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Windows and Lighting Program - 1989 Annual Report

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Windows & Lighting Program

1989 Annual Report

Applied Science Division

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Windows & Lighting Program
1989 Annual Report

Stephen E. Selkowitz, *Program Leader*

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- **WINDOWS & DAYLIGHTING GROUP** — *SE SELKOWITZ, Leader; JH KLEMS, Deputy; MD RUBIN, Deputy; CM LAMPERT*
  - OPTICAL MATERIALS
  - FENESTRATION PERFORMANCE
  - BUILDING APPLICATIONS
- **LIGHTING SYSTEMS RESEARCH GROUP** — *SM BERMAN, Leader; RR VERDERBER, Deputy; DD HOLLISTER; DJ LEVY*
  - LAMP TECHNOLOGY
  - IMPACTS
  - LIGHTING CONTROLS

April 1990

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Contents

More than 30% of all energy use in buildings is attributable to two sources: windows and lighting. Together they account for annual consumer energy expenditures of more than $50 billion. Each affects not only energy use by other major building systems, but also comfort and productivity—factors that influence building economics far more than does 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. Throughout the indoor environment, lighting systems facilitate a variety of tasks associated with a wide range of visual requirements while defining the luminous qualities of the indoor environment. Windows and lighting 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) improve building designs so that they effectively apply existing technologies and extend the market penetration of these technologies; and 2) develop advanced technologies that 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, and continue to do so through the ongoing research summarized here.

The **Windows and Daylighting Group** focuses on the technical aspects of understanding and improving the energy-related performance of windows. If, for example, 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 thereby provide net energy benefits to the building. The group's investigations are designed to develop accurate systems for predicting 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 encountered 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 using the Mobile Window Thermal Test Facility (MoWiTT), now collecting data at a field test site in Reno, Nevada. This unique facility combines the accuracy and control of laboratory 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.

Studies in building applications 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.

Research of the **Lighting Systems Research Group** is divided into three areas: advanced light sources, building applications, and impacts of new lighting technologies 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 technical approaches leading to major improvement in fixture efficiency, effective use of lighting controls, and how these factors interact with a building's heating, ventilating, and air-conditioning (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 research in electric lighting 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 two-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 & Daylighting —

S.E. Selkowitz, D. Arasteh, C. Benton, D.L. DiBartolomeo, G. Kelley, J.H. Klems, C. Lampert, K. Papamichael, M.S. Reilly, M.D. Rubin, J. Schuman, R. Sullivan, J. Warner, G.M. Wilde, M. Yazdanian

Approximately 20% of the energy consumed annually in the United States is used 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 related 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; thermal and visual comfort of building occupants; and human 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 tools and technologies necessary to accomplish this goal. Research is required for developing new technologies and systems that will 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.

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 collaborate with researchers in industry and academia.

To be useful, the technical data developed by our program must be communicated to design professionals, to industry, and to 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

Highlights for each major project area are described in the sections that follow.

OPTICAL MATERIALS

Significant reductions in energy consumption of buildings will come from the development and introduction of new high performance 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. Incorporating low-E coatings into conventional double-glazed windows produces a lighter, more compact unit showing better thermal performance than that of tripled-glazed windows. First introduced commercially in 1982, low-E coatings are used today in more than 20% of all residential 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 can the best-insulated wall.

Durable Low-Emittance Coatings

The objective of this project is to develop a second-generation low-E coating that is durable enough to be used for retrofit applications. We have been testing various protective layers for a silver-based composite coating. Last year we began fabrication of sputtered diamond-like coatings and succeeded in greatly increasing their optical transmittance. This year we investigated some of the mechanical properties that will affect long-term durability. Although these coatings can be very hard, this property is useless if the coatings do not adhere well to the substrate. These films are highly stressed, a factor that may cause delamination. Stress has been determined by measuring small changes in curvature of the sub-

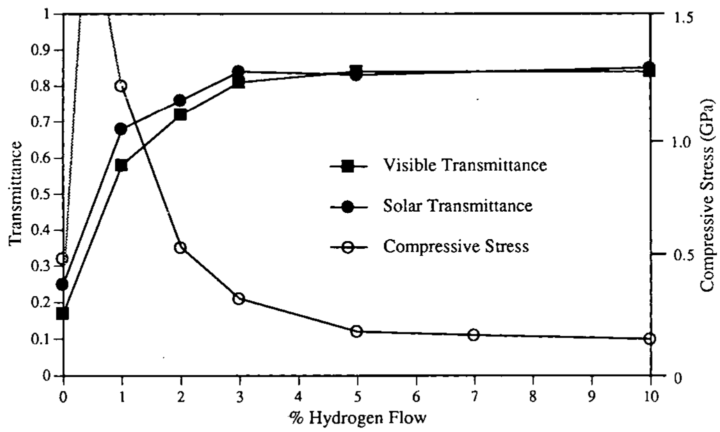

Figure 1. Compressive stress leading to delamination is reduced and solar/visible transmittances increased as the hydrogen flow rate is increased in the deposition of sputtered diamond-like carbon films. (XBL 903-767)

strate. Figure 1 shows that increasing the hydrogen content (which tends to increase transmittance) decreases stress. In 1990, optical properties will be further improved through the use of ion-beam excitation.

Low-Conductance Glazings and "Superwindows"

Window manufacturers have successfully commercialized windows that incorporate low-emittance (low-E) coatings and low-conductivity gas fills. These units have center-of-glass R-values between 3 and 4 hr-ft^2-F/Btu. In 1985, we initiated an effort to develop the technology base for the next major advancement in insulating windows (R6-10). Such windows will have a glazing unit with a third glazing layer, a second low-E coating, and an optimized (krypton or krypton-argon mixture) gas fill (Fig. 2). To achieve the best thermal performance for the entire window, however, modifications must be made to conventional window edge and frame designs to reduce heat transfer in these areas.

This year we worked with three major window manufacturers to produce prototype R6-10 "superwindows." These prototypes were installed in utility test homes in Montana and are being monitored until March 1990 (Fig. 3). Laboratory test results and preliminary field test data show the expected results: very low heat transfer rates through the center-of-glass areas but significant thermal bridges at the edges. One prototype superwindow was field tested in the Mobile Window Thermal Test Facility (MoWiTT) in Reno and compared to an insulated wall. Our measurements on this north-facing prototype demonstrated that superwindows are capable of producing an average daily winter energy performance comparable to that of an insulated wall (Fig. 4). Because north is the most unfavorable orientation for a window in wintertime, this measurement establishes the contention (hitherto based on theoretical calculation) that properly designed and installed windows can outperform insulated walls on an average daily basis during wintertime. Additional superwindow tests in MoWiTT will be conducted in 1990.

