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FY 1988 Annual Report

Windows and Lighting Program

March 1989

APPLIED SCIENCE
DIVISION

Prepared for the U.S. Department of Energy under Contract Number DE-AC03-76SF00098.

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APPLIED SCIENCE DIVISION ANNUAL REPORT

WINDOWS AND LIGHTING PROGRAM

FY 1988

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

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WINDOWS AND LIGHTING PROGRAM

INTRODUCTION

Over 30% of all energy used in buildings is attributable to two 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 facilitate a variety of tasks with a wide range of visual difficulty throughout the indoor environment while defining the luminous qualities of the indoor environment. These two building elements are thus essential components of any comprehensive building science program.

Despite important achievements in reducing building energy consumption over the past 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 potential of each application. Both the Windows and Daylighting Group and the Lighting Systems Research Group 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 and improving 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 research program is conducted with the participation and support of industry, utilities, universities, design professionals, and government. 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. Innovative concepts for large-area envelope enclosures are studied. The program helped accelerate the development and market introduction of windows incorporating high-transmittance, low-emittance (low-E) coatings for R3-R5 windows. If sales follow current trends, by the year 2000 these coatings will save consumers over $3 billion annually in heating bills alone.

Our research on 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 compose 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 productivity and health.

Our research on advanced light sources is concerned primarily with developing new technical concepts for efficiently converting electrical energy into visible light. Areas of interest include mechanisms for reducing ultraviolet self-absorption in gas-discharge lamps and excitation of the lamp plasma by radio frequency (RF) electromagnetic fields. Both areas promise more efficient conversion of electrical energy into visible light, and possibly much longer lamp life.

Our building applications research concentrates on design of lighting systems, effective use of lighting controls, and how these factors interact with a building's HVAC system.

Research in visibility concentrates primarily on gaining basic information needed to define lighting conditions that enhance productivity in a cost-effective

manner. We also seek to determine any possible undesirable visual effects such as visual fatigue, related to glare and lighting, especially as these events affect the automated workplace.

Our studies of health impacts extend electric lighting research to a wider class of human activities. In a specially designed experimental room, lighting conditions are controlled and human responses are measured objectively 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, C. Benton, D.L. DiBartolomeo, R.L. Johnson, J.J. Kim, J.H. Klems, C.M. Lampert, K. Papamichael, M.D. Rubin, R. Sullivan, 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, as well as their health and productivity.

With more intelligent use of existing technology and with development of new high-performance window materials, windows can be converted from energy liabilities to energy benefits. The aim of the Windows and Daylighting Group is to develop the tools and technologies to accomplish this goal. Research is required to develop the new technologies and capabilities to predict and improve the thermal, energy, and daylighting performance of windows and skylights. The group's work helps generate guidelines for design and retrofit strategies in residential and commercial buildings and contributes to development of advanced computer-based tools for building design.

*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 program's strength lies in its breadth and depth: 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 now 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 others in the public and private realms. 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 and utilized.

Our research is organized into three major areas:

- Optical Materials and Advanced Concepts
- Fenestration Performance
  - —Thermal analysis
  - —Daylighting analysis
  - —Field measurement of performance
- Building Applications and Design Tools
  - —Nonresidential buildings
  - —Residential buildings
  - —Design tools

OPTICAL MATERIALS

Significant reductions in energy consumption of 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 optical 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, and our DOE-supported research subsequently accelerated market introduction of high-performance low-E window systems. Several small firms began offering commercial products in 1982, and by 1985 most of the largest glass and window manufacturers offered low-E products. Incorporating low-E coatings into conventional double-glazed windows produces a lighter, more compact unit with better thermal performance than triple-glazed windows. Ultimately windows using this coating technology could have heat transfer values as low as those of insulating walls, and save more energy annually than the best-insulated wall.

DURABLE LOW-EMITTANCE COATINGS

The objective of this project is to develop a second-generation low-E coating with high transmission and clarity that will last for the lifetime of a window. Among low-E coatings made today, those based on sputtered

silver have the best optical properties and lowest emissivity. Silver, however, is a soft metal and is subject to agglomeration and loss of optical quality. We began by studying titanium nitride, a material that combines optical properties similar to those of a noble metal with the mechanical and chemical durability of a ceramic. Using advanced deposition techniques and multilayer design, we were able to produce coatings with properties exceeding those of the best commercial coatings. This year we began investigating diamond-like films for use as protective and antireflection layers for metallic low-E coatings. The first task was to deposit diamond-like films using standard industrial sputtering technology. These films tend to have low transmittance in the visible spectrum; we were able to increase transmittance by varying the deposition parameters. Figure 1 shows the beneficial effect of reducing sputtering power on the transmittance of diamond-like films. Next year we will continue to optimize the optical properties of diamond-like coatings on silver and test their durability in collaboration with industrial partners.

LOW-CONDUCTANCE GLAZINGS

With the commercial success of R3-R4 windows incorporating coatings and gas-filled insulated glass (IG) units, the next major challenge lies in increasing the R-value of windows' center-of-glass, edge-of-glass, and frame areas. In FY 88 we continued to develop our concept for a high-R window that can be manufactured using existing industrial production facilities. This high-R window is based on an innovative modification of conventional triple glazing. Two low-E coatings are placed on surfaces facing each of two krypton- or krypton/argon-filled gaps. Such a design can achieve center-of-glass R-values between 6 and 10. However, the use of conventional metal spacers to separate the glazing layers creates a large two-dimensional thermal bridge at the outer edge of the IG unit. Furthermore, even the best wood frame will degrade the thermal performance of such a window.

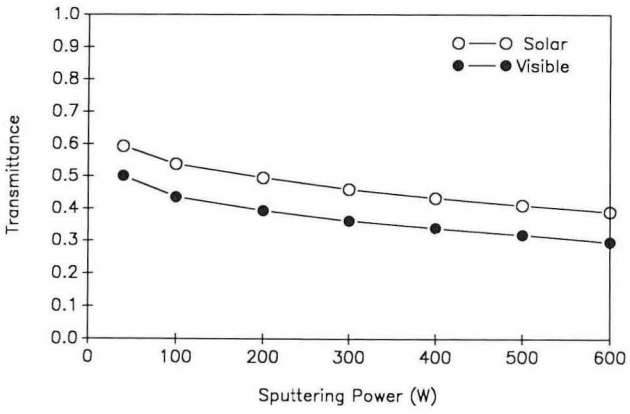

Figure 1. Total solar and visible transmittance versus fraction of H_2 flow in the Ar/H_2 mixture at 200 W. (XBL 892-643)

This year we collaborated with four major window manufacturers to design prototype high-R windows for demonstration home projects set up by electric utility companies in Montana and Wisconsin. Frame and edge designs were modified to reduce heat transfer in these areas. Field monitoring and MoWiTT testing of these windows is planned for FY 89. This work was supported by the Bonneville Power Administration and the Wisconsin Power and Light Company, as well as the U.S. DOE.

OPTICAL SWITCHING MATERIALS

Optical switching materials can be used to dynamically regulate the transmission of windows in buildings and automobiles. Initial studies of energy simulation of office buildings indicate that an automatically controlled switchable coating can provide substantial energy savings in lighting and cooling as well as economic benefits in reduced HVAC system size. The transmittance of a window can be controlled either by electrochromic, thermochromic, photochromic, or liquid crystal materials. Electrochromic devices appear to have the best combination of properties for window applications, including a wide-dynamic visible transmittance range (possibly 8:1 transmittance change), moderately fast switching times, and low power consumption.

During FY88 we developed component layers for the fabrication of devices. The component layers consist of the following materials: 1) electrochromic, 2) ionic electrolyte/conductor, and 3) ion storage. All of our devices are based on electrochromic nickel hydroxide. The best nickel hydroxide layers are deposited by anodic electrochemical deposition using sulfate/nitrate solutions developed by our group. In addition we have made films of nickel hydroxide and vanadium oxide by reactive d.c. sputtering. The optical and electrochemical properties of the films have been investigated using optical spectroscopy and cyclic voltammetry. We have synthesized a quarternary ammonium hydroxide polymer for use as an electrolyte in the device. This polymer has ionic conductivity of 8×10^{-2}S/cm. Devices using this polymer exhibited an integrated photopic response of 70-21% between bleached and colored states (Figure 2).

Our research in FY 89 is directed at improving the durability of the polymer electrolyte, altering the oxidation potential of nickel hydroxide by doping, and developing ion storing electrodes with compatibility to nickel hydroxide. Materials we will study for ion storage include manganese and niobium oxide. To simplify analysis, we will develop computer controlled instrumentation to perform in situ optical and electrochemical experiments.

