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1990 Annual Report

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Windows & Lighting Program
1990 Annual Report

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LBL-30865

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Introduction

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. This activity directly supports the efforts of the National Fenestration Rating Council to develop an accurate and fair system for rating and labeling the energy performance of windows. 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 on the basis of the disciplines and facilities involved. These are 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. Primary efforts are devoted to the development of electrodeless lamps that operate at high frequency in the range of 50 to 500 Megahertz. Replacements for both fluorescent and high intensity discharge (HID) lamps are being investigated. These lamps promise much more efficient conversion of electrical energy into visible light, and a much longer lamp life.

Our building applications research concentrates on technical approaches leading to major improvement in fixture efficiency, effective use of lighting controls, how these factors interact with a building's heating, ventilating, and air-conditioning (HVAC) system, and on issues of lighting and visual quality.

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 lighting glare, 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 electrodeless 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 high-frequency surface wave lamp promises major reductions in energy use with considerably longer lamp life.

— Windows & Daylighting —

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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.

ADVANCED 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 triple-glazed windows. First introduced commercially in 1982, low-E coatings are used today in more than 25% of all residential windows. Our work on Superwindows, which incorporates low-E technology, has recently led to several commercially available products. These highly insulating glazings have such low heat transfer rates that they can outperform the best insulated walls in winter on any orientation in virtually any U.S. climate. Modified low-E coatings which transmit daylight but reject near infrared radiation (i.e., spectrally selective coatings) have been developed for cooling dominated climates. We are supporting projects to develop improved spectrally selective coatings and to help specifiers utilize these technologies more effectively. We are accelerating our efforts to develop "smart windows," specifically electrochromic materials and devices with optical properties that respond to changing environmental conditions. These devices, and other optical materials that can control incident daylight, will provide window systems with comprehensive energy management capabilities that will allow them to deliver net energy benefits to buildings in virtually all climates.

Durable Solar-Control and Low-Emittance Coatings

The objective of this project is to develop spectrally selective coatings with low emissivity for thermal insulation and/or high solar-infrared reflectivity to cut cooling loads. Last year we increased the optical transmittance of sputtered diamond-like overcoatings and measured some of the mechanical properties affecting long-term durability. This year we collaborated with IBM Corp. to study the mechanical properties in detail. Using the IBM nanoindenter, we measured the hardness of diamond-like films with varying hydrogen content. Ion beams have been used to convert diamond-like films to crystalline diamond, but at the low temperatures required to manufacture window coatings the films partially converted to graphite. We also continued investigations of metallic compounds which are inherently more durable than silver and in some cases possess even sharper selectivity. A survey of the metallic oxides, nitrides, borides, and other compounds revealed several candidate materials with suitable optical properties. Figure 1 presents the optical and thermal performance indices of most of the currently available glasses and coated products. In FY91 we will continue our efforts to fabricate materials having higher visible transmission and lower solar heat gain (shading coefficient) than existing coatings.

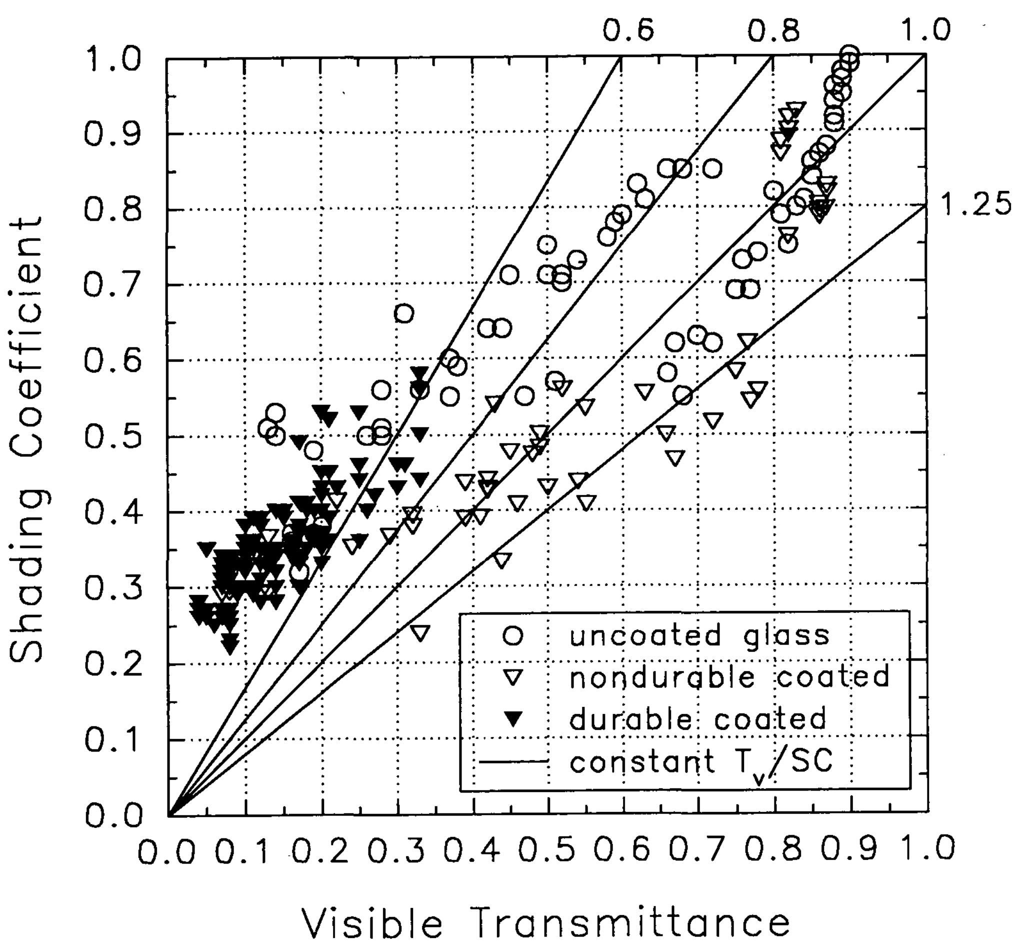

Figure 1. Distribution of visible transmittance and solar heat gain (shading coefficient) of commercial glazing products. Coatings with a superior combination of transparency and heat rejection would fall farther toward the lower right.

Low-Conductance Glazings and "Superwindows"

An increasing number of window manufacturers are offering glazing systems with low-emissivity coatings and low-conductivity gas filling. These windows have center-of-glass R-values between 3 and 4 hr-ft^2-F/Btu. Since 1985, we have been working to develop the technology base for the next generation of insulating windows. Such Superwindows will have total window R-values between 6 and 10 hr-ft^2-F/Btu and, even in northern U.S. climates, will be able to transmit more useful solar gains (from any orientation) than they lose in conduction. Superwindows will thus outperform insulated walls over a complete heating season.