Current work and planned 1990 studies are aimed at reducing the thermal bridge effect. A detailed finite element model is being used to study the critical design and materials options that influence performance of the edge and frame. A video-based infrared imaging camera will be used to validate the computer models. The long-range goal is to develop a rapid, cost-effective technique using the IR camera to determine thermal properties of the edge and frame.

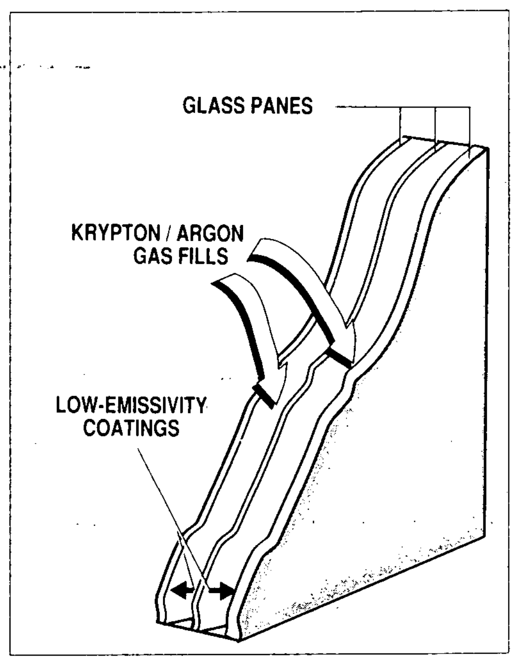

Figure 2. In a new highly-insulating window rated R-9 at the center of the unit, two outside glass panes with low-emissivity coating on the inside are separated from a third pane by gas-filled layers. (CBB 899-8973)

Figure 3. A conventional energy-saving window (left side of figure) is indistinguishable from a prototype superwindow (right side of figure). (CBB 903-1601)

Optical Switching Devices

Optical switching devices can be used to dynamically control the daylight and solar transmission of windows in buildings, in automobiles, and in aircraft. Energy simulation studies of office buildings and automobiles indicate that controlled switchable devices can provide substantial energy savings and reductions in peak loads. Other potential benefits include reduced size of HVAC systems and greater thermal and visual comfort. The most widely studied chromogenic materials are photochromic, dispersed liquid crystals, and electrochromic technologies. Electrochromic devices have the best combination of properties for window applications. They have the potential for a wide dynamic range switching between 10-80% visible light transmission, have moderately fast switching times, and consume little power.

During 1989, we modeled the energy performance of switchable glazings to better define the desired optical characteristics of advanced windows. Using a modified version of the WINDOW 3.1 computer program, our modeling work has shown that the coating placement within the window and the use of complementary, spectrally selective coatings can significantly improve the overall performance of the window. We may therefore be able to relax some of the optical criteria for the electrochromic layer and still provide an energy-efficient optical response. In our materials research, we have studied new component layers for nickel oxide-based electrochromic devices (Fig. 5). The primary device materials are the electrochromic layer, the ion conductor or electrolyte layer, and the ion storage layer. In prior years we produced good-quality electrochromic nickel oxide using an electrodeposition process to produce doped and undoped nickel oxide coatings. We concentrated on producing nickel oxide by using new deposition techniques including sputtering, vacuum evaporation, and sol-gel methods,

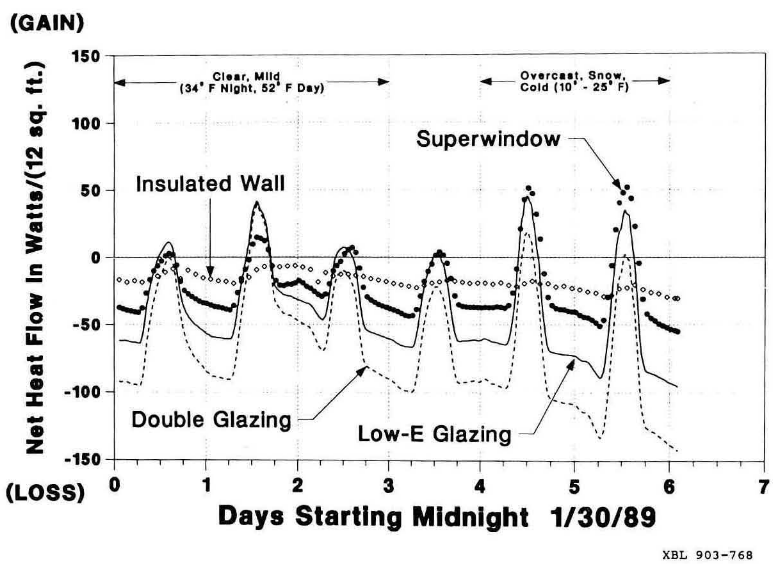

Figure 4. Comparison of a North-facing superwindow with an R-15 insulated wall in Reno, Nevada. Calculated values for conventional double-glazed windows and low-E windows are shown for comparison. (XBL 903-768)

both at LBL and in collaboration with an industry partner. Coatings are characterized by a variety of techniques involving electron microscopy and surface science analysis. In 1989, we expanded our study of reactive sputter-deposited ion-storage metal oxides to include manganese, cobalt, niobium, and vanadium oxides. Films were analyzed by cyclic voltammetry, optical spectroscopy, and surface science techniques. We refined the characteristics of our quarternary ammonium hydroxide polymer electrolyte layer to be more adherent and to exhibit less visible absorption. In collaboration with researchers from five other countries (under the auspices of an International Energy Agency Task Group), we helped develop and refine test methods for electrochromic devices.

Our research in 1990 will emphasize fabrication of complete electrochromic devices. Two major device designs will be studied: a laminated type (using a polymer or other material for the ion conductor) and an all-solid-state device. Development of improved ion storage layers and alternative electrolytes will continue as needed for device construction. Studies of the impacts of electrochromic windows on energy, load shape, and peak demand as a function of climate will be continued using a modified version of the DOE 2.1 building energy modeling program.

Core Daylighting System Design

Outdoor illuminance levels under clear skies are typically 100 times greater than required indoor illuminance levels. If only 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 luminaires providing light at other times. Several prototypes for core daylighting systems have been developed, but these systems are not cost effective on the basis of their energy savings. Our objective has been to develop designs that use cost-effective optical technology to supply daylight to core building zones. 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 coupled to a hollow light-guide system with a fiberoptic link. Engineering analysis of key optical elements and subsystems has been completed so far; the next step will be to fabricate and test a prototype system. Collaborative funding arrangements will be sought in 1990 to carry out this phase of the program.