CORE DAYLIGHTING SYSTEM DESIGN

Outdoor illuminance levels under clear skies are typically 100 times greater than required indoor illuminance levels. If just a fraction of the sunlight falling on a building could be distributed to core building zones, daylight could offset a building's entire electric lighting load during sunny periods, with automatically dimming electric

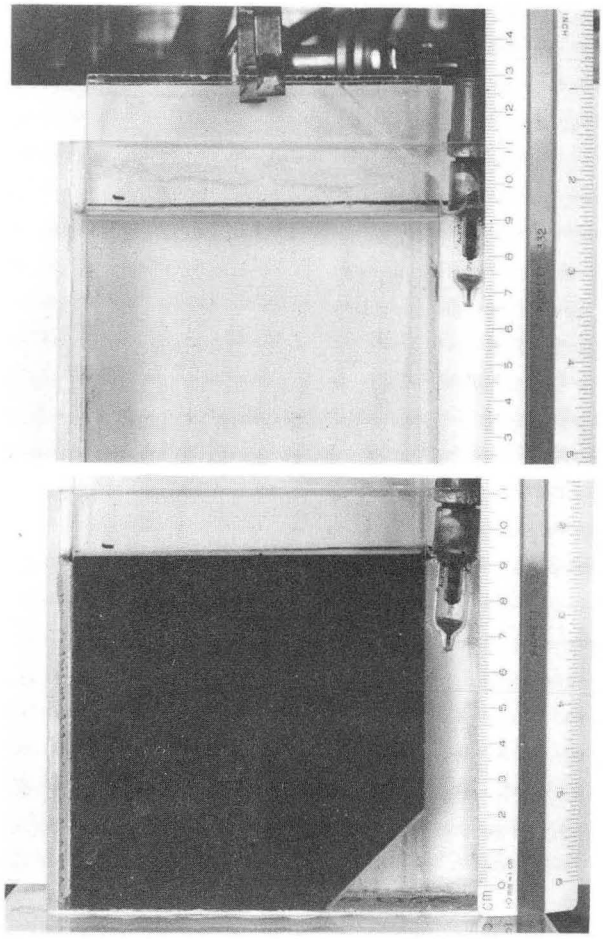

Figure 2. Electrochromic nickel oxide device shown in its colored and transparent states. (CBB 887 6776A)

luminaires providing light at other times. Several core daylighting systems have been developed, and one Japanese system is in commercial production, but these systems are not cost-effective on the basis of their energy savings. We have developed a new design, however, that could supply daylight to core building zones with a cost-effective optical technology.

Our previous work showed that direct sunlight can be channeled to core building zones through light guides small enough for retrofit as well as new-building applications. To attain this level of optical concentration, the system would use tracking solar collectors maintaining stringent tracking and optical imaging tolerances. A practical and economical collector design to achieve these tolerances was developed in FY 87. During FY 88 we developed an algorithm for optimizing the collector's mechanical design; analyzed the radiative heat gain in the system's plastic optical fiber elements and concluded that with proper design thermal gains would not exceed the fibers' thermal tolerance limit; refined the optical theory underlying the collector's Fresnel lens design and filed an initial patent application for a mechanism that substantially eliminates chromatic dispersion in the lens; and developed software for completing the optical design for the overall core daylighting system.

We will continue developing the collector's optical and mechanical design and will refine our estimates of the system's performance characteristics, cost parameters, and projected energy savings. Since subjective response to the interior environment is an important element in overall system design and cost effectiveness, we will consider using the Radiance program to evaluate the system's illumination quality and its interaction with dimmable electric lighting. This software would be used as a design guide not only in the development of core daylighting systems, but also for analyzing new optical component designs for window and skylight applications.

ADVANCED GLAZINGS FOR AUTOMOBILES

Solar heat gain accounts for a large proportion of the cooling loads requiring automobiles to be built with large, high-capacity air conditioners, which in turn release significant amounts of chlorofluorocarbons (CFCs) into the atmosphere. As part of its program to reduce CFC emissions from auto air conditioners, the Environmental Protection Agency supported a study to determine the potential for reducing air conditioner size by using advanced glazing with selective transmittance properties for controlling solar heat gain. Our objective was to define the relative performance of a range of real and hypothetical absorptive and reflective glazings under static-soak and cool-down conditions.

We completed an extensive analysis of the effects of glazing and ventilation options in standard and sports-model sedans by running parametric simulations of a wide range of absorptive and reflective glazing components using a finite-difference computer program. Figure 3 shows the peak interior air temperature under static-soak

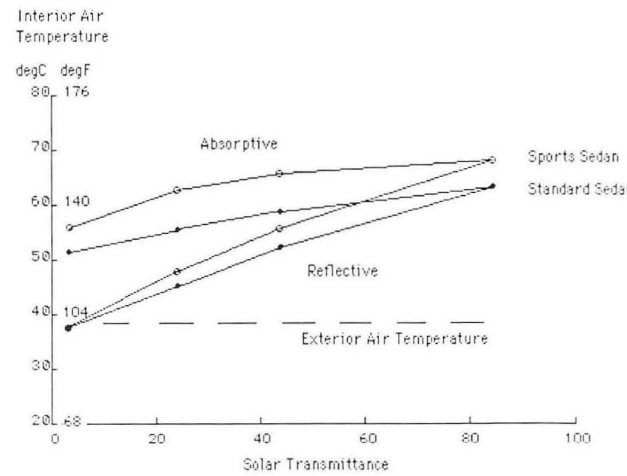

Figure 3. Peak interior air temperatures for standard and sports sedans as a function of solar transmittance. Values occur at 3 p.m. and are shown for reflective and absorptive glazings. (XBL 892-646)

conditions in Phoenix, Arizona, for glazings of varying solar transmittance. The absorptive and reflective curves represent limiting values of these properties. Our final report includes an annotated bibliography of work on solar-load control for automobiles in the form of a hypertext computer program. This gives users quick and easy access to a large volume of data that would otherwise be too cumbersome for convenient use.

Our future work will relate auto air conditioner performance and glazing characteristics to actual fuel use. Although we know that gasoline consumption increases with air conditioner use, the potential for improving fuel efficiency has not been thoroughly studied. We plan to perform analytical and experimental investigations under a variety of driving conditions in several climates. We also expect to begin development of new coating technology to meet the performance requirements we have identified.

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 develops and refines experimental techniques and analytical models for accurately determining heat-transfer and solar-optical properties of fenestration components and systems and validates 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 not only improve the accuracy of our predictions but 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 Figure 4.

THERMAL ANALYSIS

With the wide acceptance of low-E coatings and the introduction of low-conductance gases by the window industry, the number of possible window configurations has multiplied rapidly, creating a need for an accurate, convenient, and standard calculational procedure to determine window heat-transfer indices. The Windows and Daylighting Group developed a computer program to fill that need. WINDOW 2.0 was released in 1986 and distributed by LBL and a major window sealant manufacturer as a professional courtesy to over 800 window and IG-unit manufacturers. The program has since become the de facto standard in the industry, and our efforts to develop WINDOW and make it available to the private sector were recognized by the Federal Laboratory Consortium's 1988 Special Award for Excellence in Technology Transfer.

In FY 88 we added many new technical and user-friendly features to an updated version of the program. Users of WINDOW 3.1 have easy access to libraries of component information and can easily build or change a window and see the resultant thermal properties on the same screen. Version 3.1 includes help screens, and its operation is consistent with standard MS-DOS software. WINDOW 3.1 is being distributed by window and sealant manufacturers, and other industry organizations have also expressed interest in distributing this program to their members.

Our early work emphasized center-of-glass U-values, but glass-edge and frame effects are known to be significant, particularly in high-performance windows. We have begun a thermal analysis program to study these two-dimensional heat transfer effects (Fig. 5). Results from these finite-element models will be incorporated into libraries in WINDOW 3.1 in order to give the user heat-transfer properties indicative of complete windows and not just center-of-glass performance. These finite-element models have been used to study pressure and temperature induced stresses in high-performance glazings.

In FY 89 we expect to use thermographic techniques in conjunction with more extensive finite-element modeling to develop and validate the library of sash and frame heat-transfer effects. These tools will also allow us to explore the problems associated with condensation on glass edges and frames.