In 1988 we began a project with several major window manufacturers and the Bonneville Power Administration (BPA) to design and manufacture prototype first-generation Superwindows for three super energy-efficient BPA demonstration homes in Montana. These windows were designed to build on existing manufacturing processes and to produce windows with center-of-glass R-values between 6 and 10 hr-ft^2-F/Btu. In 1990, one of the manufacturers involved in this collaborative process announced the first commercially available "superwindow"; an insulated glass unit with a center-of-glass R-value of 8 hr-ft^2-F/Btu.

During the 1989-1990 winter, these three BPA homes were monitored to assess their field performance. Superwindows and control (state-of-the-art low-E gas-filled) windows were compared side-by-side. This monitoring effort and associated laboratory tests all verified our initial performance assessments. As Figure 2 shows, these glazing systems can perform as well as an insulated wall, although the total window, including the sash and frame, performs somewhat more poorly. These results suggested the need to focus attention on improving the thermal performance of sash and frame.

In 1990 we began efforts to identify generic designs for insulating window frames. Using a finite element modeling code, we showed that modified vinyl and fiberglass frames could have frame R-values as high as 10 hr-ft^2-F/Btu. We began to establish an infrared thermography laboratory to analyze frame and edge effects in detail and to validate our computer modeling. The thermographic laboratory is also being used for collaborative studies with window manufacturers to accelerate their efforts to improve the thermal properties of their specific window designs. Improved frames and edges will be the focus of our efforts for the next few years. We also began discussions with manufactured building developers to explain how superwindows might be redesigned as integral elements of wall systems.

Optical Switching Devices

Chromogenic or optical switching devices can be used to dynamically control the transmission of windows in buildings, automobiles, and aircraft. This technology can be used with smart control systems to maintain adequate lighting levels and reduce building energy consumption. Energy simulation studies of office buildings indicate that switchable glazings can provide a substantial amount of energy savings. Savings include net lighting, cooling, and peak utility loads. Other benefits include reduced HVAC system size and greater thermal and visual comfort. There are several chromogenic technologies which can be used to switch a window. The dynamically controllable ones are notably electrochromic and certain liquid crystal materials. Electrochromic devices have the best combination of properties for window applications. Electrochromic glazings have the potential for a wide dynamic range with 10-80% visible transmission, moderately fast switching times, and low power consumption.

During FY90, our ongoing studies on the modeling of the energy performance of switchable glazings have been useful in better defining the necessary characteristics of advanced

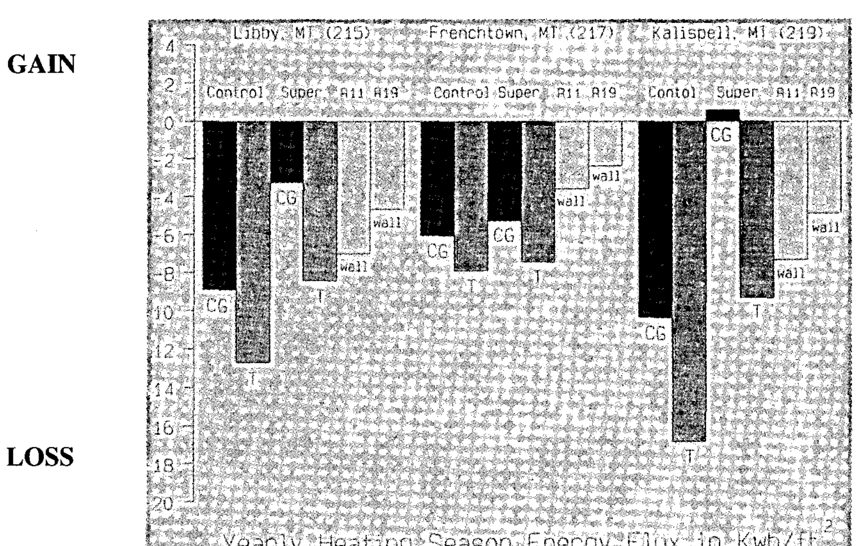

Figure 2.

Yearly heating season energy flux for 1) center-of-glass areas of the control windows and superwindows; 2) total area (center, edge, and frame) of control windows and superwindows; and 3) R11 and R19 walls. Center-of-glass heat fluxes are measured; other fluxes are based on calculations and real time data.

(XBB 916-4591)

windows. We have used our modified WINDOW 3.1 program to better understand how an electrochromic coating will work in a complete window system. Our modeling work has shown that the total design of the window and the climate and orientation of the building are strong contributing factors to the dynamic requirements of the chromogenic glazing. Our results also show that chromogenic glazings can offer substantial energy peak demand and HVAC system size savings. We have begun to verify our modeling results with tests on prototype windows in the MoWiTT test facility.

In our materials research, we have developed new materials for nickel oxide-based electrochromic devices. The major device materials are the electrochromic layer, the ion conductor or electrolyte layer, and the ion storage layer. During this year we have constructed electrochromic nickel oxide devices using polymer ion conductors. We have studied the preparation and optical and electrical properties of prototype electrochromic electrodes and complete switching devices. The electrodes studied were nickel oxide, nickel-manganese oxide, and tungsten-molybdenum oxide. We were able to make electrodes with similar properties by either sputtering or electrochemical deposition methods. We have also studied a new ion conductor based on $BaCeO_3$. Our devices use nickel oxide as the electrochromic material, with an ion conductor based on amorphous poly(ethylene oxide), a-PEO. Optical and electrical measurements are compared for different device configurations. An example of the optical properties of a NiO/polymer/WO_3:Mo device are shown in Figure 3. Our best NiO/polymer/MnO:Ni device showed a photopic transmittance range of T_p = 0.71-0.23. The corresponding integrated solar transmittance range is T_s = 0.50-0.23. Our best NiO/polymer/WO_3:Mo device showed T_p = 0.79-0.39 and T_s = 0.59-0.30 A photo of this device is shown in Figure 4. In our international studies (International Energy Agency) we have helped develop test methods for electrochromic devices. This will help industry perform standard measurements on these devices. Also in this activity we evaluated the optical and electrical properties of a Asahi Glass prototype electrochromic device.

Our research in FY91 is directed at electrochromic device construction. Two major device types will be studied. The first will be a laminated type using a-PEO for the ion conductor; the second will be an all solid-state device. Our studies will focus on polymer ion conductors and inorganic ion storage layers. Our energy modeling studies will continue using the modified DOE 2.1 Building Energy Modeling program to simulate switchable windows in a variety of climates and building designs.