Automobile Glazings

Automobiles are being designed with greater amounts of glazing for improved aerodynamics, field of vision, and aesthetics. The additional solar heat gain, however, places a higher load on the air conditioner and thus increases fuel consumption, causes occupant discomfort, and requires larger air conditioners with greater cooling capacity. Automotive air conditioners are a major source of chlorofluorocarbon emissions, which deplete the vital ozone layer of our atmosphere. In prior studies for EPA, we determined that improved automotive glazings with selective spectral transmittance coupled with venting could reduce air conditioner size by 50%. Figure 6 shows the effect of optical properties on interior air temperatures. With support from the Office of Transportation Systems, U.S. Department of Energy, we have begun to develop highly selective, durable solar-control coatings that reject the maximum amount of heat while maintaining optimum visibility. In 1990 we will expand our exploration of electrochromic and angle-selective automotive glazings.

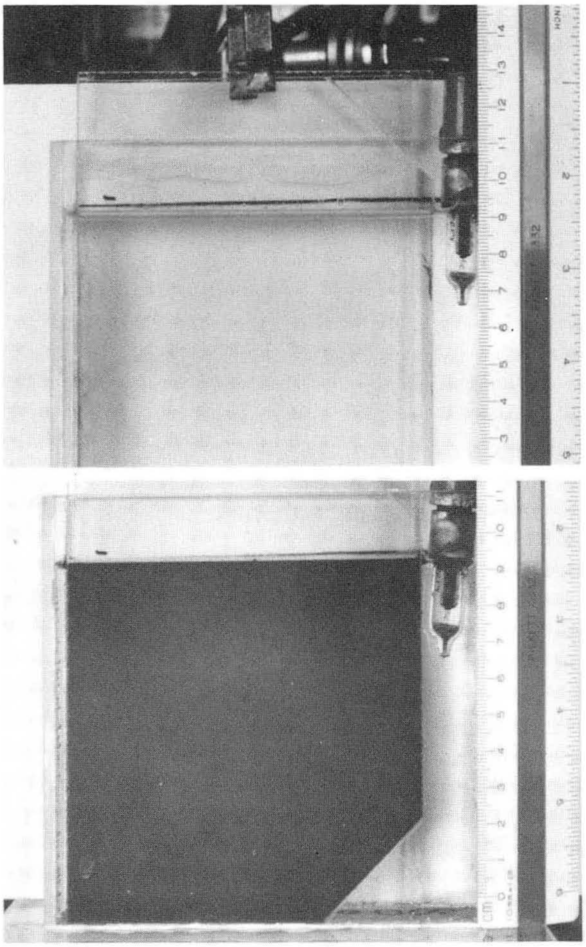

Figure 5. Electrochromic nickel oxide device shown in its colored and transparent states. (CBB 887-6776A)

FENESTRATION PERFORMANCE

Research activities in this area are intended to characterize the performance of fenestration components and of 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 in 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.

Thermal Analysis

With the growing use of low-emissivity coatings and low-conductivity gas fills in window designs, the number of possible window configurations has multiplied dramatically. Beginning in 1986, we released the WINDOW program to industry to serve as a standard tool for calculating the heat transfer indices through different combinations of glazings. The latest version, WINDOW 3.1, was released in October 1988. The software and manual are distributed free of cost by a manufacturer of window components, and more than 2000 copies of the program have been distributed to date. We have worked closely with individuals and manufacturers interested in modeling new products by customizing the software for their particular application. This customization accelerates industrial efforts to further upgrade window design and performance.

This year we improved some of the window algorithms relating to the spectral and angular dependencies of glazing materials and to two-dimensional heat transfer around window edges. Edge and frame analysis in WINDOW uses a data library of predetermined values. These values are being derived with the use of a finite element modeling program (Fig. 7). Further exploratory studies with finite-element modeling are planned for 1990, including use of an infrared camera to validate model predictions and to improve calculation techniques.

A complete methodology is needed to accurately predict thermal and solar-optical properties of all fenestration systems. The WINDOW program will be an integral part of this methodology. A first draft of this evaluation procedure has been circulated to industry for review and comment. We anticipate that this procedure might be used by the newly formed National Fenestration Rating Council, a broadly based group whose mission is to develop an accurate, credible system for rating window performance. A number of states and utilities intend to develop "window energy labels" to encourage the specification of more energy-efficient windows. A credible, objective rating procedure is an essential prerequisite for such labeling programs.

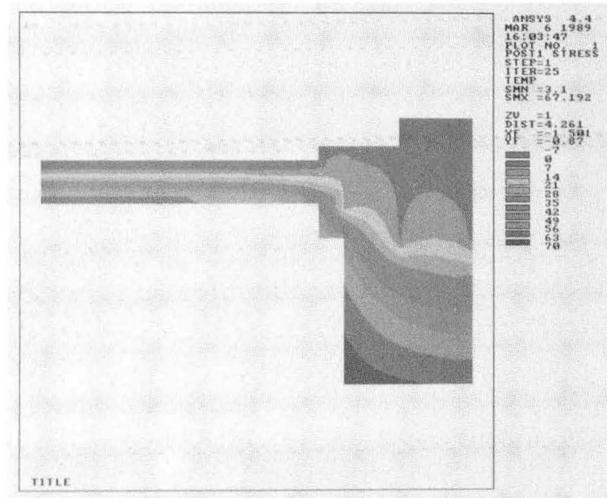

Figure 7. Finite element modeling (FEM) is used to analyze two dimensional heat transfer through window edges and frames. (SBC 890-9676)

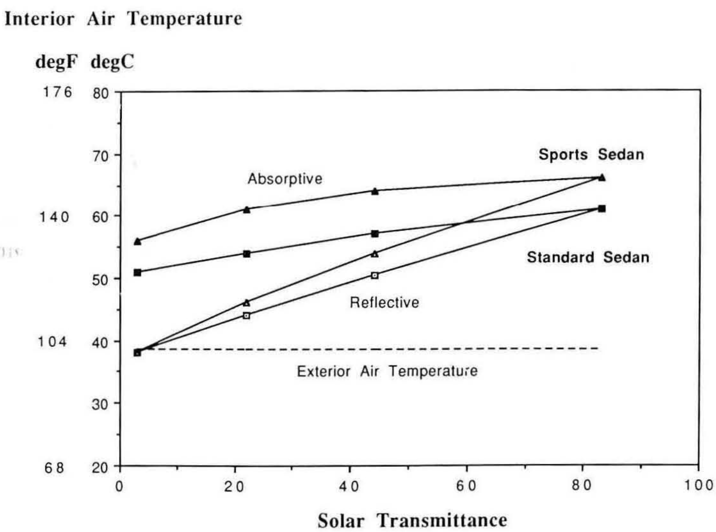

Figure 6. Peak interior air temperatures for standard and sports sedans as a function of solar transmittance. Values occur at 3 pm and are shown for reflective and absorptive glazings. (XBL 903-769)

Studies of Daylight and Solar Heat Gain

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 a cost, depending on circumstances. Analyzing the tradeoffs to arrive at an optimum solution for simple glazings is difficult; for complex fenestration with sophisticated sun control systems, this solution is virtually impossible to find using currently available tools. Our objective is to develop experimental facilities and analytic models that can 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 for accurately predicting their luminous and thermal performance in 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 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 drapes, bidirectional solar-optical property measurements are necessary. We have developed a large-scale, automated scanning radiometer/photometer to make these measurements (Fig. 8). 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 1989, we continued a cooperative project with support from DOE and ASHRAE to make this method the basis for a new treatment of solar heat gain through fenestration. Scanning radiometric 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).