DAYLIGHT AND SOLAR HEAT GAIN 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. However, the solar heat gain associated with daylight can be a benefit or cost, depending on circumstances. Analyzing the trade-offs to arrive at an optimum solution for simple glazings is difficult; for complex fenestration with sophisticated sun control systems it is virtually impossible with currently available tools. Our objective is to develop the experimental facilities and analysis models to accurately characterize the daylight and solar heat gain from fenestration systems of arbitrary complexity. We conduct a wide range of activities to establish the facilities, tools, and data to address these problems.

Solar-Optical Properties of Complex Fenestration Systems

A quantitative understanding of the solar-optical properties of fenestration systems is essential to accurately predict their luminous and thermal performance for any sun, sky or ground conditions. "Luminous performance" refers to daylight illuminance and luminance levels that determine electric lighting requirements and visual comfort. "Thermal performance" refers to solar heat gain levels that determine heating or cooling requirements and thermal comfort.

We are developing a method of calculating the solar and daylight transmission through complex fenestration systems from laboratory measurements of the solar-optical properties of window components. The method treats fenestration systems as radiation sources of varying-intensity distribution. For diffusing, diffusely reflecting, or geometrically complex components such as blinds or

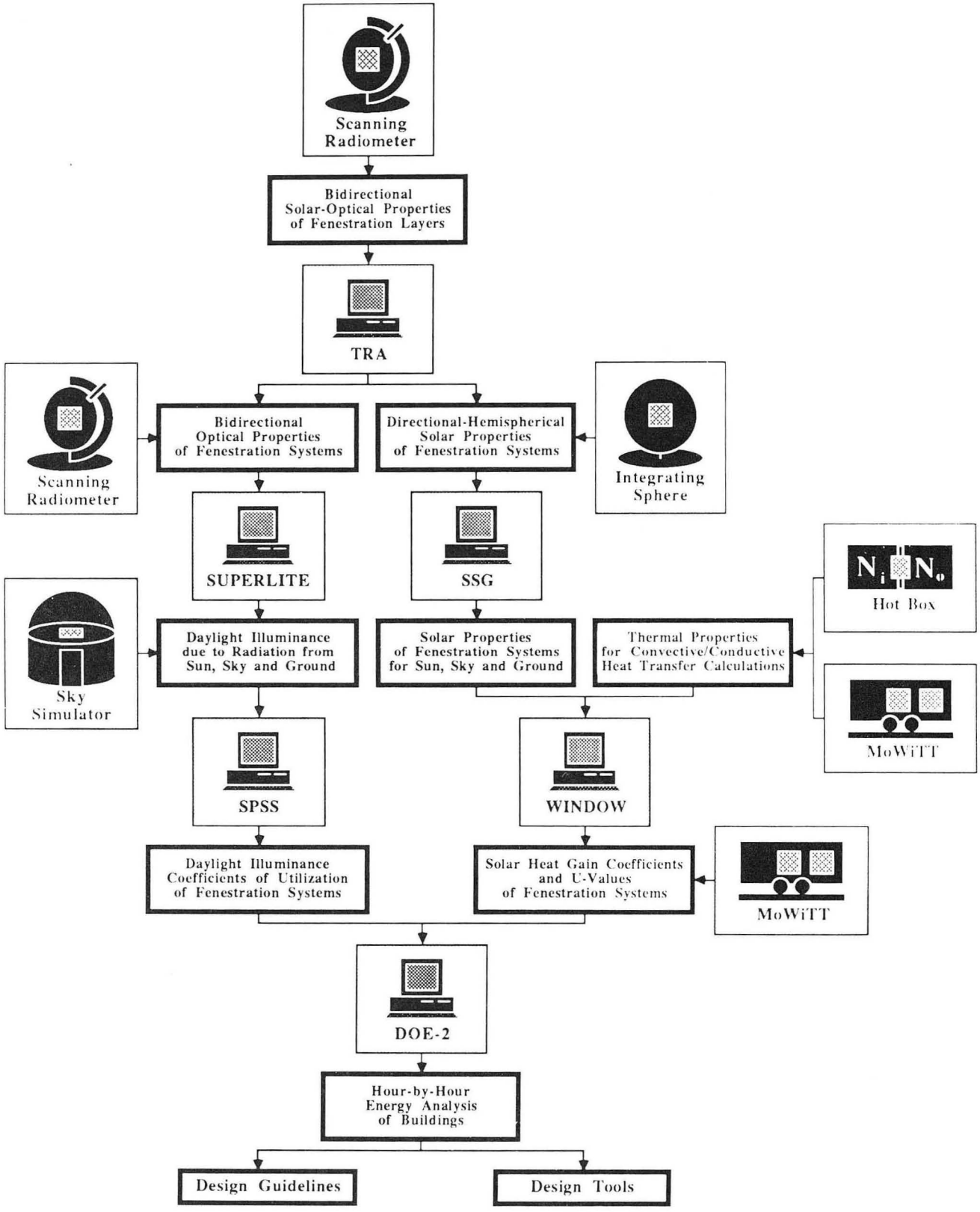

Figure 4. Schematic diagram of overall fenestration modeling capabilities under development includes new measurement facilities, computer models, and intermediate calculated and measured results. Direct measurement of some intermediate calculated results provides a validation check. (XBL 885-1479)

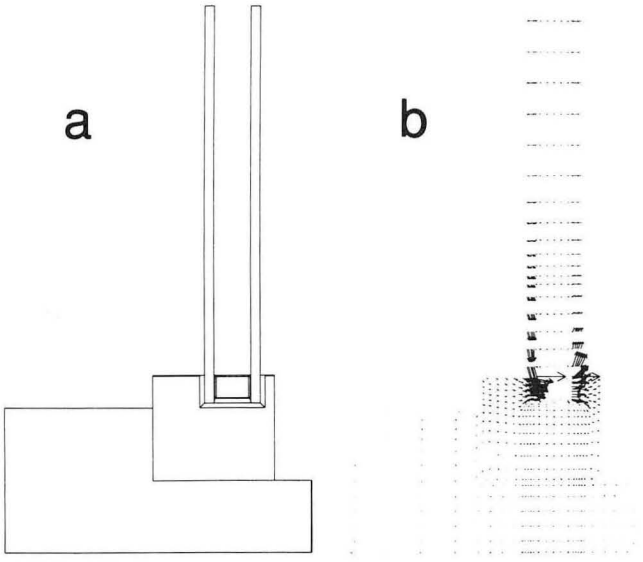

Figure 5. a) Cross section of window edge and frame. Glazing layers are separated by a dessicant-filled metal spacer sealed inside a wood sash that rests on a wood frame. b) Vector plot of two-dimensional heat transfer through the window section shown in (a). Warm interior is at left, cold exterior at right. Size of vector denotes magnitude of heat transfer; arrow denotes direction. All glass two-dimensional heat transfer occurs within the bottom 2.5 inches of glass panes modeled. Small vectors appear as dots. (XBB 892-642)

drapes, bidirectional solar-optical property measurements are necessary. We have developed a large-scale, automated scanning radiometer/photometer to make these measurements (Fig. 6). Computer software will compute the luminous or radiant distribution transmitted by a complete fenestration system for a given set of exterior conditions by combining the properties of component layers while correctly accounting for multiple reflections. During FY88 we initiated a cooperative project with support from DOE and ASHRAE to make this method the basis for a new treatment of solar heat gain through fenestrations. Scanning radiometer measurements will be made on a representative sample of fenestration components, the completed software will be used to calculate the solar heat gain, and the method will be validated by comparison with measurements made with the Mobile Window Thermal Test Facility (MoWiTT).

