roof and that daylighting is almost always an essential component of energy savings. If the installed electric lighting power density is high, the energy savings potential is large. More efficient electric lighting systems reduce daylighting benefits.

The net benefits of fenestration are highly dependent on the tradeoffs between daylighting savings and cooling loads resulting from solar gains. Visible transmittance properties, improved shading design, and window management will thus assume increasing importance for maximizing energy benefits from daylight. Our studies have demonstrated that the common assumption that daylighting is a "cooler" source of light than electric lighting is not necessarily true. We have developed and are refining a methodology for comparing cooling loads imposed by daylight (or electric light) through the use of an index derived as a fraction of three parameters:

(1) The relative T_{vis} and SC of the glazing/shading system;
(2) The distribution of daylight within the space;
(3) The time-dependent absolute transmitted solar intensity.

We continued our general studies on the peak-shaving potential of daylighting with results that

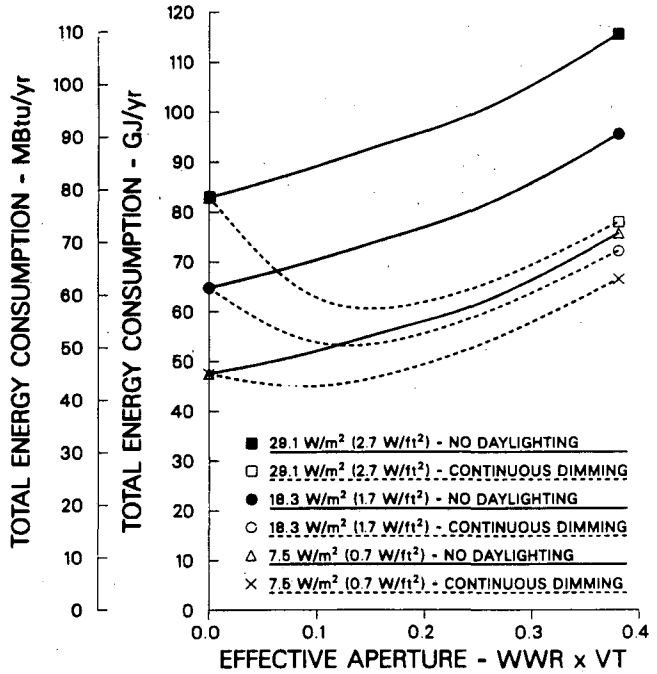

Figure 15. Annual energy consumption in the south zone of an office building in Madison, Wisconsin, as a function of window area. "Continuous dimming" indicates controlled reductions in electric lighting in response to daylight; "no daylighting" indicates no dimming. (XBL 876-2796)

show—despite solar gains—daylighting can significantly reduce peak electrical demand during summer months. The critical tradeoffs—between electric lighting reductions from daylighting and cooling load increases from solar gain—help determine the combination of window properties that minimize building peak loads. A breakdown of this load for a sample office building at the hour of peak demand is shown in Fig. 16 for both daylighted and nondaylighted cases. In Fig. 17, annual peak electrical demand is shown for our prototypical building in Lake Charles, LA. The benefits of daylight use are clearly illustrated.

Simulations of advanced glazing materials having active response functions, represented in the lower curve in Fig. 17, show large potential savings.

Skylights can also provide significant energy and cost benefits. Daylighting benefits are maximized with relatively small ratios of skylight to roof areas (0.01–0.04). Because skylights provide more uniform daylight distribution, the cooling load impact of daylighting is less than with vertical fenestration. As effective aperture is increased beyond the optimum, cooling loads in most climates rise to adversely affect net annual energy performance.

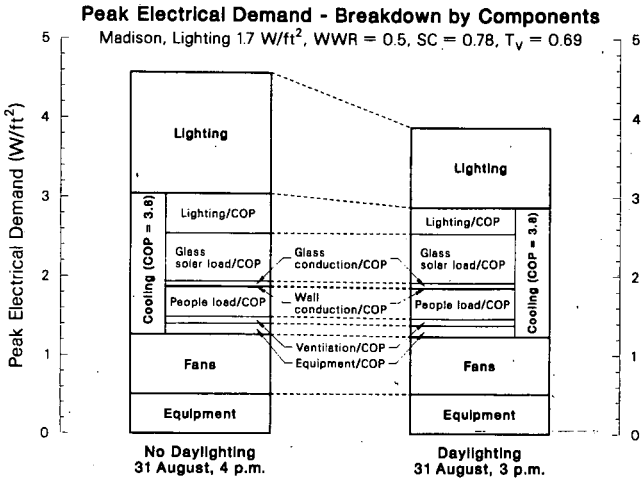

Figure 16. A comparison of peak electric demand, by component, for an office building in Madison, WI, with and without daylight utilization. (XCG 855-223)

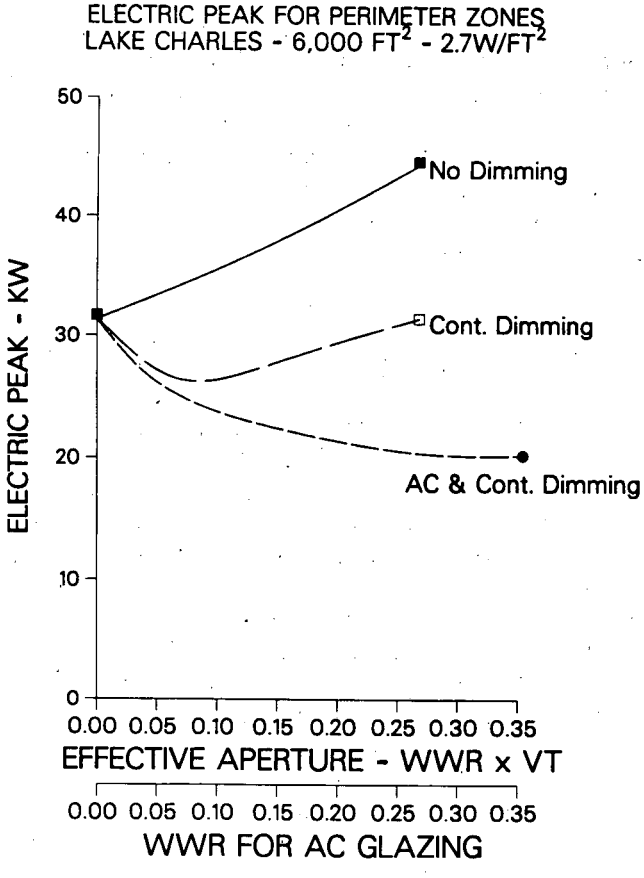

Figure 17. These results from DOE-2.1B energy simulations of a 6000ft^2 office building in Lake Charles, LA, show the effect of daylighting on peak electrical demand as a function of effective aperture. Electric lighting density is 2.7 W/ft^2. (XBL 876-2802)

A large number of DOE-2.1B runs for window and skylight studies have provided enough data for multiple regression techniques to develop analytical expressions of energy requirements as functions of glazing parameters; from these we may be able to develop a generalized expression to accommodate climate variables. The simple expressions correlate well with DOE-2 results and may become a design tool to assess energy and cost trade-offs among fenestration options. We have incorporated the regression equations developed in our skylight studies in a skylight design handbook sponsored by AIA, AAMA, and NFC, and this procedure is the basis for the LRI Fenestration performance Indices described in the next section.