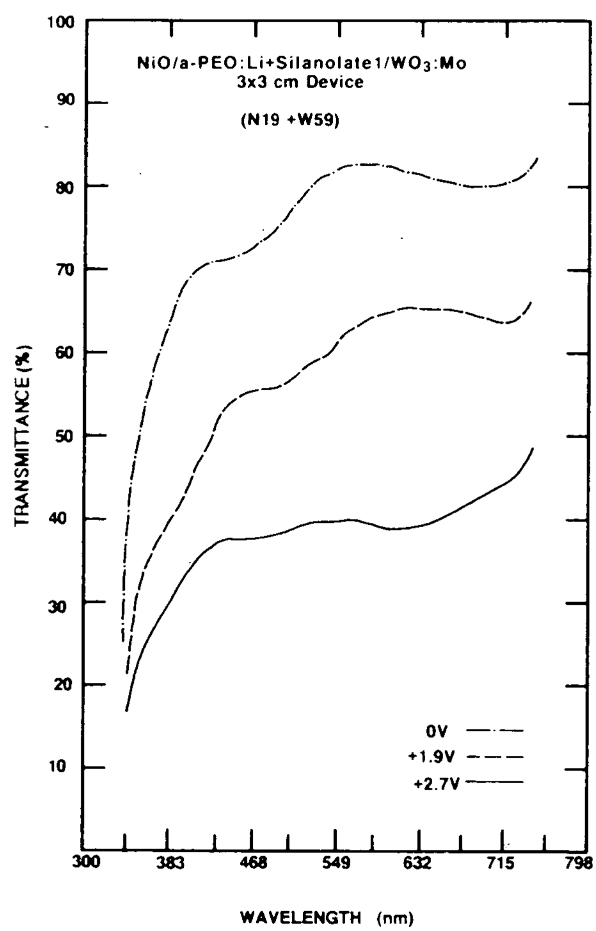

Figure 3.

Example of spectral transmittance of a NiO/polymer/WO_3:Mo electrochromic device.

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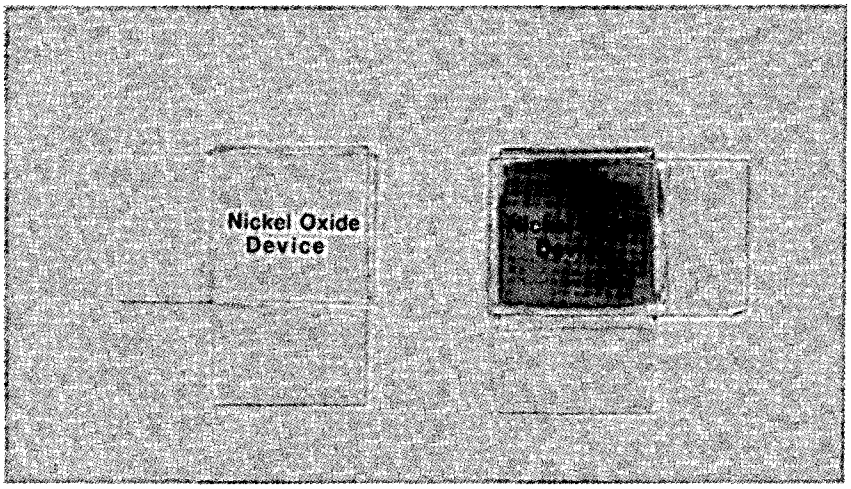

Figure 4.

NiO/polymer WO_3:Mo electrochromic device in bleached and colored condition.

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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. Engineering analysis of key optical elements and subsystems has been completed; the next step will be to fabricate and test a prototype system. Since there is no longer DOE support for this effort, collaborative funding arrangements will be sought in 1991 to carry out this phase of the program.

Automobile Glazings

Reduction of the solar load on automobile air conditioners would save fuel, reduce the utilization of CFC refrigerants, and extend the range of electric vehicles. In 1990 we continued work begun the previous year to investigate applications of durable selective coatings, electrochromic coatings, and angle-selective coatings to automobile windows. We entered a collaborative research agreement with Dow Chemical Company to develop jointly an electrochromic device using LBL sputtered coatings and Dow's polymer electrolyte. Figure 5 shows the transmission in the transparent and absorbing states for sputtered WO_3 films developed for this project. A new heat-transfer model for automobiles was used to extend our previous predictions of static loads to steady-state driving conditions. Next year we will concentrate on electrochromic device development with Dow and other industrial partners, and also extend our modeling studies to include thermal insulation properties of windows which we think will be important for future electric vehicles.

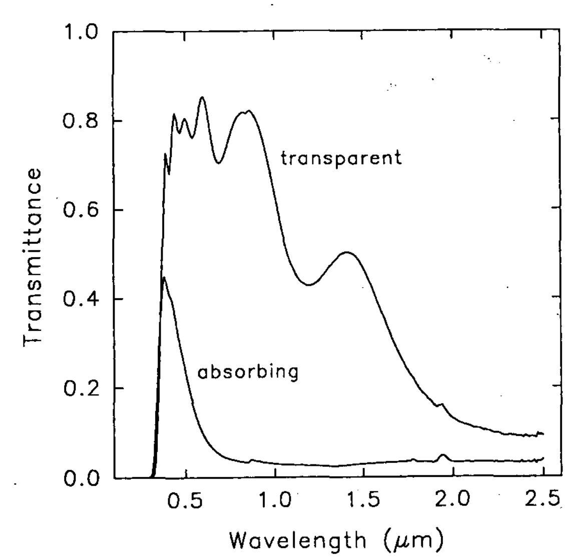


Figure 5. Solar spectral transmittance of a sputtered electrochromic WO^3 film in transparent and absorbing states.

Insulation

In 1990 we began to apply the successful approaches used to manufacture highly insulating windows towards the production of an opaque insulation. With support from the California Institute for Energy Efficiency, we showed that the use of low emissivity surfaces and multiple, low conductivity gas-filled cavities can result in a highly insulating panel that can be fabricated using existing materials and technologies. We call this new insulating material gas-filled panels (GFPs). Applications for GFPs are widespread, with a primary focus on replacing CFC blown foams in refrigerator/freezer appliances and building walls.

GFPs are not a homogeneous insulating material such as fiberglass or foam, but rather an assembly of two specialized components. The first component is a barrier envelope that contains a gas, or gas mixture, at atmospheric pressure. Placed inside the envelope is the second component, a baffle consisting of multiple, low-emissivity coated, non-permeable layers. The baffle effectively eliminates radiative and convective heat transfer, leaving primarily conductive heat transfer through the gas and baffle. GFPs can be constructed with mechanical properties ranging from flexible but self supporting to stiff and supportive.

The thermal performance of GFPs has been independently tested at Oak Ridge National Laboratory (ORNL) and predicted thermal performance values were achieved. Measurements on first generation prototypes yielded R-values per unit thickness of 36 m-K/W (5.2 hr-ft2-F/Btu-in) for air filled panels, 49.3 m-K/W (7.1 hr-ft2-F/Btu-in) for argon filled panels, and 86.8 m-K/W (12.5 hr-ft2-F/Btu-in) for krypton filled panels. Thus, air filled panels perform as well as styrene foam. Argon filled panels perform as well as CFC blown foams or at a level twice that of fiberglass. Krypton filled panels offer much higher performance levels than any currently commercially available insulation. Projected performance levels attainable for second generation prototypes are expected to be 10–20% higher.

Development, testing, and analysis of GFP components and costs will continue during 1991. Many existing manufacturing technologies in the food processing industries can be adapted to efficiently manufacture GFPs.