DAYLIGHTING ANALYSIS

The prediction of lighting quantity and quality in the luminous environment is essential for energy-efficient lighting design. Over the years, we have developed a range of daylighting design tools to expand our modeling capabilities and improve calculational accuracy. Our most advanced daylighting simulation model, SUPERLITE 1.0, was converted to run on an IBM-compatible personal computer in FY88. We continued our efforts to expand

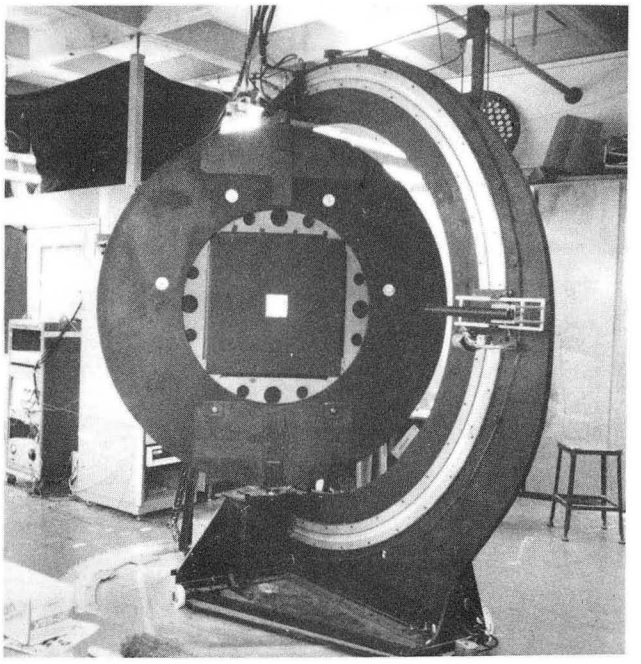

Figure 6. Scanning radiometer for measuring the bidirectional transmittance and reflectance of fenestration components and systems. (BBC 887-6823)

SUPERLITE capabilities to model more sophisticated daylighting systems such as complex sun control and shading systems. This work includes developing and upgrading modeling algorithms and initial efforts to create a photometric data base containing the complex optical properties of shading systems required by SUPERLITE. (Related work on the measurement of these properties is discussed in the earlier section titled "Daylight and Solar Heat Gain Studies.")

We also plan to develop tools to assist designers in qualitative assessment of daylighted environments by using the numerical output of the SUPERLITE program to produce luminance maps of light distributions in architectural spaces.

In FY89 we will provide an initial library of shading system optical properties for SUPERLITE using data from our luminance scanner. Further collaborative work with other university-based groups will be directed toward improving the ease of use of the microcomputer version of the program and enhancing its input/output capabilities.

The Sky Simulator and Daylight Photometric Laboratory

Scale-model photometry is a powerful tool for daylighting design and analysis. Our 24-ft-diameter hemispherical sky simulator (Fig. 7), located on the University of California's Berkeley campus, simulates the effects of uniform, overcast, and clear skies. Sky luminance distributions are reproduced on the underside of the hemisphere; light levels are then measured in a scale-model

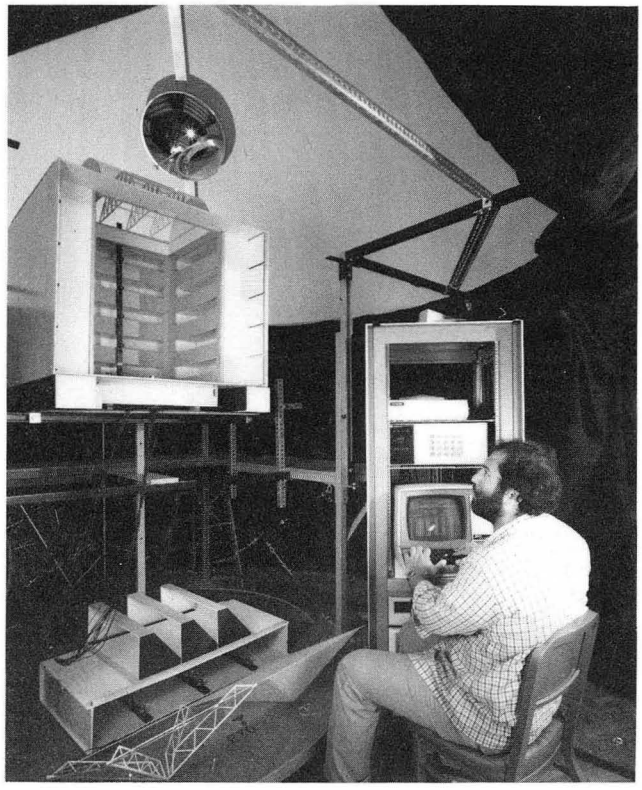

Figure 7. Interior of sky simulator shows reconfigurable scale model of a five-story atrium (with one side of model removed). (CBB 848-5926)

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, for educational purposes, and on a limited basis by architects working on innovative daylighting designs.

FIELD MEASUREMENT OF FENESTRATION THERMAL PERFORMANCE

We have known for some time that winter solar heat gain through south-facing windows in conventional buildings is a significant source of "free" energy. Subsequent calculations have indicated that it is technically possible, for any orientation in any U.S. climate, to optimize windows to the point that they become positive contributors to a building's energy needs.

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

To perform these measurements, the Mobile Window Thermal Test Facility (MoWiTT) was designed, built and calibrated. In developing this facility (Fig. 8), it was necessary to solve the problem of doing calorimetry on a

Figure 8. The MoWiTT facility at its field test site in Reno, Nevada. Two sealed insulating glass units are mounted in the two calorimeters. Portable building at left contains computer that controls the facility and records data, including data from on-site weather tower. (CBB 892-812)

room-sized enclosure (which would normally require careful maintenance of constant equilibrium conditions) in the presence of the solar fluxes and changing outdoor temperatures which control the behavior of a fenestration system. We solved this problem with a large-area heat flux sensor (developed as part of the project) and a very sophisticated measurement of the heat extracted from the calorimeter by its cooling system. The MoWiTT began operation in 1986 at a field-test site in Reno, Nevada.

During FY88 we completed a study of windows with frames (a cooperative study with support from the Bonneville Power Administration), which demonstrated that calculated U-values agree well with field measurements, provided that there is adequate knowledge of the local weather conditions. In most cases, results were also consistent with laboratory measurements of U-value; however, laboratory measurements appeared to be questionable for highly conductive frames. This study provides the first convincing evidence that U-value calculations can accurately predict field performance, a question which has been the subject of controversy for more than a decade. The study also demonstrated that the diffuse solar heat gain admitted by north-facing or shaded windows has a significant effect on the daily winter energy balance. This heat gain is frequently neglected in estimates of winter heat loss.

We have also begun measurements of solar heat gain and the inward flowing fraction of absorbed solar energy for windows with shading systems. These measurements form part of the cooperative study of solar heat gain undertaken with partial support from ASHRAE and described above (see Daylight and Solar Heat Gain Studies).

In 1989 we will extend our studies to include higher-performance windows and superwindows, continue the solar heat gain study, and explore the effect of common

shading systems on winter energy performance. We will utilize our data in support of a joint US/Canadian project to standardize the calculation of window U-values.

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

BUILDING APPLICATIONS AND DESIGN TOOLS

The development of new glazing materials and experimental characterization of fenestration system performance must be complemented by translating the benefits of such information to the building design community. The objective of our building applications activities is to apply the knowledge gained from our basic science research to real-world buildings and develop the tools to disseminate this information.

SIMULATION STUDIES: NONRESIDENTIAL BUILDINGS

Our goal is to develop a microcomputer-based fenestration performance design tool. The first phase of the project, supported by a contract from the Lighting Research Institute and DOE, has been to define a methodology for evaluating overall fenestration performance and construct a data base for conventional fenestration systems and complex operable shading systems. The second phase entails the development of the actual design tool.

A large part of our effort was directed toward reporting the results of Phase 1. In addition to completing the final report, "Commercial Building Fenestration Performance Indices Project, Phase 1: Development of Methodology," we presented a second paper, "An Approach for Evaluating the Thermal Comfort Effects of Nonresidential Building Fenestration Systems," at a comfort symposium and explained the methodology used to define comfort indices. A third paper, "An Indices Approach for Evaluating the Performance of Fenestration Systems in Nonresidential Buildings," describes the overall methodology and was presented at an ASHRAE technical conference.

We began development of the microcomputer-based design tool with special emphasis being placed on the design of the user interface. Of particular importance was our study of the combination of text and graphics that are necessary to give potential users an intuitive sense of the tool's purpose and use. We also implemented several of the algorithms derived during the analytical phase of the project. Figure 9 shows an output screen from this prototype tool. Menu items are shown along the left hand side and the bar diagrams represent calculated values for four fenestration systems.

In FY89 we will to continue our Phase 2 efforts to develop a microcomputer-based tool with co-support from LRI and DOE. The tool will allow a user to access and process the glazing and shading-systems data base to determine the key performance indices as indicated in Figure 9. Simultaneous treatment of the thermal and visual comfort effects in parallel with the energy-related performance data is a major advance over past energy models.