We also used the MoWiTT to measure the inward-flowing fraction of absorbed solar energy. This technique is providing the first detailed measured values for heat-transfer coefficients between layers of complex fenestration systems such as a venetian blind with multiple glazings. These measurements are necessary for realistic modeling of energy transfer through windows with shading devices—i.e., most windows in the United States.

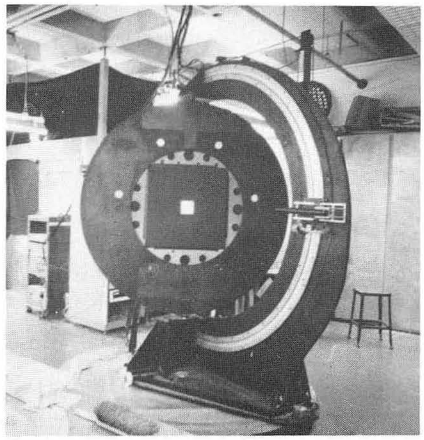

Figure 8. Scanning radiometer for measuring the bidirectional transmittance and reflectance of fenestration components and systems. (BBC 887-6823)

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 to improve calculational accuracy. Further improvements have been made to our daylighting simulation program, SUPERLITE, to allow it to model more sophisticated daylighting systems such as complex sun-control systems and shading systems. This work includes developing and upgrading algorithms for modeling as well as initial efforts to create a photometric database containing complex optical properties of shading systems as required by SUPERLITE. (Related work on measurement of these properties was discussed earlier; see Daylight and Solar Heat Gain Studies.) SUPERLITE was selected by an International Energy Agency (IEA) task group as the primary tool for a multinational daylighting research effort.

In 1990 we will complete a version of SUPERLITE that will model advanced glazings and electric lighting. Further collaborative work with the IEA group and with other university-based groups will attempt to improve the ease of use of the microcomputer version of the program and to enhance its input/output capabilities.

Lockheed Monitoring Project

We completed Phase II of an investigation funded by the Pacific Gas and Electric Company into the performance of the electric lighting control system in a large (500,000 ft^2), innovative, daylighted office building. The first phase of the study, conducted in 1985, identified operational shortcomings in the electric light control system and concluded that without modifications to the control systems, this daylighted building would not realize the substantial electrical energy savings made possible by its innovative design features. During Phase II we designed revisions to the electric lighting control system, implemented these changes in a representative zone of the building, and monitored the year-round effectiveness of the new control scheme. Our thesis was that low-cost modifications to the existing control system (primarily sensor relocation and recalibration) would produce immediate dividends in reduced power demand and in lower electrical energy consumption.

To test our control revision hypothesis, we installed four data-acquisition systems in the test zone. Analysis of these detailed illuminance and lighting energy data over the year indicates that our remedial actions were highly successful in establishing proper operation of the electric light dimming system. The revised system accurately maintains target interior illuminance with minimum electric energy consumption. We estimated annual average lighting system energy savings to be over 50%, with more than 60% reduction in lighting peak demand (Fig. 9). We plan to conduct further cooperative projects with utilities to demonstrate the potential performance of daylighting systems.

The Sky Simulator and Daylight Photometric Laboratory

Scale-model photometry is a powerful tool for daylighting design and analysis. Our 24-ft hemispherical sky simulator (Fig. 10), 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 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. A major effort will be initiated in 1990 to repaint the dome, to upgrade the lighting system, and to recalibrate the entire photometric data-collection system.

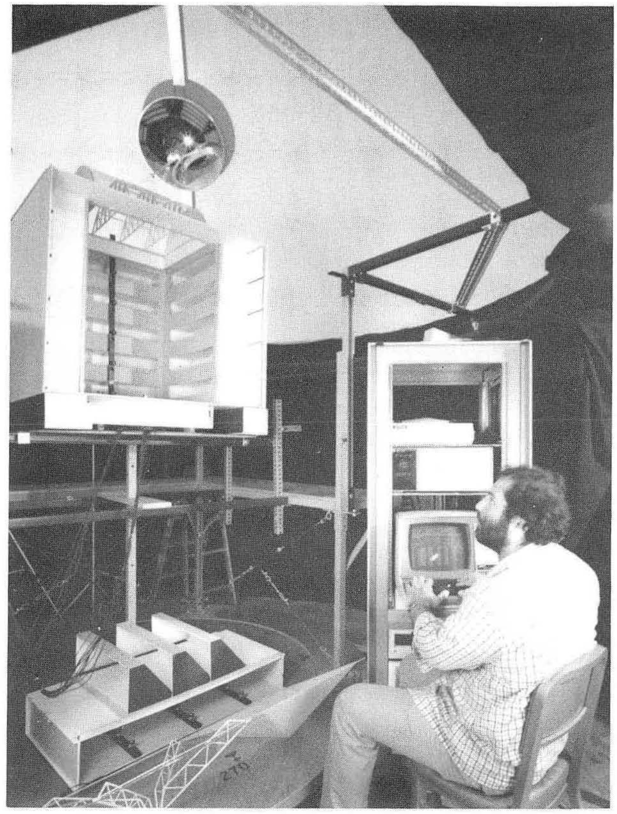

Figure 10. Interior of sky simulator shows reconfigurable scale model of a five-story atrium (one side of model has been removed). (CBB 848-5926)

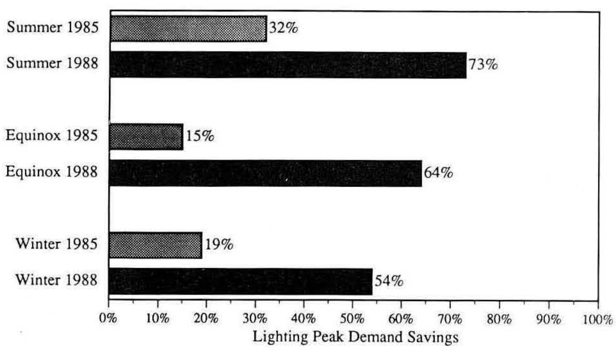

Figure 9. Lighting energy savings were significantly increased throughout the year in the retrofit zone (1988) compared to initial building operation (1985). (XBL 903-881)

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 for any orientation in any U.S. climate, it is technically possible to optimize windows so that they positively contribute to a building's energy needs.