Planned Activities for FY 1987

Simulation studies to date have examined the energy impacts of many fenestration parameters for conventional designs and have begun to explore the potentials of new optical materials. New studies will examine the performance of shading devices for which adequate solar optical data do not exist. Optical properties of shading devices will be measured in our laboratory. We will also continue to look at variations in window-shade energy performance and management strategies, issues of daylight luminous efficacy, advanced glazing materials, the effects of fenestration performance on HVAC, and the effects of various HVAC options on fenestration performance. The costs of fenestration design and daylighting as influenced by peak electrical demand, annual energy use, and chiller size will be examined.

LRI FENESTRATION PERFORMANCE INDICES

Building designers, utility auditors, and others are constantly required to compare and evaluate the performance of alternative fenestration systems in buildings. To properly address the energy-related impacts of fenestration, one must be able to quantify energy performances for all systems in a systematic and reproducible way. The objective of this study for the Lighting Research Institute Center (LRI) is to develop numerical indicators of fenestration system performance on the basis of annual energy consumption, peak electrical demand, illumination performance, and thermal and visual comfort. These indicators are to be used as guides in evaluating and selecting alternative fenestration products and systems for use in various building types and climates. In Phase 1 we are developing the basic methodology for determining the performance indicators; Phase 2 will support the measurement and analysis required

to construct a microcomputer design tool that embodies the project's results.

Accomplishments During FY 1986

Using thermal and visual comfort indices in an energy design tool is a major objective of this project. A methodology was developed that defines the relationship between fenestration characteristics, direct solar radiation, and thermal and visual comfort so that annual comfort indices can be calculated. The thermal comfort index is related to mean radiant temperature within the space. Visual comfort is based on a glare index calculated by DOE 2.

Numerous DOE-2 runs have been completed for a prototype office building in Madison, WI, and Lake Charles, LA. Simplified design charts were developed from the multiple regression coefficients obtained from these runs. Figure 18 shows the variation of an annual fuel index as a function of solar heat gain coefficient and window U-value. Four glazing types are shown as well as the variation in number of panes of glass. Similar figures have also been generated for indices of annual electric energy and peak electric load.

Most complex fenestration products and systems cannot be readily characterized using conventional analysis techniques, so we are determining the solar-optical properties and daylight transmittance/distribution functions of these systems experimentally, using the integrating sphere and the luminance/radiance scanner described previously.

Planned Activities for FY 1987

To complete Phase 1, we will develop a methodology for incorporating the proposed performance

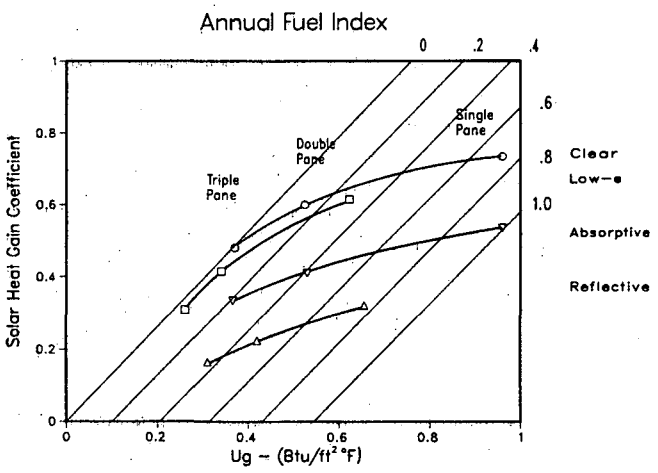

Figure 18. Annual fuel index as a function of glazing parameters. (XBL 876-2804)

indices into an overall fenestration system figure-of-merit. A weighting function will be provided so that users can assign specific relative weights to the indices they deem important. If, for example, a designer wishes to maintain comfort without mechanical cooling, minimizing the cooling requirement might be a priority task. Thus, the cooling and thermal comfort index might be heavily weighted and an appropriate fenestration option selected accordingly.

A workshop for industry representatives will be conducted to present the methodology and performance indices developed in Phase 1. Evaluation results from the workshop will help us plan the development of the microcomputer design tool that is the key product of Phase 2, which we hope to initiate by the end of the year.

SIMULATION STUDIES: RESIDENTIAL BUILDINGS

Our studies have focused on techniques to simplify accurately the very complicated heat transfer processes that occur between the components of a building. We have previously shown the feasibility of isolating window systems from other building components such as envelope insulation levels, infiltration, and internal heat gains in determining building energy performance.

Accomplishments During FY 1986

The regression expressions developed in past years to predict residential energy use as a function of fenestration parameters were expanded to include effects from the use of night insulation, shade management, and overhangs. For a given climate, orientation, and window size, we developed graphic plots that allow one to quickly evaluate seasonal performance differences in alternative existing or hypothetical fenestration systems.

In addition, we developed a procedure to directly compare the thermal loads resulting from different building prototype configurations independent of geographic location, to ultimately help us develop a design tool with broad climatic applicability.

We used these techniques to describe the performance of low-E windows in residences in hot and cold climates. This study analyzed the energy and cost implications of conventional double- and triple-pane windows and newer designs in which substrate, type, and location of low-E coating, and gas fill, were varied. The analysis showed the potential for substantial savings but suggested that both heating and

cooling energy should be examined when we evaluate the performance of different fenestration systems. The study also showed the importance of considering window frame effects for the low-conductance glazing units.

Most analysis procedures describe the performance of specific alternatives and one must analyze many cases to arrive at a solution that appears to optimize energy use. We developed a mathematical technique to directly calculate the window size or properties that minimize energy use or cost for a given climate and orientation. It will become part of the design tools developed next year.

Planned Activities for FY 1987

Our ultimate objective is to develop handbooks, charts, nomographs, and computer software that will help builders, developers, and suppliers assess different window strategies. The immediate objective in FY 1987 will be to create a prototype residential fenestration design tool that will be used to stimulate building industry interest in collaborative development of a comprehensive tool.