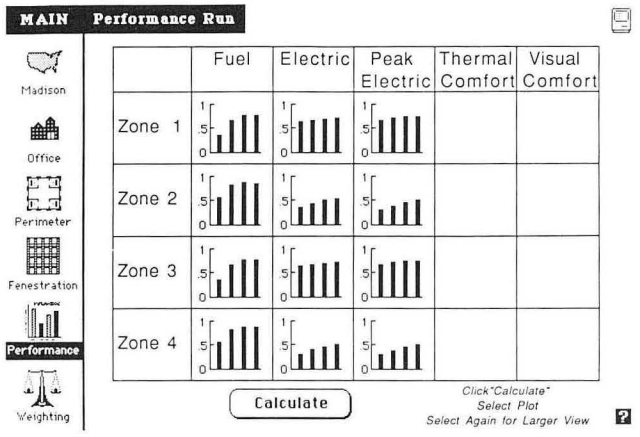

Figure 9. Screen from fenestration design tool shows calculated values of fuel use for heating, electricity use for cooling, and peak electricity demand for four different fenestration systems. (XBL 892-645)

The tool will allow the user to weight each index to find the fenestration system that optimizes energy, cost, and comfort issues based on the user's weighting factors. The tool can also be used directly in an "optimization mode". Since the performance data are stored in simple analytical form, the user can directly determine properties of a real or hypothetical fenestration system representing an optimal solution, i.e., minimum or maximum value for each performance parameter. Combining these analytical capabilities with a hypermedia user interface will produce a powerful and effective design tool. Final design of the overall tool will be based on extensive consultation and testing by project sponsors and feedback from professional user groups.

SIMULATION STUDIES: RESIDENTIAL BUILDINGS

Our objective is to provide home builders and others involved in residential design and construction with easy access to relevant results of our window performance studies. The proliferation of new window technology offers new options to builders, but at the same time the multiplicity of options creates confusion regarding optimal selections to meet all performance requirements. We prepared a draft set of "Window Notes" that define and summarize performance factors for existing and new window technologies that affect residential energy use and comfort. This information was reviewed by the National Association of Home Builders.

Simultaneously with the development of the paper version, we created an interactive computerized version of the notes that included a variety of animation features. Figure 10 shows the main menu of this tool. The highlighted items are those aspects that were completed.

In FY 89 we will begin to expand "Window Notes" into a more comprehensive residential fenestration design manual/tool. This will ultimately include the development of a microcomputer-based simplified analysis tool.

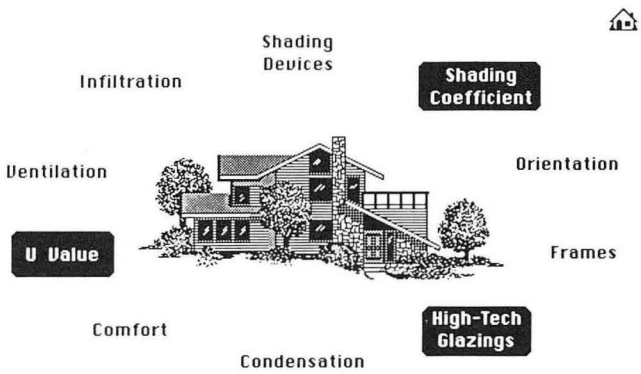

Figure 10. Main menu screen of computerized version of "Window Notes," which summarizes performance factors of window technologies. "Window Notes" will be expanded into a comprehensive residential fenestration design tool. (XBL 892-644)

DESIGN TOOLS AND TECHNOLOGY TRANSFER

To influence energy consumption trends in the United States, it is critical to communicate our results to other researchers and building industry professionals. We use a variety of conventional media to reach a widely varied audience: other research and development groups, educational institutions, design professionals and industrial firms. We continue to develop improved fenestration analysis and design tools and handbooks, carry out design assistance studies, and sponsor workshops and meetings with manufacturing and design firms and public utilities.

Of special significance over the past several years are our efforts to explore new forms of advanced electronic media to better communicate appropriate information to varied audiences. For example, the growing public and private use of CD-ROM (compact disc read-only memory) for storing thousands of pages of text, images and audio reinforces our view of the value to the building community of the technology transfer tools based on new electronic and optical media.

We continued our interactions with the Daylighting Network of North America (DNNA), a group of 35 universities with research and instructional interests in daylighting. The network continued to publish the DNNA News and distribute software packages to faculty and practitioners. The latest advances in the development of "Hypermedia and Future Design Tools" were explored by architectural faculty representing 15 member schools of the network during a Daylighting Summer Retreat in Berkeley. A prototype workstation linking a CD-ROM drive and video disc player with high-resolution color monitor was used to demonstrate the hypermedia-based Daylighting Design Guide prototype we are developing. We expect to involve DNNA members in future development of this tool.

Our research and communication efforts are enhanced by the participation of visiting researchers from the U.S. and including foreign faculty representing Switzerland, Germany, Japan, and Israel. The international perspective provided by our visitors is useful at a time when energy, economic, and environmental issues are increasingly viewed as global concerns.

ADVANCED DESIGN TOOLS

Our long standing interest in developing the next generation of sophisticated hardware and software design tools received significant funding from DOE, allowing us to pursue several exciting avenues. The Advanced Design and Operation Technologies (ADOT) Planning Project is intended to address the development of the technological basis for a family of design tools to be used by designers to achieve greater energy and cost savings in the next generation of U.S. buildings. Private-sector design tools utilizing ADOT technology would contain knowledge bases of energy-efficient technologies and methodologies, computer-aided-design capabilities, energy-analysis modules, and capabilities for visualizing interior and exterior building environments. Visualization capabilities include the ability to realistically simulate both quantitative and qualitative aspects of the building. The interface between the designer and the ADOT tools would rely heavily on visual representations of information and data.

In collaboration with the ADOT Planning Project, we studied imaging and visualization technologies to identify and evaluate the hardware and software requirements for the generation, manipulation and display of visual data for these advanced tools. To demonstrate the potential for the use of dynamic visual information for design decision making and education, we developed a prototype Daylighting Design Guide using new computer-based hypermedia approaches. The prototype is composed of Apple's Macintosh hardware and Hypercard software linked to a CD-ROM drive and video disc player with high-resolution color monitor. The primary thrust of this research is to explore the value and limitations of a hypermedia presentation of traditional daylighting design materials.

We expect to develop a prototype hypermedia information kiosk for demonstration and evaluation purposes with the support of DOE, LBL, and utilities.

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Lighting Systems Research*

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

New, efficient technologies and strategies have the potential to save our nation 50% of the electrical energy consumed by lighting, or about 12% of total electrical energy sales. This would amount to a yearly savings of some 220 billion kilowatt-hours of electricity, valued today at more than 16 billion dollars. The significance of this savings can be appreciated by considering projections of economic growth that predict a doubling of present commercial floor space by the year 2020. The 220 billion kilowatt-hours of saved energy would allow the new space to have its desired lighting conditions without the need for new electrical generating capacity, thereby providing an additional capital savings of more than $100 billion.

To help achieve this more energy efficient economy, the Office of Buildings and Community Systems of the U.S. Department of Energy has established a program combining research activities and technology transfer to the lighting community (manufacturers, designers, and users). This program represents a unique partnership between a national laboratory-university complex and industry, facilitating technical advances, strengthening industrial capability, and providing designers and the public with needed information.

Past successes from this effort include development of the high-frequency solid-state ballast for improving the efficiency of fluorescent lamps; the Controlite computer program that enables designers to determine the energy and economic benefits of lighting controls in the workplace; assistance in developing the compact fluorescent lamp; important information on how lighting can effect productivity and visual functions; and determination that both photopic and scotopic spectrum affect the vision process at typical interior light levels.

The program is now actively pursuing development of more efficient light sources through technical concepts such as using isotopically enriched mercury for fluorescent

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lamps. A variety of ingenious methods for operating lamps at high frequency without electrodes are being pursued, with the goal of improved efficiency and longevity. In addition, the program is developing comprehensive strategies to optimize the benefits obtained by introducing efficient fixtures combined with lighting controls. This effort is assisted by the use of computers that can display realistic, visual simulation of the lighted workplace. In its study of the relation between lighting variables and visual function, the program is identifying human responses to lighting conditions, leading to new innovative products that improve both energy efficiency and productivity.

The program has identified new long-range technical concepts which, although high in risk, have great potential payoff. These include development of more efficient fluorescent lamp phosphors, lamps filled with novel gases, super fixture systems that overcome the inefficiencies associated with overheating, as well as the use of the spectral quality of lighting to optimize performance and comfort.

This interdisciplinary program encourages innovation in the industry, accelerates the societal benefits obtainable from a more cost-effective and efficient lighting economy. Because of its comprehensiveness, it is unique in the United States.