Research efforts during 1991 are also aimed at building prototype GFPs for use in conjunction with non-CFC blown foams in a EPA-sponsored advanced appliance demonstration project. For all applications, additional non-thermal testing (e.g., flame spread and smoke generation, acoustical resistance, and accelerated aging) is necessary to assess potential end uses.

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 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

The growing use of advanced optical coatings, gas fills, and insulating edges and frames has increased the number of window configurations available for manufacturers to produce and for consumers to evaluate. Beginning in 1986, we released the WINDOW program to serve as a standard for calculating window heat transfer properties. Using state-of-the-art algorithms and designed to take advantage of the widespread use of personal computers, this tool has been updated twice since its initial release and it continues to gain widespread acceptance. Over 2,500 copies have been provided free of charge to the industry and the public. WINDOW is used to both aid in the evaluation of new product options and as a consistent means to calculate and report thermal performance specifications.

This year we continued to focus on research issues relating to the spectral and angular dependencies of glazing materials. A procedure to calculate the angular solar optical properties of uncoated glazing systems, given only their properties at normal incidence, was developed. Determining such properties for coated glazings is much more complex. We began to set up an experimental apparatus to accurately measure these effects; this will be the focus of our work in 1991.

Window Rating and Labeling Systems

The development of many new window systems in the last several years has also brought forth the need for an accurate, fair, and cost-effective means to evaluate the thermal performance of all fenestration products. Such a system must meet the demands of manufacturers, architects/engineers, builders, state regulators, utility incentive programs, and consumers. The National Fenestration Rating Council (NFRC) was formed in 1989 by representatives of all these groups with this objective in mind. In 1990 we took a lead role in working with the NFRC's Technical Committee to develop a procedure to rate window U-values. This procedure, drafted in 1990, is based on the simulation procedure in the WINDOW program and the Canadian program, FRAME, to provide for the accurate and inexpensive rating of window U-values. NFRC's other technical tasks include developing procedures to determine other properties (i.e., shading coefficient, visible transmittance, infiltration and condensation resistance) as well as an Annual Energy Index which combines the impacts of all properties for specific climates and building types. We are involved with all technical issues relating to the development of such procedures and will continue our active involvement in NFRC's activities in 1991.

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 (Figure 6). A major upgrade to this facility was made during 1990. 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 1990, 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. This project will be completed in 1991. Scanning radiometric measurements are 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.

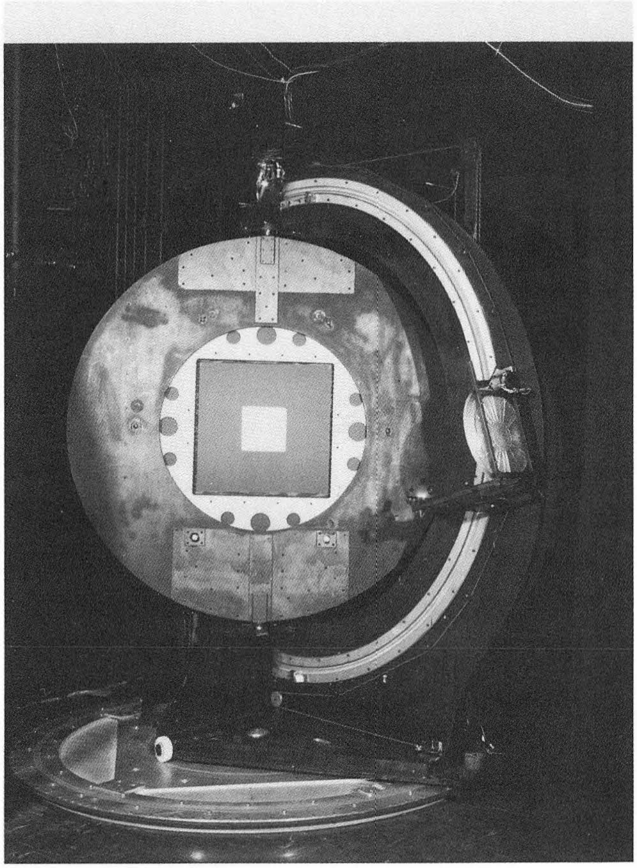


Figure 6. Scanning radiometer for measuring bidirectional transmittance and reflectance of fenestration components and systems. (CBB 910-8295)

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 to our daylighting simulation program, SUPERLITE, are in progress to allow it to model more sophisticated daylighting systems such as complex sun-control systems and shading systems. SUPERLITE was selected by an International Energy Agency (IEA) task group as the primary tool for a multinational daylighting research effort.

In 1990 we completed a version of SUPERLITE that models electric lighting. Further collaborative work in 1991 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.

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, 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 was initiated in 1990 to repaint the dome, to upgrade the lighting system, and to recalibrate the entire photometric data-collection system. This continues in 1991.

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 (Figure 7), 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.

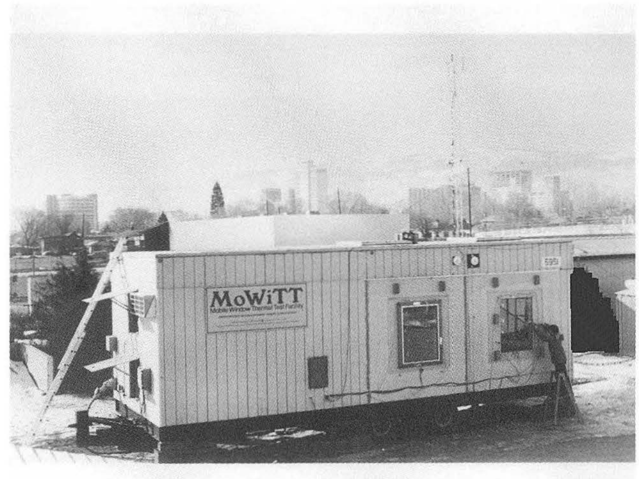
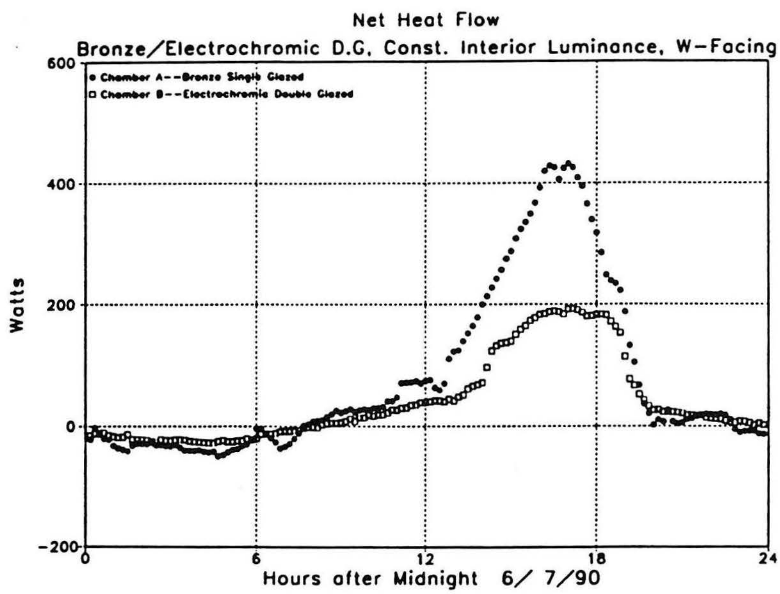


Figure 7. MoWiTT facility at field-test site in Reno, Nevada. Two sealed insulating glass units are mounted in the two calorimeters.