DESIGN TOOLS AND TECHNOLOGY TRANSFER

To influence energy consumption trends in the United States, it is critical to package and transfer our results to other researchers and professionals. The needs and motivations of this group, including designers, engineers, building owners, manufacturers, and utilities, vary widely, so we use a variety of media to reach each audience. Our activities have included developing improved daylight analysis and design tools, design assistance studies, occupant response studies, workshops, conferences, assessment reports, handbooks, and meetings with industrial and design firms and utilities. Other efforts have been designed to communicate results of our work widely to other research and development groups, educational institutions in the U.S. and abroad, and professional and industrial societies.

Technology Transfer

We continue to communicate research results to design professionals and industry through conferences, workshops and seminars. In addition, we can disseminate our research results through the newly formed Daylighting Network of North America.

Daylighting Conferences. We planned and cosponsored the 1983 and 1986 International Daylighting Conferences. Underwritten by Southern California Edison, the U.S. Department of Energy, and other organizations, the 1986 conference took place November 3-7 in Long Beach, California. These two conferences generated more than 200 papers and attracted more than 800 building industry professionals.

The 1986 conference's *Proceedings I*, prepublished by ASHRAE, includes all presented papers and extended abstracts of technical papers. *Proceedings II*, to be published in 1987 by ASHRAE, will include a complete set of refereed papers.

Serving on the organizing committee for the 1984 and 1986 Pan Pacific Lighting Conferences, we contributed to seminar curricula and exhibition design, and conducted workshops on daylighting design applications. This activity helped establish closer links with manufacturers, educational institutions, and professional and industrial societies with which we normally do not interact.

Daylighting Network of North America. Several years ago we initiated and helped develop The Daylighting Network of North America (DNNA), a loose confederation of universities with an interest in daylighting. With more than 30 universities designated as regional and instructional center members of the Network currently, the DNNA expands the avenues for transferring daylighting research results to professionals, educators, and students.

The Centers make a concerted effort to plan and implement professional, educational, and design assistance programs. SUPERLITE and DOE 2.1B and C were transferred to one of the universities for dissemination to key faculty in each of the Network schools. We assisted the Network in developing three specific funded tasks over the past year: an electronic bulletin board network, a physical modeling handbook, and a newsletter.

The Network will continue to develop the electronic link between member schools and our research group, and will publish the modeling handbook for both academic and professional distribution. In addition, design software distribution and promotion of joint research projects will continue to be a priority.

Design Tools

The Windows and Daylighting Program and subcontractors develop and distribute daylighting design tools to industry and educational institutions. Private-sector software firms continue to introduce new design tools for daylighting but it is difficult for a potential user to evaluate and compare them. There is thus a need: (1) for a comparative matrix

identifying existing tools, and (2) for photometric data and evaluation procedures to compare these tools.

Accomplishments During FY 1986

Development of a general procedure for comparing design tool predictions to a photometric data base derived from sky simulator measurements and SUPERLITE simulations continued. The Daylighting Design Tool Survey was published, describing the capabilities of more than 30 tools including nomographs, protractors/tables, and micro, mini, and mainframe computer tools. The design tools tested and disseminated in FY 1986 are described below.

Clear Sky Protractors. Developed with Harvey Bryan at the Massachusetts Institute of Technology (MIT), the protractors consist of a series of transparent overlays that are placed over architectural plans and elevations to determine a window's daylight contribution at any point in a room.

SUPERLITE 1.0. We began to get professional market evaluation using the Daylighting Network, supplemented by building industry professionals in North America and abroad.

Daylighting Nomographs. The completed manual and set of nomographs to estimate potential energy and peak-load savings in commercial buildings continued to be a popular professional energy seminar package. More than 400 copies were distributed.

Skylight Design Handbook. Using established research and professional links with the American Architectural Manufacturers Association (AAMA), and their Skylight and Space Enclosure Division, we developed a Skylight Design Handbook/Energy Design Guidelines. In a cooperative project with a professional architectural firm, we converted energy design data into a an easy-to-use worksheet the design professional can use to answer basic questions about the skylight design best suited for a building. AAMA will publish and distribute the Handbook to association members and the building industry at large.

Advanced Envelope Design Tool. Our attention has turned during the past several years to the development of the next generation of sophisticated hardware and software tools. We envision a tool that relies heavily on imaging technologies, expert-systems software, and design process studies.

We have developed an Advanced Envelope Design Tool concept. A schematic illustrating the key factors of this tool concept is shown in Fig. 19. A computer data base of relevant hardware and software developments was established to assist in identifying and tracking market trends. Several major slide presentations were made to organizations in the building professions (AIA, ACEC, ASHRAE), and a concept paper published.[17] Planning was initiated to integrate this project with the U.S. Department of Energy's Intelligent Building Design project, to begin in FY 1988.

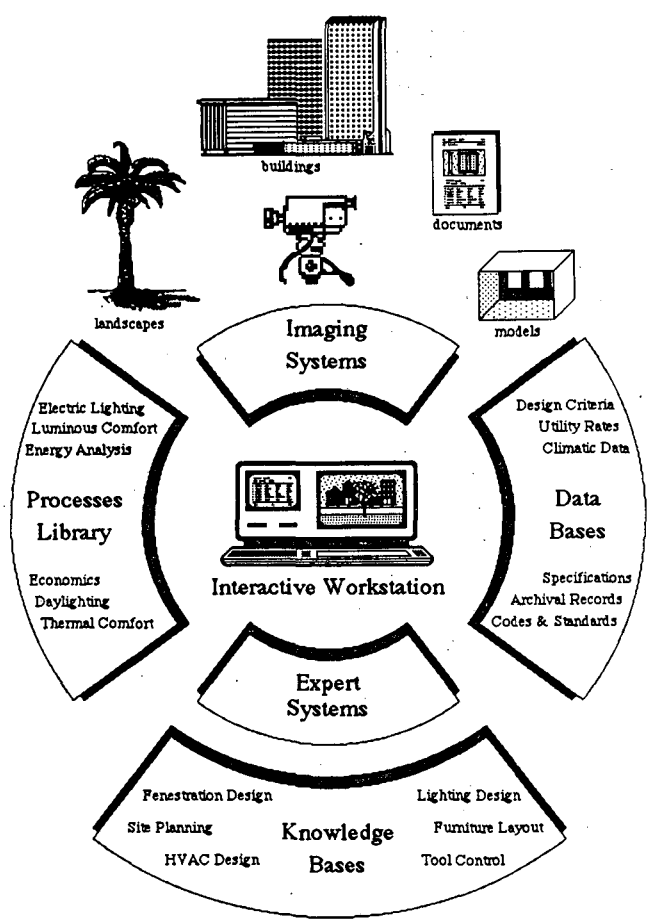

Figure 19. Schematic illustrating the key features of the Advanced Envelope Design Tool concept. (XBL 876-2799)

Planned Activities for FY 1987

In the short term, we believe that we can (1) influence the development of such an advanced design tool by networking with contributors to the tool, and (2) develop a prototype interactive video microcomputer program to better illustrate the potential of such a concept. Complete development of the Advanced Envelope Design Tool would require greater support than is probably obtainable in the short term. We hope to link our efforts in FY 87 and beyond with DOE work on Intelligent Building Design.