Since its inception in 1976, the LBL Lighting Program has produced more than 124 reports and publications. These reports, available to the public, document research on subjects such as solid-state ballasts, operation of gas-discharge lamps at high-frequency, isotopically enriched fluorescent lamps, energy-efficient fixtures, lighting control systems, and visibility and human productivity. In addition to its research activities, the internationally recognized interdisciplinary staff 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).

Described below are highlights of the accomplishments realized in FY 1988 by each of our three major efforts: advanced light sources, building applications, and health impacts. Discussion of activities planned for FY 1989 are included in the highlight descriptions. Publications and conference presentations from the past year may be found at the end of this chapter.

ADVANCED LIGHT SOURCES

The advanced light sources effort promotes new lamp technology and light source development. To see what can be accomplished in this area, consider that the most efficacious four-foot fluorescent lamp, operated at high frequency (20 kHz), has a luminous efficacy of approximately 100 lumens of light output per watt of electrical power input. Although this is more than five times as efficient as an incandescent lamp, still greater efficacies are possible. White light can, theoretically, be produced at almost 350 lumens per watt. The advanced lamp technology program is developing the engineering science that will help us achieve a target efficacy of 200 lumens per watt within the next few years.

In the area of fluorescent lamps, three loss mechanisms are candidates for efficiency improvements. These are self-absorption of ultraviolet (UV) radiation, electrode losses, and energy loss in lamp phosphors. In the first case, we would like to reduce self-absorption of UV radiation, a process that occurs within the lamp plasma before the radiation strikes the phosphor-covered inner wall (the phosphor converts UV radiation into visible light). If UV self-absorption is decreased, thereby reducing the chance of quenching electron collisions, the amount of UV radiation available to be converted into light at the lamp wall is increased.

In the second case, energy losses associated with electrodes can be eliminated by exciting the lamp plasma at radio frequencies (RF). The problem is to find an efficient method for coupling the RF energy into the lamp without causing new losses.

In the third case, we would like to develop a more efficient phosphor matrix that will convert one energetic UV photon into two visible photons. These concepts could lead to significant improvements in lamp efficacy.

LBL is studying several ways of reducing UV self-absorption. The first method is altering the isotopic composition of mercury. In its natural state, mercury 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. The most promising possibility is isotope alteration-enrichment with ^{196}Hg, which is being pursued in a joint effort by LBL and GTE Lighting. Should isotopic alterations prove economical, modified lamps would enter the market quickly. 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 based on the application of a d.c. magnetic field having a direction parallel to the main current. Axial magnetic field strengths of about 600 gauss can increase light emission by about six percent. LBL and major firms in the lamp industry are studying practical ways to apply this technique.

A highly promising mechanism developed at LBL uses a plasma coupling principle that eliminates the need for electrodes; it allows lamp plasma excitation to occur primarily near the inner lamp wall, thereby reducing both the electrode loss and the likelihood of entrapment loss. This surface wave mode of operation occurs at high frequencies in the RF range between 100 and 500 MHz, permitting efficient lamp excitation without electrodes. The surface wave fluorescent lamp shows approximately 40 percent increased energy efficacy over normal fluorescent lamps, operates without starting circuits, and should be very long-lasting because of the absence of electrodes.

Reducing the effects of energy loss in the phosphors requires alteration of 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 conversion of the UV photon into two visible photons, this process must occur quickly to prevent heat-producing collisions. LBL and GTE lighting are 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 and the extensive research required to provide solutions, is extremely interested in this cooperative effort.

If these research projects at LBL come to technological and commercial fruition, future fluorescent lamps would operate at high frequency without electrodes and would 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, doubling the efficiency of today's best fluorescent lamps.

Other lamp 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 us to use 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 could be used in many new ways. It would improve energy efficiency and would be aesthetically attractive enough for widespread use by lighting designers.

Mercury Isotope Separation and Enrichment of Fluorescent Lamps

Continued progress has been made in assessing the feasibility of photochemical separation of natural mercury to produce mercury enriched in the isotope mass ^{196}Hg. Most of the FY 1988 effort has been involved in designing and building a scaled-up reactor that can produce several grams per day of enriched mercury. This has required the development of a high flux light source now in place. Several new scientific and technical personnel have been added to the project, and a number of new developments are expected in FY 1989. These include in situ measurement of reactor performance, allowing continuous monitoring, production of enough enriched mercury to permit a high speed dispensing procedure (suitable for filling a large number of lamps with the enriched product), and economic analyses of the complete photochemical process that will permit conclusions on the feasibility of enriched mercury lamps as a market product.

Surface Wave Lamp (SWL)

Two important new findings were made during FY 1988. First, the surface wave mode of coupling was extended into a much higher power range, achieving about 10 watts per inch of discharge (as compared to the previous loading of about 1 watt per inch, typical of today's fluorescent lamps). This new level is still an order of magnitude below the 100 watts per inch typical of commercial high intensity (HID) lamps. The intermediate level achieved, which we refer to as the MID lamp, still maintains the zero reflected power condition essential for achieving high efficacy. A noteworthy aspect of the MID surface wave lamp is its instant restrike capability compared to the typical 10-minute period needed for commercial HID lamps. The question of effective coupling and restrike capabilities at an HID condition will be considered during the next year.

Our second major achievement is the development of a launcher and the finding of a frequency that allows a two-foot lamp to be energized by the surface wave mode. Efficacy improvements of about 30% for the longer-length lamp have been achieved.

Our first written examination of possible SWL power supplies indicates that a Class E amplifier with a solid state switching transistor is the most likely candidate. Further work in FY 1989 in this area will be undertaken with an outside contractor familiar with Class E amplifiers.

Electrodeless High-Intensity Discharge (HID) Lamp

The complete system for back-filling lamps 1 in. and .75 in. in diameter has been completed. These lamps are spherical in shape and are to be filled with various candidate materials for efficient HID light production. Successful glow-to-arc transition has been obtained with a pure mercury fill at slightly over 100 watts of lamp power.

Knowledge of the actual pressures in the lamp at operating conditions will be absolutely essential. For this purpose, several techniques have been initiated. The potentially best method involves insertion of a small amount of scandium (about 1% by mass) into the lamp. Scandium has some optically thin emission spectra in the visible region, and these line widths can be measured quite accurately. These scandium lines have been observed, and the success of this method will depend on an accurate calibration procedure which will be developed during FY 1989.

Lamp Fabrication Facility

Much effort in FY 1988 has been expended on developing our own lamp fabrication facility, which will enable us to build lamps from the basic glass tubing, fill with the desired gases and salts, include glass electrode seal if needed, and use all the extensive combined vacuum and oven systems needed for fill control and maintenance

of high purity. The facility required a new laboratory room that was constructed by conversion of a large, partially open storage area. Our personnel designed the facility and monitored its rehabilitation. The various fabrication components were tested and incorporated into the integrated facility. Numerous difficulties were encountered because of scheduling delays brought about by overall LBL plant complications; nevertheless, the lamp facility achieved 90% completion by the end of FY88, with the 100% level expected in early FY 1989 (Figures 1 and 2).

Isotope Modeling

This project, a joint effort with New York University, has the primary objective of developing a theoretical model to account for the effects of variations in isotopic mercury composition upon emittance of a low-pressure discharge. The secondary objective is to include the effects of partial redistribution, surface effects, and line-shape factors that affect the emittance, and hence the efficacy, of UV radiation.

The practical goal is to specify the isotope composition that maximizes emittance.