(CBB 892-812)

During 1990 we began the testing of emergent window technology with a study of the winter performance of windows with a pyrolytic low-E coating as compared with that of the standard sputter-coated low-E. The data from this study, which had fenestration industry support, was important to the subsequent market introduction of the new pyrolytic coatings. This represented a significant step forward for energy conservation because the new coatings, which are durable, can be used in a variety of applications for which the more fragile sputter-coatings are unsuitable. We also made exploratory studies of windows with switchable electrochromic coatings (Figure 8) and continued our active field-test program in support of the US/Canadian study of nighttime energy loss rates (U-values) in windows.

In 1991 we will improve the MoWiTT accuracy in order to carry out studies on high-performance windows as part of the U.S./Canadian project. We will also extend previous studies of solar heat gain and expect to continue testing emergent window technology with fenestration industry support. Industry is interested in field-test data from the MoWiTT to guide development of new products and designs. These field measurement from the MoWiTT have the potential for removing uncertainties about window performance that have slowed progress in energy conservation for the past decade.



XBL 916-1200

Figure 8.

Performance comparison between electrochromic and tinted glazing. In a side-by-side test, a prototype electrochromic window was gradually darkened during the afternoon to maintain a constant interior daylight level. Graph shows consequent reduction in afternoon cooling load. When electrochromic window is in its clear state, both windows have the same visible transmittance.

BUILDING APPLICATIONS AND DESIGN TOOLS

The development of new glazing materials and the analytical and experimental determination of fenestration system performance must be complemented by defining how such information benefits the building design community. Our objective in the Applications area is to apply the knowledge gained from our more basic science research efforts to real world buildings and develop the tools that are necessary to disseminate and use this information.

Nonresidential Buildings

In 1989 we developed a Macintosh-based Commercial Building Fenestration Performance Design Tool with support from the Lighting Research Institute/EPRI/NYSERDA. This prototype design tool is based on a regression analysis of many DOE-2 simulations and calculates both energy and comfort performance of window systems. We are now using this tool to demonstrate the versatility and usefulness of such a design procedure and are continuing our investigations on the use of color, multiple windows, and animation in the design tool environment. In 1990 we transferred this software to a PC-based computer with the WINDOWS graphics user interface.

We continued detailed analysis of the DOE-2 simulation data that was generated for the Public Works Canada Daylighting Manual. This study enabled us to better understand the performance characteristics of glazing systems in very cold climates and complements past work done on glazing performance in hot and humid locations.

Envelope and Lighting Technologies to Reduce Electric Demand in Commercial Buildings

At the end of 1990 we began a new project which brings together many of the tools and capabilities previously discussed. This project is supported by the California Institute for Energy Efficiency (CIEE), with joint support from major California utilities and co-support from DOE. California utilities have been leaders in the U.S. in developing and implementing incentive, rebate, and design assistance programs to accelerate use of new technologies in buildings. We are collaborating in this project with the Graduate School of Architecture and Urban Planning, University of California, Los Angeles.

Electric lighting loads and cooling from solar heat gain and from lights are the two largest components of energy use and peak demand in many buildings. The most cost effective demand side management solutions are generally those that directly reduce or eliminate these loads. Existing technologies can provide modest reductions, however they are typically applied in a piecemeal manner that yields less than optimal results. This project will help achieve the full potential of existing technologies by integrating them into more useful systems and by providing more effective design tools for architects and engineers. Emerging and novel technologies will also be developed to provide even greater savings and extend the savings over a larger portion of the building floor area.

The project goals are to provide designers with cost-effective demand-reduction technologies and to demonstrate their use in built projects, targeting peak load reductions of 15-40%. The project includes the following research areas and tasks:

- Minimize total cooling and lighting energy use and demand in commercial buildings.
- Minimize envelope cooling loads by controlling solar gain but admitting daylight.
- Minimize perimeter zone heating loads.
- Optimize electric lighting with use of efficient lighting hardware, controls and daylight; minimize associated cooling impacts.
- Integrate total envelope/lighting systems with HVAC control and thermal/visual comfort requirements.
- Provide perimeter zone electric power with photovoltaic systems.
- Develop and commercialize integrated hardware systems that accomplish the energy objectives.
- Provide utility planners with research results and projections to influence demand side planning.
- Provide design tools and knowledge bases to allow designers, engineers, and owners to confidently specify these technologies.

Residential Buildings

We began preparation of a Residential Window Design Handbook. This handbook will provide fenestration design guidelines to architects, engineers, builders, and homeowners. As part of this effort, we also began defining the requirements of a computer-based methodology for predicting seasonal energy performance and cost. The simplified methodology will serve as a prototype for a fenestration rating procedure that will be developed in future years.

A six-page article was prepared for Home Energy entitled "A Consumer Guide to Energy-Saving Windows." The article contained basic information on the heat conduction, solar gain, and infiltration characteristics of windows in residential buildings. The paper was subsequently reprinted and distributed by other periodicals and state agencies.

An interactive Residential Windows Notes computer program was completed for use on IBM-PC compatible computers. The notes were structured so that users would have immediate access to a data base discussing such things as heat transfer basic concepts, window systems and components, heating and cooling performance, window placement strategies, etc. Figure 9 shows one of the screens from the window note package. Information systems of the future will increasingly rely on computer-based delivery systems. This project is part of an ongoing effort to better understand how to use such emerging technologies.

Technology Transfer

In order to influence energy efficiency trends in the United States, our results need to be communicated to other researchers and to professionals in the building industry. We use a variety of media to reach a widely varied audience, including trade journal articles, network and utility-based television production, and exhibits. We 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. The group's commitment to technology transfer was recognized by several awards in 1990.