This claim is not likely to be widely accepted without firm experimental verification. Measuring the performance of highly optimized window systems in a realistic way is a formidable measurement task, however, 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. 11), it was necessary 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 solar fluxes and changing outdoor temperatures, both of which control the behavior of a fenestration system. We solved this problem by using 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 1989, we began work on a joint U.S./Canadian study of nighttime energy-loss rates (U-values) in windows. The intent of this study is to determine the extent to which computer model calculations and laboratory U-value measurements are consistent with field-measured thermal performance of windows. Preliminary results have indicated that exterior film coefficient values (which must be arbitrarily fixed in laboratory measurements or computer calculations) are a significant source of uncertainty for currently marketed windows. For higher-performance windows, this becomes less important and heat losses attributable to frames and glazing edge spacers become correspondingly more important.

During 1990 we will continue our active field-test program in support of the U.S./Canadian project and will complete the inward-flowing fraction measurements for the Solar Heat Gain Project. We also expect to begin testing emergent window technology with support from the fenestration industry. Industry is interested in field-test data from MoWiTT to guide development of new products and designs. These field measurements from 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

In order to reduce national energy use, new glazing materials and new data on the performance of fenestration systems must be properly used by building designers. Our objective in the applications area is to apply to real buildings the knowledge gained from our basic research and to develop the tools necessary to disseminate and utilize this information. We use computer-based simulation studies to help understand the performance of fenestration in buildings and then use this understanding as the technical basis for design tools that can be readily applied by a variety of user groups.

Simulation Studies: Nonresidential Buildings

Our goal is to develop a microcomputer-based fenestration performance design tool. A methodology for analysis and design had previously been developed in a project jointly supported by the Lighting Research Institute and DOE. We have continued developing a prototype design tool, emphasizing issues of user interface. The results were summarized in a paper, "Development of a Methodology to Evaluate the Energy and Comfort Performance of Fenestration," that was presented at the Building Simulation '89 Conference in Vancouver, Canada. Investigations were conducted on the use of color, multiple windows, and animation in the computer-based design tool environment. Recent software/hardware advances have facilitated these studies. We conclude that such methods significantly enhance the usefulness of computer-based tools.

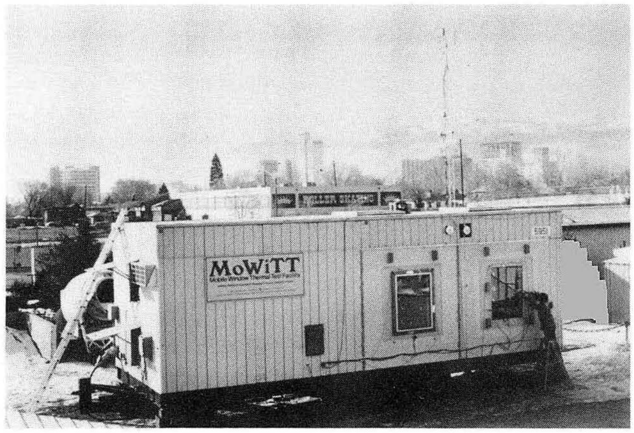

Figure 11. The MoWiTT facility at its field test site in Reno, Nevada. Two sealed insulating glass units are mounted in the two calorimeters. (CBB 892-812)

A Daylighting Manual for commercial buildings, similar in scope to the Skylight Handbook completed two years ago, was developed for Public Works Canada in collaboration with Charles Eley Associates. DOE-2 parametrics for four Canadian cities and subsequent regression analysis yielded simplified algebraic expressions that were used in a microcomputer spreadsheet template to complement the text-based handbook (Fig. 12).

In 1990 we will continue our efforts to develop a microcomputer-based design tool. We intend to pursue two parallel options: 1) development of a spreadsheet template for U.S. locations (similar to the one developed for Canada) for a tool that will run on widely available PCs; and 2) a tool that uses state-of-the-art user interface techniques and expert systems for the current generation of more powerful microcomputers. The technical database for each of these tools will be similar and will include sets of regression coefficients from DOE-2 building energy simulations as well as comfort indices.

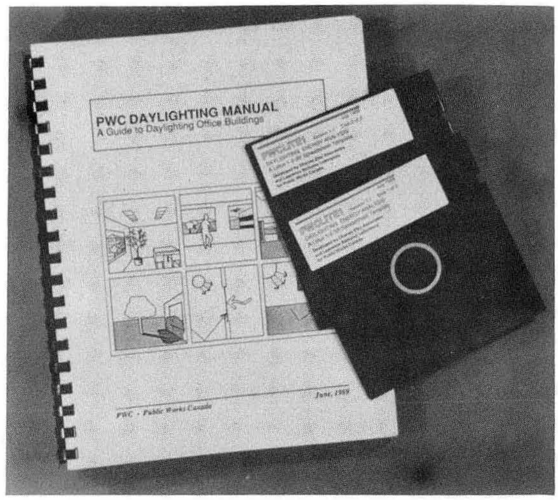

Figure 12. Daylighting Manual and microcomputer spreadsheet template for commercial buildings. (XBB 903-1760)

Simulation Studies: Residential Buildings

Our residential work has concentrated on developing new methods of documentation so that home builders and others in the design community have easy access to our research efforts. As part of this effort, we have gathered information from homebuilders to ascertain their opinions regarding the types of information that would be most useful to architects, engineers, builders, and homeowners. This information will assist us in completing the first version of a Residential Window Design Handbook. This handbook will present guidelines for the use of fenestration systems and will include a simplified computer-based methodology for predicting energy performance for several geographic locations. The simplified methodology will serve as a prototype for a more comprehensive design tool to be developed in future years.

We also have completed a technical note on condensation issues in window systems. This document will be used as a chapter in a handbook on moisture being prepared for builders by DOE. The data presented in this note will be revised to take advantage of recent technological changes such as the availability of the WINDOW-3 program and the ANSYS finite-element computer program. These programs enable more accurate prediction of condensation onset than was previously available.

Design Tools and Technology Transfer

To influence energy consumption trends in the United States, our results must be communicated to other researchers and to professionals in the building industry. We use a variety of media to reach a widely varied audience and are developing more effective approaches to technology transfer by experimenting with new electronic and optical media. Our primary audiences include other research and development groups, professional and industrial societies, manufacturers, and educational institutions. We continue to develop improved design tools and handbooks, to carry out design assistance studies, and to sponsor workshops and meetings with manufacturers, design firms, educators, and utilities.

In 1989, we hosted more than 50 visits to LBL by individuals and groups; in addition, sabbatical visitors from Israel, Japan, and Norway made technical contributions to our work. The international perspective afforded by these interactions is useful at a time when energy, economic, and environmental issues are increasingly viewed as global concerns. The group's commitment to technology transfer was recognized by several awards in 1989. Group members received three 1989 Technology Transfer Excellence Awards as a part of LBL's new program to recognize outstanding technology transfer. Members of the group also received a Research Citation from the 39th Annual Progressive Architecture Awards program for development of the Skylight Handbook and Design Guide.