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Lighting Systems Research*

S.M. Berman, R.R. Verderber, R.D. Clear, C. Greene, D.D. Hollister, F. Li, D.J. Levy, O.C. Morse, F.M. Rubinstein, M.J. Siminovitch, and G.J. Ward

We estimate that 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's National Lighting Program is to help the lighting community (manufacturers, designers, and users) achieve a more efficient lighting economy. The program, carried out at Lawrence Berkeley Laboratory (LBL), represents 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.

To implement its objectives, the Lighting Program has divided its work into three major categories: advanced light sources, building applications, and impacts on human health and productivity.

The advanced light sources component 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 which it does not pursue on its own, and from which significant benefits could accrue to both the public and industry if the technical barriers were surmounted.

The building applications component undertakes research on the electromagnetic compatibility of high-frequency lighting with building functions, including machinery, computers, and other electrical and electronic systems, as well as the interaction of lighting with building energy systems.

The impacts component examines relationships between workers and the physical lighting environment to ensure that energy-efficient technologies contribute to human productivity and health. These efforts are interdisciplinary, involving engineering, optometry, and medicine.

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Since its inception in 1976, the LBL Lighting Program has produced more than 118 reports and publications. These reports are available to the public, and document research on subjects such as solid-state ballasts, operation of gas-discharge lamps at high frequency, daylight availability, energy-efficient fixtures, lighting control systems, and visibility and human productivity. The program's internationally recognized interdisciplinary staff spans the fields of engineering, physics, architecture, optometry, and medicine and is involved in a variety of professional, technical, and governmental activities.

The Lighting Program combines the facilities and staff of LBL with those of the University of California College of Environmental Design and School of Optometry, both on the Berkeley campus, and the School of Medicine in San Francisco (UCSF). Because results are directed at enhancing the capabilities and long-term viability of the lighting industry and providing the design profession and the general public with needed information, the program is unique in the United States.

Described below are highlights of the accomplishments realized in FY 1986 by each of our three major efforts—engineering science, building applications, and health impacts—and activities planned for FY 1987. Publications and conference presentations of the past year may be found in the publications list at the end of this chapter.

ADVANCED LIGHT SOURCES

The Advanced Light Sources effort focuses on advanced lamp technology and light source development. To see what can be accomplished in this area, consider that 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, still greater efficacies are possible. White light can, theoretically, be produced at almost 400 lumens per watt. The advanced lamp technology program is working to supply the engineering science that will provide the basis for a target efficacy of 200 lumens per watt within the next few years. Table 1 lists the series of technical improvements that are the technical elements proposed to reach that goal.

Two significant loss mechanisms have been isolated among the technical targets for achieving more efficient fluorescent lamps: self-absorption of ultraviolet (UV) radiation, and energy loss in lamp phosphors. In the first case, we would like to reduce self-absorption UV radiation, a process that occurs

Table 1. Targets for improving lighting technologies.

Technology	Comment	Total efficacy (lm/W)	Year entering market
Fluorescent lamps			
High-frequency operation		90	1980
Narrow-band phosphors		100	1983
Isotopically enriched	LBL/DOE	110	1988
Magnetically loaded	technical	120	1990
Two-photon phosphor	initiatives	180	1995
Gigahertz/electrodeless		230	1995
HID Lamps			
Today with (high-freq. ballast)			
400-W high-pressure sodium		(CRI-25) 100	1984
400-W metal halide		(CRI-66) 80	1984
400-W mercury vapor		50	1984
Electrodeless/high/freq.			
1000-W lamps	10-15% improvement		1989
Low-W lamps	30% improvement		1989
New gases	20-25% improvement		1990
Color-constant/dimmable	20-25% improvement		1993

within the lamp plasma before the radiation strikes the phosphor-covered inner wall (the phosphor converts UV radiation into visible light). In the second case, we would like to develop a more efficient phosphor matrix that will convert one energetic UV proton into two visible photons. Reductions in self-absorption could provide a significant improvement, and a two-photon phosphor could double lamp efficacy.

LBL is studying several ways of reducing UV self-absorption. The first method is altering the isotopic composition of mercury. This element has seven stable isotopes, each with slightly different resonance UV emission spectra. Altering the naturally occurring isotopic composition can provide more escape channels for the resonance radiation, thereby reducing the probability of quenching collisions and increasing the amount of UV radiation reaching the phosphor. One possibility for isotope alteration-enrichment with ^{196}Hg is being pursued in a joint effort by LBL and GTE Lighting. Should isotopic alterations prove economical, modified lamps would enter the market quickly, as lamps would simply be loaded with isotopically enriched rather than natural mercury, with other lamp manufacturing processes remaining the same.

Another method of reducing UV self-absorption was recently discovered at LBL. It 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 about 6%. LBL and major firms in the lamp industry are studying practical ways to apply this technique.

Reducing the effects of energy loss in the phosphors requires altering a lamp's phosphor material. The materials used today convert each UV photon into, at most, one visible photon. Improving this conversion rate would increase the efficacy of low-pressure discharge lamps. Although a UV photon has sufficient energy to permit the cascade conversion of the UV photon into two visible photons, this process must occur quickly, and the intermediate level in the cascade must be tuned carefully to ensure that both emitted photons are in the visible spectrum. LBL is examining the possibilities of a program in phosphor chemistry designed to discover whether the two-photon phosphor is feasible. The lamp industry, long aware of the complexity of this

problem along with the extensive research effort required to provide solutions, is extremely interested in our results.

A highly promising mechanism developed at LBL uses a plasma coupling principle that allows for lamp plasma excitation to occur primarily near the inner lamp wall thereby reducing the UV transport distance and the likelihood of entrapment loss. This surface wave mode of operation occurs at high frequencies in the radio frequency (RF) range between 100 and 1,000 MHz and permits the lamp excitation without electrodes. This surface wave lamp shows approximately 40% increased energy efficacy over normal fluorescents, operates without starting circuits, and should be very long lasting because of the absence of electrodes.

If these research projects at LBL come to full technological and commercial fruition, 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, nearly three times that of today's 60-cycle fluorescent.

Other lighting technology research concentrates on high-intensity discharge (HID) lamps, which could 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; it may also permit lamps to function with just one or two metal halides and no mercury or sodium. Electrodeless operation would also enable the use of compounds that have desirable light output and color but that are excluded today because they would harm electrodes. Finally, an electrodeless lamp that could be dimmed without observable spectral changes and that could provide instant restrike would appeal to lighting designers. Table 1 summarizes these goals.

To address the lack of data on the plasma discharges, a program on plasma diagnostics has been initiated to measure electron and ion distributions in both optically thin and thick plasmas.