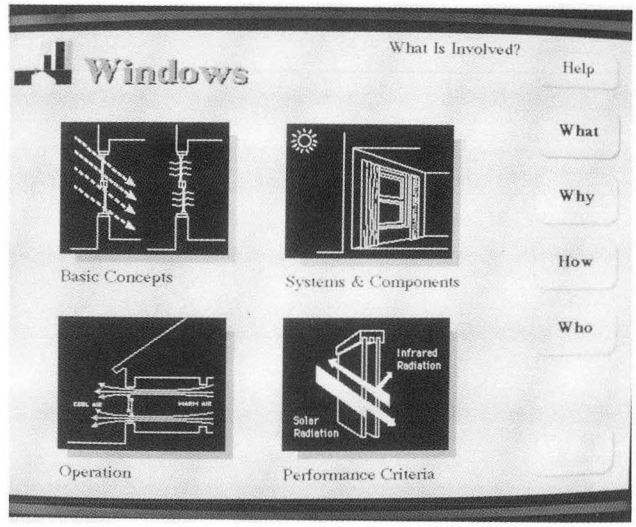


Figure 9. The "WHAT" menu screen of the Residential Window Notes interactive computer-based database. Users can navigate to obtain information on Basic Concepts, Systems and Components, Operation, and Performance Criteria of residential windows. (CBB 916-4309)

In 1990, we hosted numerous short term visitors as well as longer term visitors from Norway and the Soviet Union. 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 Energy Information Kiosk, incorporating state-of-the-art interactive multimedia technology, was completed and evaluated for Southern California Edison in their new Customer Technology Application Center (CTAC). Consisting of a personal computer with touch screen, the kiosk provides information linked to video images stored on an optical disk. This project helps demonstrate effective utility-laboratory cooperation, and highlights SCE's commitment to provide relevant and useful energy services, guidance, and incentive programs to building design professionals.

A friendly and intuitive user interface is the key innovative feature of this information kiosk. The user selects information for a wide range of topics by simply touching the computer screen. The level and amount of information detail is controlled by the kiosk user. This multimedia-based technology supports extensive use of animation and video to explain concepts to attract and hold the attention of the user.

Besides enhancing the CTAC information displays, the information kiosk was integrated into a major LBL exhibition of energy efficient technologies at the RETSIE '90 Conference in San Diego (Figure 10). There, it received extensive evaluation by utility customer service personnel, building owners and developers, architects, engineers, and lighting designers.

With the observance of the 20th Anniversary of Earth Day, we developed exhibits on advanced window technologies and were invited to participate in several major energy conservation conferences, including RETSIE '90 in San Diego, EarthTech '90 in Washington, DC, and Earth Day '90 Berkeley (CA, USA).

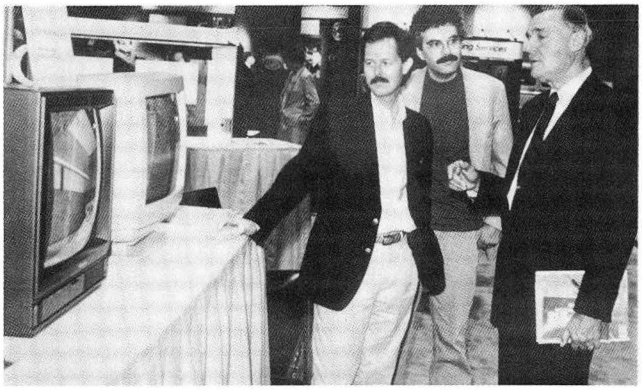


Figure 10. Attending RETSIE '90 (San Diego, CA), U.S. Secretary of Energy James D. Watkins discusses Lawrence Berkeley Laboratory's new Energy Information Kiosk, an interactive computer-based information product. (XBB 916-4311)

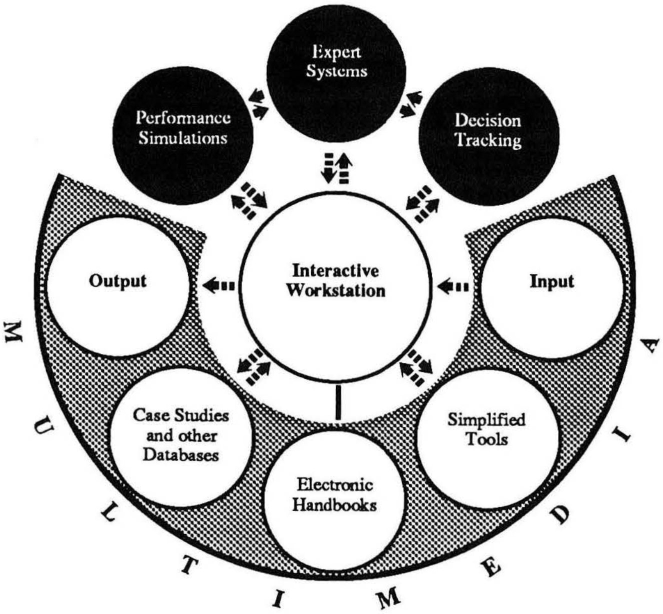


Figure 11. Diagram of integrated components in the BDSE.

Advanced Design Tools: Building Design Support Environment

The Building Design Support Environment (BDSE) is a framework of computer-based applications to assist building designers in more easily incorporating energy-related design issues and new technologies into building designs (Figure 11). We began to explore new concepts for architectural design tools several years ago, after observing that energy efficiency remains a low priority in standard building practice. Our original image of an intelligent and integrated package of design tools to assist designers in all aspects of building design, construction, and operation has since been developed into an experimental prototype, the BDSE (Figure 12). During the past year, we continued the design and development of the various modules of the BDSE independently. We are exploring new computer technologies such as multimedia and hypertext in the search for more effective mechanisms to reach and engage building designers. Additionally, we are pursuing an understanding of a designer's decision process, expert systems, and seamless integration between different applications to make the package more effective. Our activities in this area also support the Advanced Energy Design and Operation Technology (AEDOT) project, now beginning with support from DOE.

Expert Systems and the Design Process

Expert systems have traditionally been developed to solve well-defined problems, such as a diagnostic problem. Little progress has been made to date in the development of an expert system that will be useful for design. Through a detailed analysis of the design process, we identified key, generic design activities and the various types of knowledge used in each activity. This has led to development of an approach in which the designer works cooperatively with a computerized "expert assistant." To test this new approach, we started the implementation of a software module for the design of fenestration and lighting systems with respect to comfort, energy requirements, and cost. This BDSE module will assist designers by providing information on how to satisfy specific design criteria, as well as by indicating the effect of design modifications on the design criteria considered. Moreover, this module will automatically select building components from product catalogs based on acceptable design criteria value ranges, as specified by the designer. The designer preferences are recorded in run-time developed knowledge bases. In this way, this module of the BDSE "learns" from and grows with the designer.

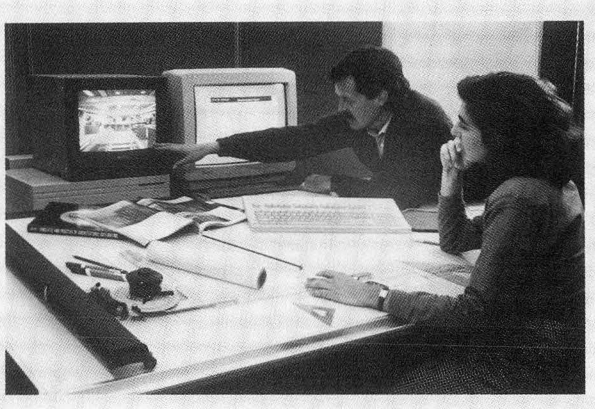


Figure 12. The *Building Design Support Environment* enhances but does not replace an architect's traditional design methods. (BBC 918-5596)

Electronic Handbooks, Case Studies, and Databases

Over the past year we have added modules in these areas of daylight design issues: Educational "handbooks" explaining daylighting design principles; complex "hypermedia" daylighted case-study buildings; rule of thumb applications to calculate atrium performance or to assess visual comfort; and large databases of daylighting references, video images, and buildings.