Figure 1. Evacuated glove box where hydroscopic salts are prepared as additives for lighting producing fills in electrodeless HID lamps (CBB 876-10627)

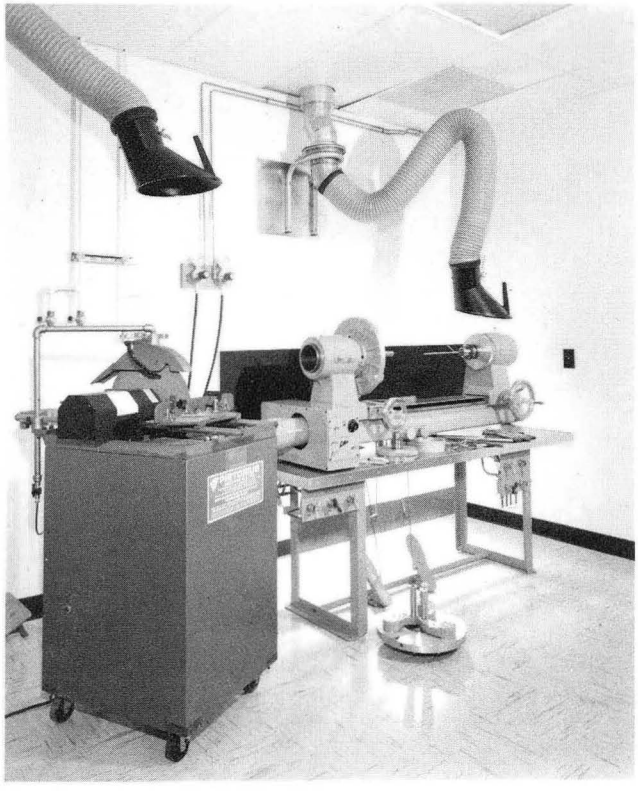

Figure 2. Lamp fabrication components including glass lathe (right) and high-speed glass saw (left). (CBB 891-341)

We have formulated a variational theoretical model of the radiant emittance of the mercury-argon discharge used in fluorescent lighting. The model includes the effects of the fine structure and isotope shifts in the resonance radiation line as well as those of atomic diffusion, resonant exchange of excitation, and radiation transport. The result is a variational principle which, when evaluated using suitable trial functions, yields a variational estimate of the radiant emittance of the discharge. This principle is used to study the effects of isotopic mercury enrichment on emittance. The special case of a single pure isotope, as well as mixtures of all seven naturally occurring isotopes, are presented. Recent experiments with enhanced ^{196}Hg and ^{201}Hg concentrations are discussed within the context of this theory. The relative merits of three isotopic mixtures recently proposed for commercial development by Alchemie, Inc. are assessed, and one of the mixtures (case 2) can be expected to lead to a greater improvement of the emittance of the discharge than the other two, with about a four percent increase over that of natural Hg. Further refinements, including additional physical effects as well as improved numerical codes, are planned for the final stage of the model.

BUILDING APPLICATIONS

Real energy savings depend on the transfer of energy-efficient technologies and strategies to the lighting

community. The building applications activities aim to assess and develop energy-efficient lighting technologies and to combine their technical performance characteristics to model energy-efficient and cost-effective lighting geometries and controls. Our analysis uses knowledge of the relationship between visual performance and physical aspects of lighting, such as illumination level, distribution, contrast, and glare. As part of this effort, a computer program has been developed that provides accurate simulations of illuminated spaces with their contents. The simulated scenes are visibly indistinguishable from real photographs; using them, we can model effects of changes in the illumination systems. Validation of luminance values produced by these simulations requires physical measurements of luminances in complex environments. Therefore, the project uses a number of novel techniques for real luminance mapping of interior environments with complex objects to obtain actual luminance values. The technology development component of this program examines engineering approaches to reducing light losses associated with thermal factors of conventional lighting fixtures. The conclusion of these efforts will be a combination of lighting systems technologies and analysis. Visual simulation of the proposed application represents the most compelling tool for promoting the implementation of energy efficient lighting.

Advanced Lighting Design

The primary objective of this effort is the development of simplified guidelines for assessing lighting contrasts, and hence, performance available in a given space as a result of illumination, fixture geometry, lamp type, and interior reflectance. The procedures involve examination and analysis of available computer programs.

During FY 1988, parametric runs on Lumen-Micro were studied to examine the question of the effect of luminaire spacing and the light distribution from particular luminaires on predicted visual performance in an open-office environment. Optimal spacing geometries have been determined. A cost-benefit analyses will be undertaken during FY 1989, taking into account the tradeoffs between higher light levels and tighter spacing with potentially diminishing returns on productivity.

Energy-Efficient Luminaires and Thermal Control Devices

Ceiling-mounted four-lamp luminaires, lens and parabolic types, were evaluated during FY 1988. The minimum lamp wall temperature of the in-place lamps were measured with various ventilation schemes and distances from the ceiling. Simple convective cooling reduced the excessive lamp wall temperature 10° to 15°C and was a function of distance from the ceiling. The thermal performance of the luminaires was measured for standard ballasts with 40-watt and 34-watt lamps, and for electronic high-frequency ballasts. The convective cooling strategy was able to recover most of the thermal loss due to lamp overheating.

During FY 1989, the thermal performance of enclosed and parabolic four- and two-lamp troffers will be measured. We will also develop optimum venting to convectively cool the fluorescent lamps controlling the ambient and plenum temperature. Measurements using a standard two-lamp F40 lamp-ballast system will be conducted for reference and compared with measurements for energy-saving magnetic ballasts and electronic ballasts.

In the area of specific devices to control lamp wall temperature, our major effort has been on concepts that use the Peltier effect coupled with a heat pipe acting as the heat sinking component.

The power to the Peltier device was obtained from the secondary filament windings of a standard ballast. This was accomplished by a filtered full wave rectifying circuit. The capacitor required is relatively large; operating the Peltier device from an unfiltered source would have a practical advantage.

An experimental variable conducting heat pipe was designed and constructed. This elegant concept requires no external power source to control lamp wall temperature.

An experimental test station constructed to evaluate the performance of these devices was used to measure the lamp-ballast combination (Figure 3).

A number of important questions regarding the efficiency of heat transfer will be examined during FY 1989. In addition, a study of the limitations of using rectified AC power (instead of DC power) for Peltier devices will be carried out. If the devices can be operated by half-wave or full-wave rectified power, the DC conversion costs could be greatly reduced.

Quality Illumination and Performance

During FY 1988, we completed an analysis of our 17-subject study of the speed of reading unrelated words. The time to read these words was measured with an

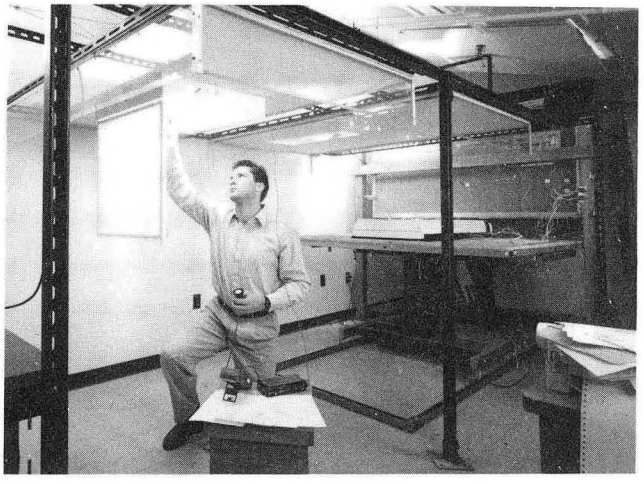

Figure 3. Luminaire laboratory with heat pipe being installed on fluorescent lamp. (CBB 89-345)

eyetracker that could determine fixation time as well as the time for a saccade. The contrast, luminance, and size of the words was controlled and varied over ranges typical of office work. The analysis showed the remarkable result that the reading speed data could be solely a function of the ratio of letter size to threshold size; the dependence on contrast and luminance occurs only through their effect on threshold size. The results indicate that a useful and simple field test can be made available to determine if a given individual has adequate illumination (or contrast) for any given reading task.

The work is currently being prepared for journal publication and for the 1989 annual meeting of the Illuminating Engineering Society.

Additional efforts on improved cost-benefit techniques have been pursued. A new model of basic visual performance shows promise of overcoming the criticisms leveled at the models by Rea and by Blackwell.

Computer Imaging

The RADIANCE modeling system was ported to the SUN workstation in FY 1988. "Alpha" test versions of the RADIANCE program were released to selected faculty and students at UCB Schools of Architecture and Optometry and to the University of Michigan Architecture Department to solicit comments and feedback from users. In 1988, RADIANCE was validated against Superlite and against daylit scale models composed of diffusely reflecting surfaces. Further validation needs to be carried out with physical measurements of specular and semi-specular materials under artificial light. A three-dimensional editor has been developed on the Macintosh and was ported to the X-windowing system on the SUN workstation. Additional utilities to improve program usability were also added.

Effort in 1989 will be devoted to completing the verification of RADIANCE accuracy by comparing calculations with empirical measurements from both scale and full-size models.

In addition, a lighting design firm will be selected to work with LBL, using RADIANCE software to design a complete energy-efficient lighting system.

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 lacking, especially to ascertain whether new energy-efficient technologies adversely affect human health and productivity.

Performance and productivity may be influenced by lamp electronics and associated controls, fixtures, 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 these 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 two areas: 1) direct effects of lighting on the human autonomic system (carried out at University of California, San Francisco and LBL); and 2) interactions of lighting that affect visual performance and productivity or comfort (carried out at the UC School of Optometry and LBL), which are termed here "lighting ergonomics."