Accomplishments During FY 1986

Mercury Isotope Studies

The photochemical separation process has been identified as the most promising candidate for an economic mercury separation process. Several key steps are crucial to obtaining more information about scavenger processes and scaling up the size of the separation reactor. With this information, better estimates can be made of the engineering and economics of a system viable for the large amounts of mercury isotope needed for lamp application. The problems designated to be studied in FY 1987 are (i) scaling up the mini-reactor to a production rate of a few grams per day, (ii) diagnostic studies relating to the emission on absorption line shapes for the 3P1 state (iii) chemical diagnostics to evaluate any reactor processes that lead to undesirable products.

The procedure developed for obtaining a weighed amount of ^{201}Hg isotope in a lamp has been perfected and the ^{201}Hg was amalgamated on a gold foil and weighed before and after the Hg was removed by heating. A novel spectroscope procedure has been developed to independently determine the precise amount of added isotope ^{201}Hg. This method does not utilize the diffusion concept which is now in use but will be used to check that methodology. Spectroscopic examination of the hyperfine structure of the green line at 5461A and the blue line at 4046A shows that certain peaks are optically thin and their height proportional to the fractional composition of the ^{201}Hg present in the discharge. A more detailed report and a journal article are in progress.

Magnetic Enhancement

We have developed a number of new test lamps to study the effects of magnetic fields on lamps of different length and diameter. Preliminary results indicate both length and especially diameter cause significant changes in the behavior of magnetic enhancement. General Electric Co. lamp division has agreed to provide us a number of test lamps as a professional courtesy. Some delay is expected in their availability because of scheduling at the GE plant. We expect delivery some time in mid FY 1987.

Surface Wave Lamp

Further improvements have been made in a surface wave launcher with good impedance matching. This new system permits instant starting of the lamp and assures perfect impedance matching once the lamp is ignited, which means that all the RF power is delivered to the plasma with no reflected component--a requirement for improved efficiency. This surface wave launcher caused a 40% gain in efficacy in a standard F15, T-8 fluorescent lamp (15 watt, 1 in. in diameter, 18 in. long), compared to operation at normal power input of 60 Hz. In addition, we have designed and built a new thermal con-

trol that provides air movement with extremely tight thermal conditions.

Variable Positive Column Diagnostic

A fundamental problem in surface wave lamp improvements is quantifying the separate contributions of electrode elimination and positive column efficacy. To determine these contributions we have designed and built an electroded lamp that can vary distance between its anode and cathode. The positive column axial dimensions are determined by the use of a precise moving fiber-optic system. As the length between anode and cathode increases, the positive column size increases, and its light output is measured. The end-fall voltages will remain constant during the procedure and thus, by measurements at constant current of total voltage and light output, an extrapolation can be made to determine the end-fall contribution. A more detailed discussion of this topic is being prepared in a technical report and a journal article. Figure 1 shows the variable cathode lamp.

Planned Activities for FY 1987

Mercury Absorption Studies

A lamp has been constructed and enriched with ^{201}Hg from its naturally occurring concentration of 15% to amounts ranging from 30% to 60%. Measurements on the lamp will be made to confirm the Richardson-Berman theory, which predicts that a maximum increase in lamp efficacy will occur in this isotope-concentration range. The results will have significant bearing on the final method used to separate the Hg.

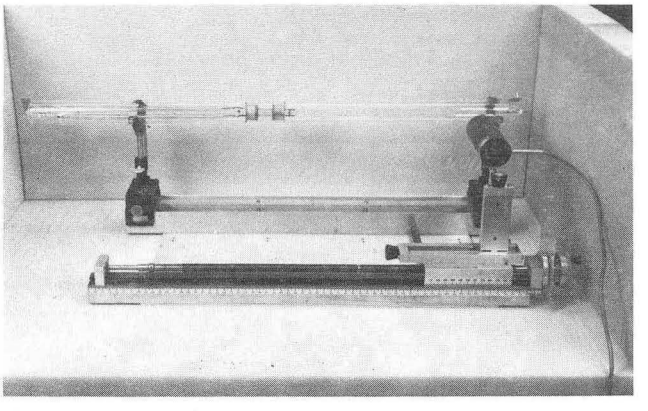

Figure 1. Picture of variable cathode lamp. The moveable system is on the left side of the lamp. (CBB 867-5749)

We are planning to complete detailed measurements of the ^{201}Hg-enriched low-pressure gas-discharge lamp. Measuring the amounts of Hg and isotope additions by both the diffusion method and spectroscopic examination methods will assure the high degree of accuracy critical to selecting the Hg isotope for separation.

The second phase of the photochemical mercury isotope separation program to be carried out by GTE Lighting will begin with the building of the scaled up reactor.

Magnetic Enhancement

LBL will systematically measure the newly designed lamps housed in the UV integrating cylinder to characterize the phenomenon of magnetic enhancement. The effect will be studied as a function of field intensity, lamp-wall temperature, gas fill, and input power, as well as length and diameter. The angular distribution of the ultraviolet radiation will be examined to determine the extent of polarization. Finally, the change in hyperfine structure will be studied with the high-resolution Jarell-Ash spectrometer that has been installed.

Surface Wave Lamp

The movable length lamp experiment will be carried out at both 60 Hertz and high frequency (30 to 50 Kilohertz). Measurements of the light output will be made by a fiber optics system. Figure 2 shows the experimental setup.

Figure 2. The surface wave lamp is shown with the launcher at the right end. The lamp is surrounded by a wire cage to prevent accidental escape of any RF radiation. (CBB 862-1276)

We will continue investigating methods of screening lamps to contain electromagnetic radiation. Initial measurements indicate that the levels at a distance of one foot from the lamps are negligible.

Electrodeless HID Lamp

The initial goal of this project was to develop a low-wattage, efficient HID lamp to replace the incandescent lamp. The effort to date has examined high-wattage, 400-watt lamps. A model of an electrodeless mercury-discharge HID lamp is under development to determine the minimum wattage lamp feasible.

Diagnostics

The Lighting Program has developed a new technique to view and study slices of plasma that are both optically thin and thick. The data can be analytically unfolded to determine the spatial distribution of mercury in the excited state through the plasma. A technical paper on this subject is scheduled to appear in the Journal of Quantitative Spectroscopy this year. A special precision-stepping motor mounted on an optical bench is required for scanning the plasma, and will be designed and constructed for conducting the measurements.

BUILDING APPLICATIONS

This component of the Lighting Program considers technical design mechanisms for assuring the incorporation of energy-efficient lighting in buildings. Specific applications must take into account building types as well as user activities. Building applications also considers the manner in which the lighting system affects other building apparatus, e.g., the HVAC system and indoor air quality. The activities of highest priority include dynamic lighting design (based on the use of automatic lighting controls), the thermal characterization of luminaires, and the use of Peltier devices to prevent lamp thermal losses.