With DOE and LBL support, we explored the potential for adopting advanced electronic and optical media for more effective technology transfer and research utilization. Read-only optical disks (CD-ROM) can provide low-cost access to vast amounts of information. We promoted the use of CD-ROM databases as a mechanism for distribution of Department of Energy design data and analysis tools. We developed a concept for a state-of-the-art electronic information kiosk that provides interactive access to a qualitative and quantitative database. Southern California Edison funded an exploratory project to develop a prototype interactive kiosk (Fig. 13) on energy efficiency for use in their new Customer Technology Application Center (CTAC). The kiosk features information for architects, engineers, builders, and developers. It consists of a personal computer with touch screen linked to a videodisc player. This prototype will be completed and evaluated in 1990.

Figure 13. This prototype model of a computer-based interactive information kiosk was used in the development of projects for Southern California Edison and for the U.S. Department of Energy. (CBB 902-1127)

Advanced Design Tools: Building Design Support Environment

Over the past year, we produced and demonstrated a prototype hypermedia-based design tool which we call the Building Design Support Environment (BDSE). The BDSE is a framework for computer applications that will assist designers in incorporating energy conservation into all aspects of building design, construction, and operation. The tool uses a multimedia computer system with hypertext, graphics, still and moving video images, sound, and animation. The current development platform (Fig. 14) is a microcomputer linked to an optical disc player.

Expert system modules are under development for the BSDE. A model has been developed to systematically formulate rules for the knowledge base(s) and will be tested in a prototype knowledge base for the design of fenestration systems. We videotaped and analyzed sessions with experienced consultants and designers to test knowledge acquisition procedures. We then identified appropriate expert-system shells that will allow us to link the knowledge base with the multimedia and with the simulation modules of the BDSE.

Our prototype tool was highlighted at the American Institute of Architects 1989 Annual Convention. The response of the design community at this and other presentations confirms our belief in the value of this approach to new design tools.

Figure 14. Development platform for the Building Design Support Environment. (CBB 901-57)

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— Lighting Systems Research —

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New, efficient lighting technologies and strategies have the potential to save 50% of the electrical energy consumed by our nation for lighting, or about 12% of total U.S. electrical energy sales. Annually, these savings would amount to some 220 billion kilowatt-hours of electricity, valued today at more than 16 billion dollars. The significance of these savings can be appreciated by considering economic projections that predict a doubling of present commercial floor space by the year 2020. The 220 billion kilowatt-hours of saved energy would allow desired lighting conditions for the new space without the creation of new electrical generating capacity; in this scenario, the United States would realize 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 of research activities and transfer of technology to the lighting community (manufacturers, designers, and users). Representing a unique partnership between a national laboratory-university complex and industry, this program facilitates technical advances, strengthens industrial capability, and provides 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 lamps. We are pursuing a variety of ingenious methods for operating lamps at very high frequency without electrodes, attempting to improve efficiency and longevity. In addition, the program is developing comprehensive strategies to optimize the benefits obtained by combining efficient fixtures and 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—research that can lead to innovative new lighting products that improve both energy efficiency and human productivity.

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

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

Since its inception in 1976, the LBL Lighting Program has produced more than 141 reports and publications. These reports, available to the public, document research on 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 School of Optometry (Berkeley campus) and the University of California School of Medicine in San Francisco (UCSF). We highlight here the accomplishments realized in 1989 by each of our three major efforts: advanced light sources, building applications, and impacts on productivity. Activities planned for 1990 are discussed in the highlight descriptions.

ADVANCED LIGHT SOURCES

The work on advanced light sources promotes development of new lamp technology and light sources. 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. Theoretically, white light can be produced at almost 350 lumens per watt; our advanced lamp technology program is developing the engineering science that will help achieve a target efficacy of 200 lumens per watt within the next few years.

In the area of fluorescent lamps, three energy-loss mechanisms are candidates for improvements in efficiency: self-absorption of ultraviolet (UV) radiation, which eventually leads to losses by electron quenching of excited mercury atoms; electrode losses; and energy loss by lamp phosphors in their conversion of UV radiation to visible light. 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.

To improve the efficiency of phosphors, a more efficient phosphor matrix that will convert one energetic UV photon into two or more visible photons is being developed. These concepts could lead to significant improvements in lamp efficacy.

LBL is studying several ways of reducing UV self-absorption. The first is to alter 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 by enrichment with ^{196}Hg, an effort being pursued jointly 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 mercury (instead of natural mercury); other lamp–manufacturing processes would remain essentially the same.

A highly promising mechanism developed at LBL uses a plasma coupling principle that eliminates the need for electrodes. This mechanism 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 energy efficacy approximately 40% greater than that of normal fluorescent lamps; in addition, the surface wave fluorescent lamp operates without starting circuits and should last a long time because of the absence of electrodes.

Reducing the causes of energy loss in the phosphors requires alteration of a lamp's phosphor material. The materials used today convert each UV photon into one visible photon at most. Improving this conversion rate would increase the efficacy of low-pressure discharge lamps. Although a UV photon has sufficient energy to permit conversion into two visible photons, this process must occur quickly if it is to prevent heat-producing collisions. LBL and GTE Lighting are examining technical possibilities with a program in phosphor chemistry, designed to discover whether multiple photon phosphors are feasible.

If these research projects come to technological and commercial fruition, future fluorescent lamps would operate at high frequency without electrodes and would be isotopically enriched and coated with a multi-photon phosphor. Such lamps would have an efficacy of more than 200 lumens per watt more than 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; such operation 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 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

We have continued to make progress in assessing the feasibility of photochemically separating natural mercury to produce mercury enriched in the isotope mass ^{196}Hg. Most of our 1989 effort involved 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 capabilities have been added to the project. These include in situ measurement of reactor performance, which allows 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 analysis of the complete photochemical process that will permit conclusions on the feasibility of enriched mercury lamps as a market product.

Surface Wave Lamp (SWL)

We are continuing to work on determining the optimal parameters of operating this. These parameters include the tradeoffs between three operational factors: frequency of operation, argon pressure, and power loading. In order to accomplish this task, outside vendors fabricated a large variety of lamps. Unfortunately, most of these failed to meet the quality requirements needed to carry out the experimental program. We therefore have established our own dedicated facility which is now producing clean, effective lamps now being studied for optimization (Fig. 1). Additional effort has also been leading to highly improved thermal control for the test facilities. In addition, we have built a system for measuring angular distribution of emitted UV radiation and have compared AC and RF operation of the same lamps. These data are now being analyzed.