Integration of Components

All modules that we create in the BDSE are intended to be linked together. Additionally, we are linking our modules with existing applications like CAD drawing packages and the RADIANCE lighting simulation program. It is the integration of disparate design applications that will significantly affect designers' use of computer tools and the ability to include energy concerns in the design process. This year we made significant progress towards this goal by linking together two commercial CAD packages with RADIANCE and our hypermedia environment.

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— Lighting Systems Research —

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New, efficient lighting technologies and strategies could 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 Building Technologies 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). This program—which represents a unique partnership between a national laboratory-university complex and industry—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 lamps providing scotopically rich spectra can permit major energy savings in a highly cost-effective manner.

The program is now actively pursuing the 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 144 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 1990 by each of our three major efforts: advanced light sources, building applications, and impacts on productivity. Activities planned for 1991 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; the 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 major energy-loss mechanisms are our present candidates for improvements in efficiency. These are: electrode losses; energy loss by lamp phosphors in their conversion of UV radiation to visible light; and self-absorption of ultraviolet (UV) radiation, which eventually leads to losses by electron quenching of excited mercury atoms.

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. Because phosphor conversion process is only about 50% efficient, there is a major opportunity here that could lead to significant improvements in lamp efficacy.

A highly promising mechanism developed at LBL uses a plasma coupling principle that eliminates the need for electrodes. This wave-guide type mode of operation occurs at high frequencies in the RF range between 100 and 500 MHz, permitting efficient lamp excitation without electrodes. This fluorescent lamp, which operates in the transverse magnetic (TM) wave propagation mode, shows an energy efficacy approximately 40% greater than that of normal fluorescent lamps. In addition, the TM mode fluorescent lamp operates without starting circuits and should have an extended lifetime because of the absence of electrodes.

Reducing the causes of energy loss in the phosphors requires alteration of lamp 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 on an atomic level 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. Electrodeless operation would also enable the use of compounds that have desirable light spectrum, but that are excluded today because they 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 have the optical character for widespread use by lighting designers.

In order to eventually achieve a commercially marketable concept for high-frequency electrodeless lamps, we initiated during this past year a development program in high-frequency electronic power supplies. Presently, there is a total lack of availability of an efficient RF power supply in the 20- to 100-watt range. Since the high-frequency lamp behaves as an interactive electronic component, new concepts need to be developed in order to maintain the inherent efficiency of the high-frequency lamp.

TM Mode Lamps

We are continuing to work on determining the optimal parameters of this low-pressure discharge functioning as a fluorescent lamp. These parameters include the tradeoffs between three operational factors: frequency of operation, argon pressure, and power loading. So far, we have determined that there is an optimum frequency range where the large increase in efficiency can be maintained. This range is between 200 MHz and 250 MHz. Outside this range, efficacy drops precipitously. We have also determined that better efficacy can be obtained at an argon pressure of about 0.25 Torr, an order of magnitude lower than occurs in typical commercial fluorescent lamps. These lamps require the higher argon pressure in order to reduce electron bombardment damage to the filament surfaces. The high-frequency lamps have no such problem because they operate without electrodes and therefore can gain the added efficacy benefit from reduced argon pressure.

In the area of HID (high-intensity discharge) lamp development, we have achieved the *first ever* high-frequency, stable, low-power (less than 100 watts), high-pressure mercury-argon lamp (Figure 1). These light sources have a very short arc of order (between 1 and 2 cm) and are thus potential replacements for incandescent lamps where optical control is important (e.g., in merchandising). These high-frequency electrodeless HID's are potentially six to seven times more efficient than today's incandescent lamps.

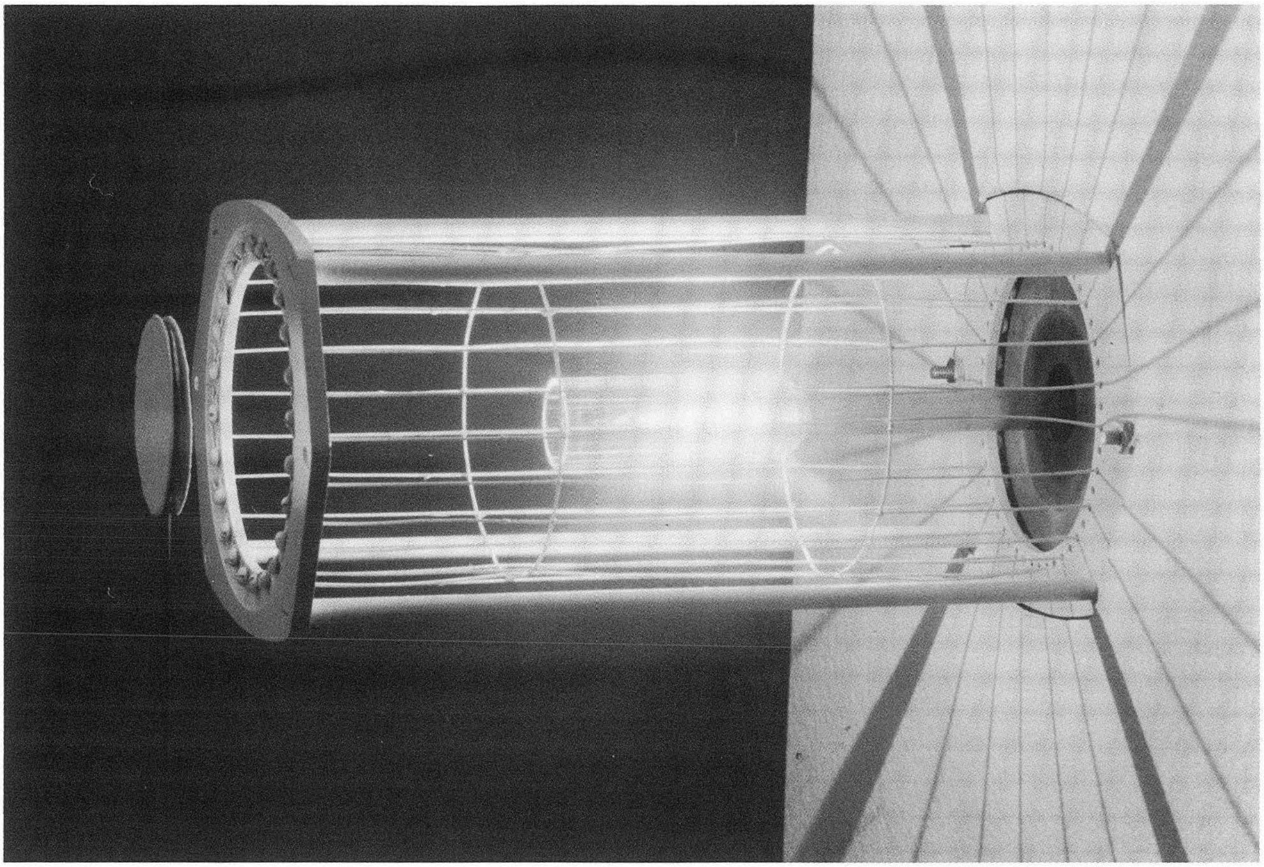

Figure 1. Photo of electrodeless mercury-argon HID lamp in operation. The discharge length is only 2.5 cm. It is operating at 90 watts directly into the lamp with no reflected power. (CBB 915-3690)

The high-frequency electronic power supply development has enjoyed spectacular progress during the last year by taking a research model amplifier developed for LBL by DAI (Design Automation Inc.) and modifying its circuitry. The modified amplifier reached an efficacy of about 80%, indicating that the eventual goal of an efficient high-frequency power supply will be feasible.