Accomplishments During FY 1986

Advanced Lighting Design

A technique has been developed to correctly position photocells to sense the ambient illumination level when using daylighting for interior illumination. Photocells should be directed toward the task and measure the illuminance from the task and a suitably large area around the task. The photocell should be shielded so that it does not "see" any portion of the window that is admitting daylight. In addition, the electric lights should be calibrated when there is no daylight (to determine their maximum light output), and during the day (to adjust their proportional response to the amount of illumination the photocell is sensing). Experiments have shown that daylight and electric light can provide specified illumination throughout the entire day.

Fixtures

We have employed a Peltier device to control the minimum lamp wall temperature (MLWT) of a fluorescent lamp at its optimum 40°C temperature. At this temperature a fluorescent lamp's light output and efficacy is maximum. Figure 3 below shows the light output of a fluorescent lamp in ambient temperatures ranging from 25°C to 50°C. The lamp, MLWT controlled by the Peltier device, maintains its light output over the entire range, while the light output of an uncontrolled lamp decreases by 25% at a 53°C ambient temperature.

Computer Imaging

A computer imaging technique is being developed for obtaining images of both office and roadway scenes by tracing the path of rays from the source of illumination. The method is an advance over past imaging methods used since actual luminances resulting from both specular and diffuse surfaces can be obtained. This technique permits one to obtain computer images of spaces that appear as realistic as actual photography.

The method has been applied to interior spaces illuminated with daylight as well as electric lights. Recently we have shown the method can provide

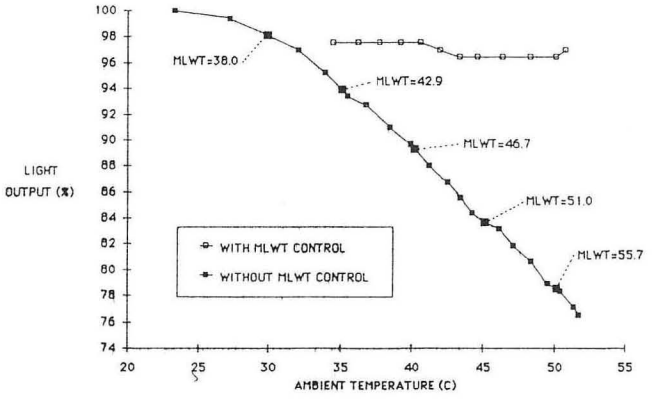

Figure 3. Light output vs ambient temperature, with and without Peltier device to control minimum lamp wall temperature. (XBL-8612-5021)

images of roadways illuminated with lamps and automobile headlights. The technique can be used to show the appearance of pedestrians and roadway signs under different lighting conditions. Figure 4 below shows the computer developed image of a roadway scene.

Planned Activities for FY 1987

Advanced Lighting Design

We will develop optimum lighting layouts with computer aided designs, showing the cost effectiveness of static and dynamic designs. The measured performance of various lamp-ballast-fixture systems will be the input to the computer programs, rather than the ideal specifications listed for these products by the manufacturers. Subsequent analysis will include the changes in illumination that occur with the introduction of objects in the space (furniture, etc.). Computer images of the spaces will also be employed to plot the luminances of the surfaces. The analysis will measure the quality of the illumination.

Fixtures

The application of the Peltier device to control the MLWT of fluorescent lamps will be used for the evaluation of fixture parameters. Currently when we measure the efficiency of a fixture, the MLWT of the lamp is different when total light output of the lamp is measured in open air and in the fixture. That is, in the open air the ambient temperature of the lamp will be 22°C to 25°C while in the closed fixture it may be as great as 53°C. To properly assess fixture designs, we need an efficiency metric that is only dependent on the geometric factors of the fixture. We will examine how the Peltier device can be used to obtain this goal.

Figure 4.. A computer generated roadway scene showing a model pedestrian with light colored clothes walking near a high mast streetlight and in front of an automobile with headlights. (CBB 860-10213)

Computer Imaging

We will study the possibility of using computer imaging of scenes to improve visual performance of drivers on the road as well as in a selection of interior workplace environments. The computer program allows one to alter the lighting of spaces so it can be used to evaluate different lighting techniques. We are attempting to obtain several industrial sponsors to support this work.

Lighting Controls Demonstration Laboratory

In promoting the use of lighting controls, we are attempting to develop a control laboratory to conduct workshops on the proper use of lighting controls. We are seeking financial support from the controls industry, utilities, and government agencies. In addition to conducting workshops, this laboratory would do lighting control research and monitor onsite installations of controls.

IMPACTS OF NEW LIGHTING TECHNIQUES ON PRODUCTIVITY AND HEALTH

The idea that lighting might negatively affect health has appeared often in the lay press during the past few years. Scientific data are, however, lacking, especially to ascertain whether new energy-efficient technologies adversely affect human health and productivity.

Performance and productivity may be influenced by the lamp, the electronics and associated controls, the fixture, or the geometry and location of the lighting system. We classify these lighting factors as: color variations; glare; intensity fluctuations; spectrum variations, including 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 seeks to assure that new energy-efficient lighting technologies do not adversely affect

human health and productivity. We are investigating whether any aspect of new technologies can produce responses in humans. If we identify responses, we will characterize the effects and identify the necessary changes in lighting technologies. Although subjective responses of workers provide some information, such responses are generally confounded by a mix of sociological factors and individual motivations; the investigations carried out by LBL use objective responses to establish cause and effect and ensure repeatability.

The impacts program is divided into three areas: (1) direct effects of lighting on the human autonomic system (carried out at UCSF and LBL), (2) interactions, between lighting and visual display terminal operation, that affect productivity or comfort (carried out at the UC School of Optometry and LBL), and (3) analysis of the general relationship between lighting and visual performance (carried out at LBL).

In the first area of this program, lamps to be evaluated include incandescent, cool-white fluorescent, high-pressure sodium, and metal halide. Human responses to various lighting conditions will be assessed by monitoring autonomic responses, including heart rate, galvanic skin response, muscle strength, exercise tolerance, facial expression, and pupillary response. 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 will probably be included.

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 concern the effects of visible-spectrum and low-frequency radiation on human muscle strength; and as described previously they indicate that subjective psychological factors are the likely cause of reported effects. A second set of experiments using pupillometry has however shown very robust and surprising effects of spectrum on pupil responses to different lamps.

Accomplishments During FY 1986

UCSF/LBL Program

We have completed experiments using infrared pupillometry to investigate pupil reactions to high-pressure sodium and incandescent lamps. Under conditions of steady state viewing, the results from six subjects have shown a larger pupil diameter from HPS exposure compared with incandescent lamps for the same levels of illumination. This initial result implies that, for visual acuity equivalent to that with incandescent lamps, higher illumination levels will be required with HPS lamps. But, on the other hand, for conditions when acuity is not important, HPS lamps might be used with less illumination. The pupil size differences affected by these lamps is shown in Figure 5.