In the area of high-pressure surface wave operation, we have designed a new test system that incorporates improved thermal controls, RF shielding, and an entirely new optical system to accommodate the changes in thermal and RF designs.

Initial design of the class E amplifier for the low-pressure surface wave lamp power supply has been completed. A breadboard unit is being fabricated by DAI Company (Boston, MA). When completed, the unit will be tested at LBL.

In order to provide experimental proof of the new in situ method for evaluating the electrode losses of a specific lamp, a new test facility is being built to provide highly accurate measurements of temperature, light output, and voltage.

Electrodeless High-Intensity Discharge (HID) Lamp

We have completed a new system for back-filling spherical lamps 1" and 0.75" in diameter . These lamps 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, we have initiated several techniques. The method offering greatest potential 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 to be developed during 1990.

Isotope Modeling

This project, a joint effort with New York University, has the primary objective of developing of a theoretical model that accounts for the effects of variable isotopic mercury composition on the emittance of a low-pressure discharge. The project's practical goal is to specify the isotope composition that maximizes the emittance. A final report has been drafted and is undergoing minor revisions.

Multi-Photon Phosphors

During 1989, the multi-photon phosphor project was initiated in a joint effort with GTE Lighting. In Phase I, GTE computed the Energy Level Diagram of Willemite by the Scattered Wave Approach. Measurements were made at Brookhaven Synchrotron on two Zn_2SiO_4:Mn samples verified the multiple photon emission (MPE) reported previously by the researchers. MPE in Zn_2SiO_4:Mn starting at less than 11.3 eV was observed. The early rise in quantum efficiency (QE) of these samples is attributed to a modified IBA process, labeled the *impurity–assisted interband Auger* (IAIBA) process.

Using field theoretical techniques, GTE scientists have reformulated the theory of interband Auger transition. On the basis of electronic structures they predicted that ZnO and ZnS phosphors would have multi-photon emission.

The following table lists all of the phosphors that were investigated with QE significantly greater than 1.

Sample	*Maximum QE*
Y_2O_3:Eu	2.4
Zn_2SiO_4:Mn	2.2
YVO_4:Eu	1.6
$Zn_3(PO_4)_2$:Mn	1.6
ZnS:Cu,Ag	1.4
ZnO:Zn	1.2
ZnS:Cu,Al	1.2
ZnS:Ag	1.2

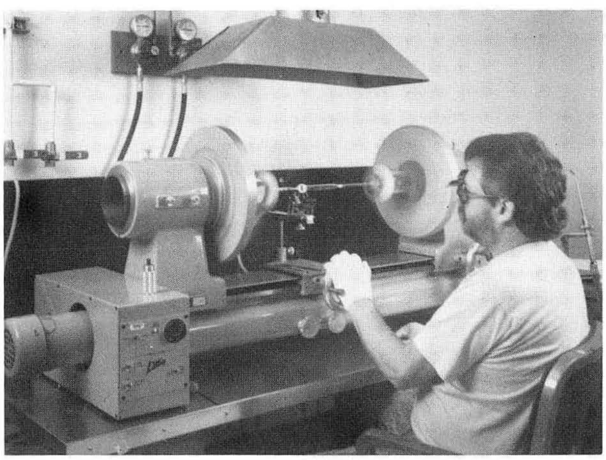

Figure 1. High-intensity discharge surface wave lamp is formed and extruded on high-temperature glass lathe. (CBB 901-343)

The process of cooperative luminescence (originally proposed by Dexter) was also critically reviewed. Using the Brueckner-Goldstone manybody approach, GTE demonstrated that this process can at best be a small, second-order process; the possibility of designing a two-photon phosphor based on a modified version of the cooperative process shows more likelihood of success.

BUILDING APPLICATIONS

Real energy savings depend on transfer of energy-efficient technologies and strategies to the lighting community. Our building applications activities aim to assess and develop energy-efficient lighting technologies and to combine their technical performance characteristics in modeling energy-efficient, cost-effective lighting geometries and controls. Our analysis uses the relationship between visual performance and physical aspects of lighting, e.g., illumination level, distribution, contrast, and glare. As part of this effort, we have developed a computer program that accurately simulates illuminated spaces and their contents. Using the simulated scenes—which are visually indistinguishable from rea' photographs—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, to obtain actual luminance values, we use novel techniques for determining real luminances of interior environments containing complex objects. In the technology development components of this program, discussed below, we examine engineering approaches to reduce lighting losses associated with the thermal and optical factors of conventional lighting fixtures. The culmination of these efforts will be a variety of advanced luminaires, concomitant analysis, and visual simulation of the proposed application—the latter representing the most compelling tool for implementing energy-efficient lighting.

Energy-Efficient Luminaires and Thermal Control Devices

During the past year, we measured the thermal performance of enclosed and parabolic four- and two-lamp troffers. We also studied the effects of optimizing the venting to convectively cool the fluorescent lamps controlling the ambient and plenum temperature. We used a standard two-lamp F40 lamp-ballast system as a baseline for the measurements, which were compared with those for energy-saving magnetic ballasts and electronic ballasts.

In the area of specific devices to control lamp-wall temperature, a major effort has been concentrated on the concept of a liquid thermal bridge as the heat-sinking component. The 3M Company would like to market this concept as soon as the technical research work is completed. To achieve the necessary testing capability, we will design and construct a thermal chamber simulating the geometry, thermal dissipation, and ambient temperature conditions within a fixture. This apparatus will facilitate the parametric testing of different heat sink concepts under controlled conditions. This apparatus will also monitor lamp wall temperatures, ambient temperatures of the fixture, and the electrical and photometric characteristics of the lamp ballast system. Subsequently, we will design and construct a series of heat sink geometries for cooling lamps. These designs will use existing configurations of the liquid heat sink concept. We will also study methods to improve the efficiency of compact fluorescent luminaires, which are at present very inefficient. A range of compact fluorescents systems will be tested measuring minimum lamp wall temperature (MLWT), light output and overall efficacy (Fig. 2).