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. Behavior 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 psychological factors are the likely cause of reported effects. A second set of experiments using infrared pupillometry has, however, demonstrated that the spectral response of the pupil at typical interior light levels is the scotopic spectrum and thus that red photoreceptors are active at these light levels.

The second area of this program primarily studies issues of glare and flicker resulting from lighting systems.

Present knowledge and prescriptions by the lighting community for dealing with glare are based on subjective responses without support by objective criteria. It is reasonable to implicate pupillary responses as relevant to glare discomfort because pain receptors are present in the iris, and the nervous pathway necessary to signal pain is present in the fifth trigeminal cranial nerve. Some studies by vision scientists have suggested pupillary response as a possible objective correlate to the sensation of discomfort, but this conclusion is not generally accepted in the vision community. We have undertaken a series of studies to

clarify the possibility that pupillary dynamics can be used as an indicator of glare response.

Visual system responses to the oscillating light levels pervasive in our interior environments has also been implicated in many anecdotal reports. The program has undertaken a series of direct physiologic measurements to investigate whether such responses can be established.

Direct Effects of Lighting on the Human Autonomic System

The first phase of work on brightness perception has been completed, clearly demonstrating a significant contribution of scotopic spectrum to brightness as perceived by subjects in a room. This result, coupled with our previous finding showing the scotopic spectral response for pupil size, implies that under typical interior light levels, vision function is mesopic, i.e., both rods and cones of the retina are active. Our present experiments are consistent with a brightness function expressed by the equation $B = \log P + 0.9 \log S$, where B is the perceived brightness while P and S are the values of the viewed photopic and scotopic luminance. The significance for energy efficiency demonstrated by this equation can be seen by comparing warm white and daylight fluorescent lamps of equal wattages, in which case the daylight illuminant will appear twice as bright. The value of 0.9 in the above equation has some uncertainty, and the second phase of this effort (to be accomplished in 1989) will determine more precisely the quantitative mix of photopic and scotopic spectrum that correlates with perceived brightness.

The most compelling demonstration of rod contribution to brightness perception will be shown by the pupil stimulator. This device, under development at LBL, will allow brightness comparisons to be made with periodic time, varying luminances where the oscillation rate can be adjusted to occur below and above the rod fusion frequency. Currently, the instrumentation is undergoing revisions and the system optics are being altered in order to incorporate the new, more intense light sources. These new light sources will allow a much better focusing capability into the fiber optic system that was not very efficient with the previous choice of light source, i.e., the tungsten halogen lamps. The construction is expected to be completed during FY 1989.

The effects of pupil size on visual performance are being studied by observing the contrast sensitivity of subjects. The experimental protocols have been established and the software developed to allow the equal-luminance double grating to appear simultaneously on the TV screen. Subjects will then choose which of the two presentations is the grating, i.e., only one side of the rectangular page projected will actually be a vertical grating (the other will simply be a uniform equal-mean-luminance rectangular patch). Figure 4 shows the chamber at the UCSF laboratory where the pupil measurements are performed.

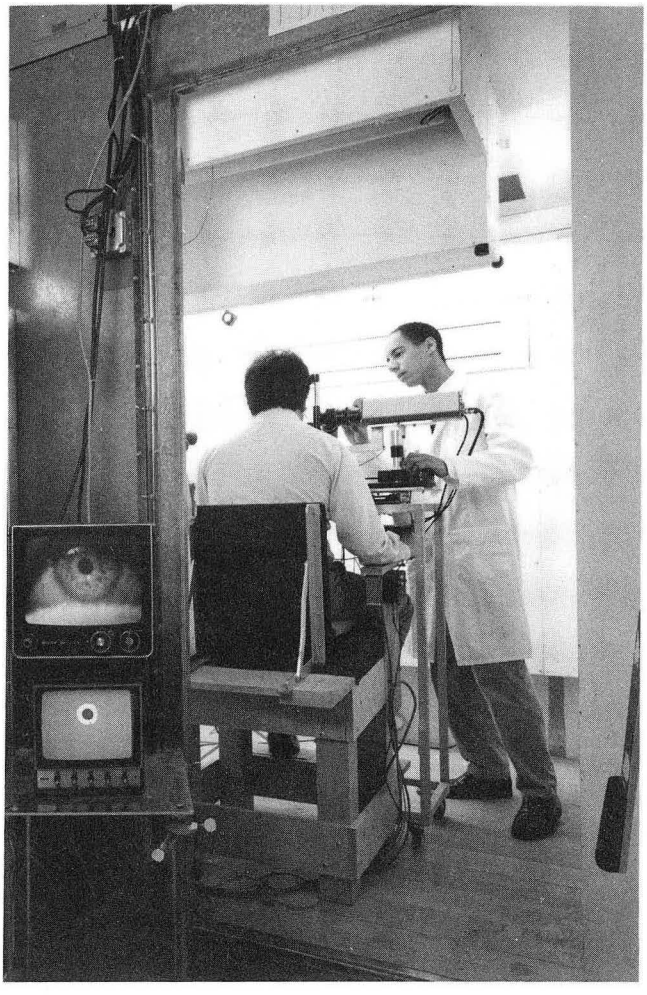

Figure 4. Subject seated in lighting test chamber is being prepared for pupil measurements by remote infrared pupilometry. (CBB 870-10637)

Lighting Ergonomics

Discomfort Glare Studies

We have completed experimentation on the frequency spectrum of pupillary unrest (hippus) under conditions of the absence of discomfort glare and in the presence of discomfort glare where the light levels were set to provide equal mean pupil area. This condition is achieved by producing the pupil size with a bright but large area source while the discomfort glare condition is achieved with a small, intense glare source in a relatively low-level uniform surrounding. The frequency spectrum is then determined by Fourier transform of the time, varying pupillary unrest and the two lighting conditions compared. The results show no observable differences in spectrum shape

or intensity. Our conclusion is therefore contrary to previous results and claims that argue for a difference on the hippus spectrum.

Experiments planned for FY 1989 will test the hypothesis that pupillary response is associated with the sensation of discomfort glare. A pilot study on the influence of color on discomfort glare showed that for small geometric sizes of the glare source, the sensation of discomfort had a definite spectral response, with the more blue or red portions of the spectrum being more efficacious in eliciting the discomfort. This preliminary result is consistent with brightness perception for small sources. This is the first known controlled effort on the spectral response of discomfort glare, and this effort should give lighting designers and users useful information about this form of glare. The effort is anticipated to be completed during FY 1989.

Electroretinogram Studies of Flicker

Microelectrode studies in the cat visual system as well as visual evoked potential and electroretinogram (ERG) studies in humans have demonstrated synchronous responses to periodic time-varying stimuli at frequencies higher than human perceptual fusion. We have determined the time-averaged ERG responses of two human subjects who viewed text on a visual display unit (VDU) at typical values of luminance and contrast. The refresh rate of the VDU was varied in 5 Hz increments between 46 and 81 Hz. In addition, we measured the ERG response in one subject with intense flickering light, provided by a projector and rotating sector disc, to examine whether synchronous ERGs could be obtained at frequencies as high as those found to produce responses in the cat eletrophysiologic studies (100-120 Hz). For the VDU stimulus, we found clearly identifiable synchronous ERG responses at refresh rates as high as 71 Hz. Synchronous responses to the more intense source were clearly evident at frequencies as high as 162 Hz. Figure 5 shows subject with the electroretinogram lens in place.

A further study was initiated to examine whether this subject would show an ERG response when directly viewing a two-lamp fluorescent light fixture. Fluorescent lamps conventionally operate on line frequencies of 50 Hz in Europe and 60 Hz in the United States and provide light output that is modulated and oscillating at twice this line frequency. At these "high" frequencies, any consequencies of "flickering" light level have been presumed to be absent because the oscillation rate is above that perceivable by humans. However, the subject showed a direct physiologic response to fluorescent lamp modulation in terms of synchronous retinal responses in electroretinogram measurements at frequencies even higher than the 120 Hz oscillation rate. Thus, there is some evidence of responses to light oscillation even though they are not directly perceived. Whether such responses could be related to the reported symptoms of headaches and eyestrain remains to be established. The studies are now being prepared for submission for publication in the vision science and lighting literature.

Figure 5. Close-up view of subject with electroretinogram lens inserted into left eye. Lens consists of a circular wire on a contact plastic on the cornea and a silver speculum resting against the sclera. (CBB 876-4387)

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