In addition, the potential effect on pupil size of modulation frequency i.e., 60 Hz and 30 kilohertz, has been studied for four different lamps under sponsorship of LRI (Lighting Research Institute). The absence of any measurable effects has been reported.

Visual Performance Program

A model using cost-benefit analysis was applied to the problem of light level recommendations. These recommendations for interior and exterior spaces are currently provided by the Illuminating Engineering Society (IES) on the basis of consensus of expert opinion. Analytical procedures to determine light level recommendations are of concern to the IES and also to those offices in DOE that have responsibilities for proposed building energy use standards and/or guidelines. Cost-benefit analysis results were compared to the IES recommendations. In many cases the results were consistent, but under conditions where the workers were older or the working materials had low reflectivities, recommended light levels were too low. A lengthy report is in progress detailing the specifics of the analysis.

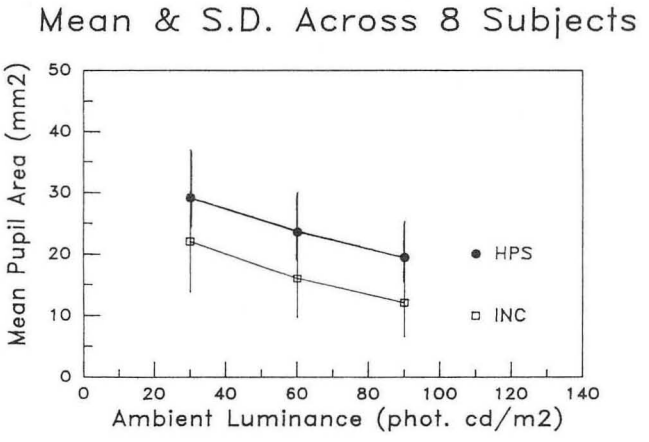

Figure 5. The mean pupil area for eight subjects under conditions of equal luminances of incandescent (Inc) and high pressure Sodium (HPS) lamps. (XBL-864-1338)

The Effect of Glare on Visual Display Terminals and Other Visual Tasks

Glare from general and task lighting is a concern of both lighting designers and users. One of the most common complaints about lighting results from the perceived presence of glare. The Illuminating Engineering Society provides some guidance on this issue in the Visual Comfort Probability (VCP) concept. Unfortunately this concept has very limited application and is based on experimental work, which, in many cases, is not representative of the modern workplace environment. On the other hand, vision scientists have been unable to find an objective correlate to the subjective sensation of glare. Thus there is much anecdotal concern about lighting glare, but a considerable gap in knowledge about what functions are affected by it.

One of the few conjectures made by vision scientists is that the pupil of the eye or its musculature is the most likely physiological system where glare effects should be manifest. This conjecture is based on the past thirty years of study by Glenn Fry and his co-workers on pupil hippus (small continuous uncontrolled pupil oscillations) and of claims of reduced glare sensitivity under conditions of mydriasis (drugs used to cause the pupil to be partially or totally dilated).

We have undertaken a number of studies carefully examining the frequency spectrum of hippus under a very wide range of illumination conditions using Fourier analysis and methods of infrared pupillometry. Preliminary findings show lack of any dominant frequencies, in contradiction to the results of Fry and others. Furthermore, under conditions of discomfort glare, no apparent changes occurred in the hippus spectrum other than those related to the smooth reduction in oscillation swing observed with continued pupil contraction. Further preliminary results found no support for previous conjectures on the reductions in glare sensation under mydriasis. These studies are continuing and are expected to be completed during FY 1987.

Planned Activities For FY 1987

UCSF/LBL Program

On the basis of our work on pupil size under HPS and incandescent lamps, we believe that, under illumination conditions common indoors, the subjective sensation of brightness is correlated with pupil size. Thus it is possible to have a comparison between two different light sources both providing the same luminance level and color appearance (metameric sources), but each producing different pupil sizes. This is possible because we have found a means of producing metameric sources with very different ratios of scotopic to photopic luminance. Under these conditions we can study whether equal luminances and color but different pupil sizes elicit different perceptions of brightness. The predicted response is that the light source with the lower illuminance but larger S/P ratio (smaller pupil) will appear brighter, which is counterintuitive. Several studies along these lines will be undertaken during FY 1987. The first study will use four different fluorescent lamps to create the metameric but differing S.

We will also begin to examine the ways in which pupil size differences induced by lamp spectra affect certain visual functions. The first study will examine the effect of different pupil size (with equal luminance) on contrast sensitivity. The contrast sensitivity stimulus will be provided by a specially designed video display that can present a full range of spatial frequencies both in steady-state and time-varying conditions.

Visual Performance Program

We will continue work on cost-benefit methods applied to light level recommendations; the first report will be completed for presentation at the summer 1987 national meeting of the IES.

A luminance mapper for rapidly and accurately determining luminances in interior environments will be designed, and a first prototype may be constructed depending on availability of components from the video industry.

A strawman research program will be developed to provide information that will help us objectively determine appropriate light levels in the work place. This effort will be coordinated with all the various members of the lighting community that are presently considering this question, such as NEMA (National Electrical Manufacturers Association), LRI (Lighting Research Institute), IES (Illuminating Engineering Society), ASHRAE, etc.

UC/LBL Optometry Program

Work on the relationship between glare and pupil response will continue. Presentation of efforts and peer review is planned for the April 1987 ARVO (Association for Research in Vision and Opthamology) meeting. Other conditions, such as the effect of differential glare stimuli to each eye, will be examined in terms of their effect on VDT visual performance. We will complete the report summarizing the

effects on visual performance of different color letters on VDT screens under both incandescent and fluorescent lighting.