We have been continuing our efforts to internalize the Peltier device so as to make it an integral component of the fluorescent lamp. The concept makes uses available power at the filaments and involves the design of a power supply integrated with the lamp ballast. Results of the variable inducting heat pipe have been presented at the annual IEEE

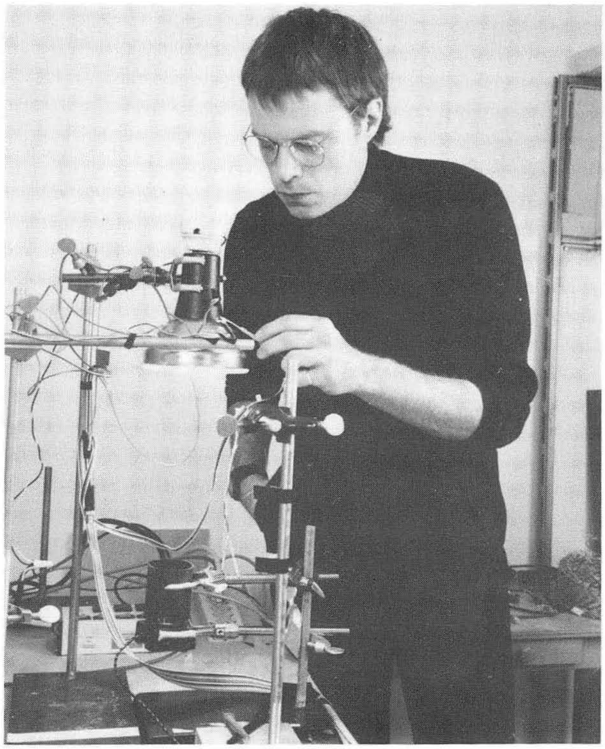

Figure 2. Test system for examining efficacy of compact fluorescent fixtures.
(CBB 901-339)

conference, and a technical paper has been written summarizing the excellent energy efficiency improvement this elegant device can provide.

A new effort during 1990 will be undertaken in the area of expert system development. The difficulty of achieving optimum or nearly optimum lighting solutions argues for an analytical methodology to precisely diagnose the energy performance of an existing lighting system (in the case of retrofit) or to predict the performance of a proposed system in the design phase (for new construction and major renovation markets) while assuring that lighting quality objectives are met. Knowing how the system performs, facilities managers can begin to make well-informed choices for appropriate retrofit measures, and designers can examine alternative design solutions for new construction.

Quality Illumination and Performance

This past year, we introduced a new analysis of our 17-subject study on the speed reading of unrelated words. The time to read these words was measured with an eye tracker that could determine fixation time as well as time for a saccade. Contrast, luminance, and size of the words was controlled and varied over illumination ranges typical of office work. Preliminary analysis showed the remarkable result that data on reading speed could be well fit solely as a function of the ratio of actual letter size to threshold size. Dependence on contrast and luminance occurs only through their effect on threshold size. Our results indicate that a very useful, simple field test can be made available to determine if a given individual has adequate illumination (or contrast) for any given reading task.

The publication of our new model of visual performance (reading speed) has provoked strong reactions, both supporting and contesting the model. The model explicitly predicts the minimum amount of time needed for strictly visual processing. The minimum times on the numerical verification test are considerably longer than this visual processing time. During 1990, we plan to run a simple experiment to see if subjects can improve their reading times by using different processing procedures. A rough test of the idea gave promising results, and a plan for a more formal experiment has been developed. The results of this experiment should help to resolve some of the controversy that has arisen from publication of our model.

Computer Imaging

We are continuing to develop and disseminate a practical, validated tool to predict luminances and visual quality in real workplace environments, as well as to evaluate energy-efficient alternatives. This will be accomplished by incorporating experimentally validated reflectance code for specular and semispecular surfaces into the RADIANCE lighting simulation program. The code will be based on empirical measurements of light interactions with typical interior and exterior surface materials and will modify or replace existing theoretical models. In addition, documentation for RADIANCE will be developed and disseminated at an LBL workshop intended to assist designers in using RADIANCE.

IMPACTS OF NEW LIGHTING TECHNOLOGIES ON PRODUCTIVITY AND HEALTH

Performance and productivity may be influenced by lamp photic output, its electronics and associated controls, fixture type, 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 (i.e., by the lamp, ballast or controls), and flicker. All these factors 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 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 LBL investigations use objective responses to establish cause-and-effect relationships while ensuring repeatability.

The program on lighting impacts is divided into two areas: 1) direct effects of lighting on the human autonomic system (carried out at University of California School of Medicine, San Francisco); and 2) lighting interactions that affect visual performance, as well as human productivity or comfort (carried out at LBL and at the University of California School of Optometry, Berkeley). The second area of study is termed "lighting ergonomics."

Direct Effects of Lighting on the Human Autonomic System

Efforts in the first area of this program have shown that an important aspect of the visual effects of the large variation in lamp spectra in commercially available lighting is to characterize lamps by their ratio of scotopic to photopic luminance. This is because results of our studies have shown that both the rods and cones of the human retina are involved in the vision process at the illumination levels typical of the interior environment. That the rod system is operative at these levels has been demonstrated by a series of studies on human subjects showing that pupil size is predominantly controlled by scotopic luminance and that the perception of brightness depends on both photopic and scotopic luminance.

During the past year, a detailed 12-subject study was performed to determine the precise amounts of both scotopic and photopic luminances that control steady-state pupil size. Earlier studies at UCSF had determined that scotopic luminance was the predominant factor, but these studies could not rule out a small contribution purely photopic in nature, i.e., cone-driven. Improved controls and automation coupled with new experimental protocols enabled us to determine the small photopic contribution. The result defines an effective "pupil lumen" that can be expressed as $P(S/P)^{3/4}$, where P and S are the photopic and scotopic lumens (or luminances) of the given light source. These results were presented at the Biannual International Pupil Colloquium.

During the coming year, we will study subjects to determine the dependence of their visual performance on changes in pupil size varying scotopic luminance but with photopic luminance fixed. Vertical gratings and Landolt C's will be used as targets. A further study will also attempt to determine quantitatively the contribution of photopic and scotopic luminance to perceived brightness. This latter study will be carried out in full field of view with the relative scotopic and photopic luminances provided by ballasts controlled directly by a pre-programmed personal computer.

Lighting Ergonomics

This second area of the impacts program focuses on human responses to light flicker and to discomfort glare. Typically, light from lamps oscillates at a frequency of 120 Hz and is not perceived as flickering. Therefore, the visual system is traditionally assumed not to respond to these high-frequency light oscillations. Our studies of visual display terminals and of fluorescent lamps using the electroretinogram have shown clear retinal responses to the oscillations in light emanating from these devices. During 1990, these studies will be extended to examine whether the responses to light flicker extend further along the visual pathway. This will be accomplished by comparing visually evoked potentials (VEP) to low frequency checkerboard reversals under conditions of the presence and absence of high frequency flickering light. A new data-gathering system for recording and amplifying very low-level electrode signals has been designed, and several subjects will be tested in a pilot study.

A major concern in lighting design and in promotion of energy-efficient lighting is to ensure that discomfort glare is minimized. Because lamp spectrum is a variable quantity that can be directly controlled in lamp manufacture, the latter could advantageously provide the spectrum that minimizes discomfort glare. Without experimental verification, the intensity of discomfort glare has been assumed to be independent of spectrum, i.e., depending only on luminance. We have performed some preliminary pilot studies that indicate a spectral dependence of discomfort glare which is not only photopic luminance; during 1990, we will begin a detailed study of this spectral dependence, using calibrated, narrow-band filters with a tungsten-halogen light source.

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