PUBLICATIONS

1. Verderber, R.R. (1986), *Impacts of Daylighting Design Features on the Choice of Lighting Control Systems*, LBL-22043.
2. Richardson, R., and Berman, S. (1986), *Determination of the Excited State Density of an Optically Thick Line.* Presented at the Fourth International Symposium on the Science and Technology of Light Sources, University of Karlsruhe, Germany, April 1986, LBL-21475.
3. Siminovitch, M.J., Rubinstein, F.M., Verderber, R.R., and Clark, T.A. (1986), *The Effects of Fixture Type and HVAC Integration on Fluorescent Lamp/Ballast Performance*, Presented at the IEEE-IAS 1986 Annual Meeting, Denver, CO, LBL-21775.
4. Hollister, D. (1986), "Overview of Advances in Light Sources,". To be published in the *Proceedings of the Society of Photo Optical Instrumentation Engineers*, LBL-21820.
5. Li, F., Verderber, R.R., Hollister D., and Berman, S. (1986), *Improvement of the Efficacy of Fluorescent Lamps by Isotope Blending*, Presented at the Pan Pacific Lighting Exposition, San Francisco, March 1986, LBL-21828.
6. Rubinstein, F.M., Clark, T., Siminovitch M.J., and Verderber, R.R. (1986), *The Effect of Lighting System Components on Lighting Quality, Energy Use and Life-Cycle Cost.* Presented at the Institute of Electrical and Electronics Engineers, Denver, CO, October 1986, LBL-21884.
7. Berman, S., Jewett, D., Bingham, L., Nahass, R., Perry F., and Fein, G. (1986), *Pupillary Size Differences Under Incandescent and High Pressure Sodium Lamps.* Presented at the National IES Conference, Boston, MA, August 1986, LBL-21476.
8. Rubinstein, F.M., Ward, G., and Verderber, R.R. (1985), *The Effect of Control Algorithm and Photosensor Response on the Performance of Daylight-Linked Lighting Systems*, LBL-20562.
9. GTE Lighting Products, (1985), *Annual Report: Test, Evaluation, and Report on the Mercury Enrichment for Fluorescent Lamps*, LBL-20614.
10. Jewett, D., Berman, S., Greenberg, M., Fein, G., and Nahass, R. (1985), "Lack of Effects on Human Muscle Strength of the Light Spectrum and Low Frequency Electromagnetic Radiation in Electric Lighting", *Journal of the IES*, November 1985, LBL-20615.
11. Siminovitch, M.J., Rubinstein, F.M., Clark, T., and Verderber R.R. (1986), *Maintaining Optimum Fluorescent Lamp Performance Under Elevated Temperature Conditions*, Presented at the IES Conference, Boston, MA, August 1986, LBL-21004.
12. GTE Lighting Products (1986), *Physical Diagnostics for Low and High Pressure Gas Discharge Lamps: Final Report*, LBL-22849.

PUBLICATIONS LIST

This list of publications for the Windows and Lighting Program covers FY 1986. For earlier or more recent publications, please contact each group individually.

Windows and Daylighting

Building 90, Room 3111
Lawrence Berkeley Laboratory
Berkeley, CA 94720

1986

LBL-20087: "Instrumentation for Evaluating Integrated Lighting System Performance in a Large Daylighted Office Building," M. Warren, C. Benton, R. Verderber, O. Morse, and S. Selkowitz, *Proceedings of the National Workshop on Field Data Acquisition for Building and Energy Use Monitoring,* October 16-18, 1985, Dallas, TX.

LBL-21466: "Evaluation of Integrated Lighting System Performance in a Large Daylighted Office Building," M. Warren, C. Benton, R. Verderber, O. Morse, and S. Selkowitz, *Proceedings from the 1986 ACEEE Summer Study on Energy Efficiency in Buildings: Large Building Technologies* (Vol. 3), p. 218, 1986.

LBL-21411: "Field Measurements of Light Shelf Performance in a Major Office Installation," C. Benton, B. Erwine, M. Warren, and S. Selkowitz, *11th National Passive Solar Conference Proceedings,* American Solar Energy Society, Inc. 1986.

LBL-21421: "Spectroscopic and Electrochemical Studies of Electrochromic Hydrated Nickel Oxide Films," P. Yu, G. Nazri, and C. Lampert, *Optical Materials Technology for Energy Efficiency and Solar Energy Conversion V,* Proceedings of SPIE's 1986 International Symposium on Optics and Electro-Optics, Innsbruck, Austria, April 14-18, 1986.

LBL-20347: "The Effect of Daylighting Strategies on Building Cooling Loads and Overall Energy Performance," R. Johnson, D. Arasteh, D. Connell, and S. Selkowitz, *Proceedings of the ASHRAE/DOE-ORNL Conference, Thermal Performance of the Exterior Envelopes of Buildings III,* Clearwater Beach, FL, Dec. 2- 5, 1985.

LBL-20079: "Window Performance Analysis in a Single-Family Residence," R. Sullivan and S. Selkowitz, *Proceedings of the ASHRAE/DOE Conference, Thermal Performance of the Exterior Envelopes of Buildings III,* Clearwater Beach, FL, Dec. 2-5, 1985.

LBL-18234: "Transmittance Measurements in the Integrating Sphere," J. Kessel *Applied Optics,* Vol. 25, No. 16, p. 2752-2756.

LBL-20236: "Measured Net Energy Performance of Single Glazing Under Realistic Conditions," J. Klems and H. Keller, *Proceedings of the ASHRAE/DOE-ORNL Conference,* Thermal Performance of the Exterior Envelopes of Building III, Clearwater Beach, FL, Dec. 2-5, 1985.

LBL-20348: "Prospects for Highly Insulating Window Systems," D. Arasteh and S. Selkowitz, Presented at Conservation in Buildings: Northwest Perspective, Butte, MT, May 19-22, 1985.

LBL-20080: "Advanced Optical Materials for Daylighting in Office Buildings," R. Johnson, D. Connell, S. Selkowitz, and D. Arasteh, May 1986.

Lighting Systems Research

Building 46, Room 125
Lawrence Berkeley Laboratory
Berkeley, CA 94720

1986

LBL-21004: "Maintaining Optimum Fluorescent Lamp Performance Under Elevated Temperature Conditions," T. Clark, F. Rubinstein, M. Siminovitch, and R. Verderber, April 1986. Presented at the Illuminating Engineering Society Conference, Boston, MA, August 20, 1986.

LBL-21775: "The Effects of Fixture Type and HVAC Integration on Fluorescent Lamp-Ballast Performance," T. Clark F. Rubinstein, M. Siminovitch, and R. Verderber, June 1986. Presented at the IEEE/IAS 1986 Annual Meeting, Denver, CO, September 29-October 1, 1986.

LBL-22360: "Magnetic Enhancement of Ultraviolet Radiation Efficiency of Low Pressure Hg-Ar Discharge," T. Zhou, L. Wang, D. Hollister, S. Berman and R. Richardson, July 1986. Presented at the Annual IES Conference, Boston, MA, August 16-23, 1986.

LBL-21884: "The Effect of Lighting System Components on Lighting Quality, Energy Use, and Life-Cycle Cost," F. Rubinstein, T. Clark, M. Siminovitch and R. Verderber, July 1986. Presented at the IEEE Conference, Denver, CO, September 29-October 1, 1986.

LBL-22271: "Building Design: Impact on the Lighting Control System for a Daylighting Strategy," R. Verderber, J. Jewell and O. Morse, October 1986. To be presented at the IEEE/IAS 1987 Annual Meeting, Atlanta, GA, October 19-23, 1987.

LAWRENCE BERKELEY LABORATORY
TECHNICAL INFORMATION DEPARTMENT
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720