Isotope Modeling

This project, a joint effort with New York University, had the primary objective of developing a theoretical model that accounts for the effects of variable isotopic mercury composition on the emittance of a low-pressure discharge. A final report has been completed.

Multi-Photon Phosphors

Theoretical calculations and experimental measurements were both carried out in order to explore a number of phosphor systems for multiple photon emission (MPE). Many schemes have been proposed in the literature which would theoretically lead to MPE. The processes considered during the present project can be classified into three types: cascade processes, cooperative processes, and interband Auger (IBA) processes. The first two processes involve only the energy levels of the impurity ions which leads to localized states in the solid. These impurities can both be activators or sensitizers. The last process involves multiplication of electron hole pairs due to the Auger process which involves the electronic states of the valence and conduction bands.

Of the three processes, the cascade and interband processes have been experimentally shown to exist. Last year we showed that the cooperative process originally proposed by

Dexter is not a first order process, and therefore is not likely to be of any practical use for MPE. We did, however, propose an alternate modified cooperative process (MCP), which is a first-order process.

Of the two experimentally verified MPE processes the cascade process has received the most attention by the lighting industry. The classic example of this process is YF3:Pr where a blue and a red photon are emitted for each VUV photon absorbed. The energy levels involved in the emission process are the excited levels of Pr^{+3}.

This leaves us with the area of interband MPE processes as the least studied, and possibly the most fruitful, field to explore. During this past year we have concentrated our efforts in this area. Specifically, we have carried out calculations and QE measurements for phosphor systems looking for MPE through the IBA process as first described by Ilmas and Savikhina.

The theoretical work revolved around our efforts to use quantum mechanical methods to understand the luminescence process for specific phosphor systems and to predict the suitability of a particular system as a candidate for the IBA process. Calculations were performed for Zn_2SiO_4:Mn, ZnO:Cu ZnS:Cu,Al, ZnS:Cu,Cl, $LaPO_4$:Tb,Ce, Y_2O_3:Eu, and TiO_2.

Of these possibilities, the electronic structure calculations in ZnS:CuY_2O_3:Eu were started in Phase I and were carried over into Phase II of this project. The $LaPO_4$:Ce,Tb calculations showed us that this phosphor was not a good candidate for IBA MPE. We used the results from these calculations to make predictions as to the feasibility of obtaining "good" MPE phosphors from the studied systems. In addition, a theoretical investigation of the IBA process was performed using the many-body theory. The most significant aspect of the IBA investigation was the establishment of criteria for a good IB phosphor.

Our experimental QE measurements covered an excitation range of 5 eV to 25 eV. This broad energy range was made possible by using synchrotron radiation provided by the National Synchrotron Light Source at Brookhaven National Laboratory. A number of phosphor systems were measured. Of these, several were found to exhibit IBA MPE.

In addition, we have set up an in-house apparatus for making QE measurements from 6 eV to 10 eV. This apparatus uses high-pressure, electrodeless rare gas discharges as the excitation source. This apparatus allows us to look for the IBA MPE process in materials with small band gaps (2.5-4 eV). Our initial measurements have verified the synchrotron results by repetition of QE measurements of several phosphor samples. In addition, we investigated the effect of changing the concentration of Cu in ZnS:Cu,Al.

BUILDING APPLICATIONS

Real energy savings depend on the 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 real 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. To obtain actual luminance values, we use novel techniques for determining real luminances of interior environments containing complex objects. We have examined 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

A range of approaches and technologies for improving the thermal performance of fluorescent fixtures have been developed and these techniques have been successfully applied to a number of fixture systems. These technologies include convective venting and heat sink systems.

Feasibility of these techniques has been demonstrated and industry has shown strong interest and support of this work. In order for these technologies to enter the marketplace, they need to be further researched and refined and then advanced prototypes developed and presented to industry.

Figure 2 shows a prototype thermal control fin developed to improve the energy-efficiency of a compact fluorescent fixture. The concept was licensed with the manufacturer and is an excellent example of improved technology transfer. The inventor, Michael Siminovitch, received an award for this concept.

Expert System for Specifying Energy-Efficient Lighting Equipment

A literature review of expert systems for building applications was conducted and a database of references established. A draft technical report describing the project scope was produced. We conducted a search for hardware and software that would serve as a development platform for an expert system for lighting applications. Several hardware/ software configurations were assessed. We developed an attributes list for the lamp and ballast data bases, and developed a prototype database of 150 lamps and 25 ballasts. A first draft of the lighting-energy analysis spreadsheet (code-named *LEAR, Lighting Energy Analysis for Retrofits*) for 2 × 4 fluorescent lighting systems was begun but will not be completed until FY91.

Quality Illumination and Performance

During the past year, we conducted an experiment that demonstrated how instructions to subjects can affect the trade-off that occurs between speed and accuracy in task performance. This study also demonstrated that speed and accuracy are mutually offset even at suprathreshold conditions, but the primary cause was probably cognitive in nature and not visual. The study also supported the concept that non-visual components in any performance study must be separated in order to derive possible relationships between lighting conditions and visibility.

Discrepancies found in the Bailey size vs. performance data prevented the completion of the size-performance algorithms. New analysis procedures were established which will also be beneficial in the development of the field tool for assessing the adequacy of a given light level for a particular individual and task.

Computer Imaging

This past year we made considerable progress towards a validated reflectance model for Radiance. We designed and constructed a new device for efficiently measuring surface bidirectional reflectance distribution functions (BRDF's) using an imaging hemisphere, and used this device to characterize a few common classes of architectural materials. The imaging gonioreflectometer will be used in the future to measure BRDF's of luminaire surfaces for dirt depreciation and luminaire simulation.

We also developed some utilities to improve the speed and usability of Radiance. Namely, we developed a new algorithm for generating animated walk-throughs of simulated spaces, which greatly increases Radiance's usefulness for architectural lighting analysis. We also wrote a translator for manufacturer's luminaire data in the IES standard format, which makes the creation of large luminaire databases prac-

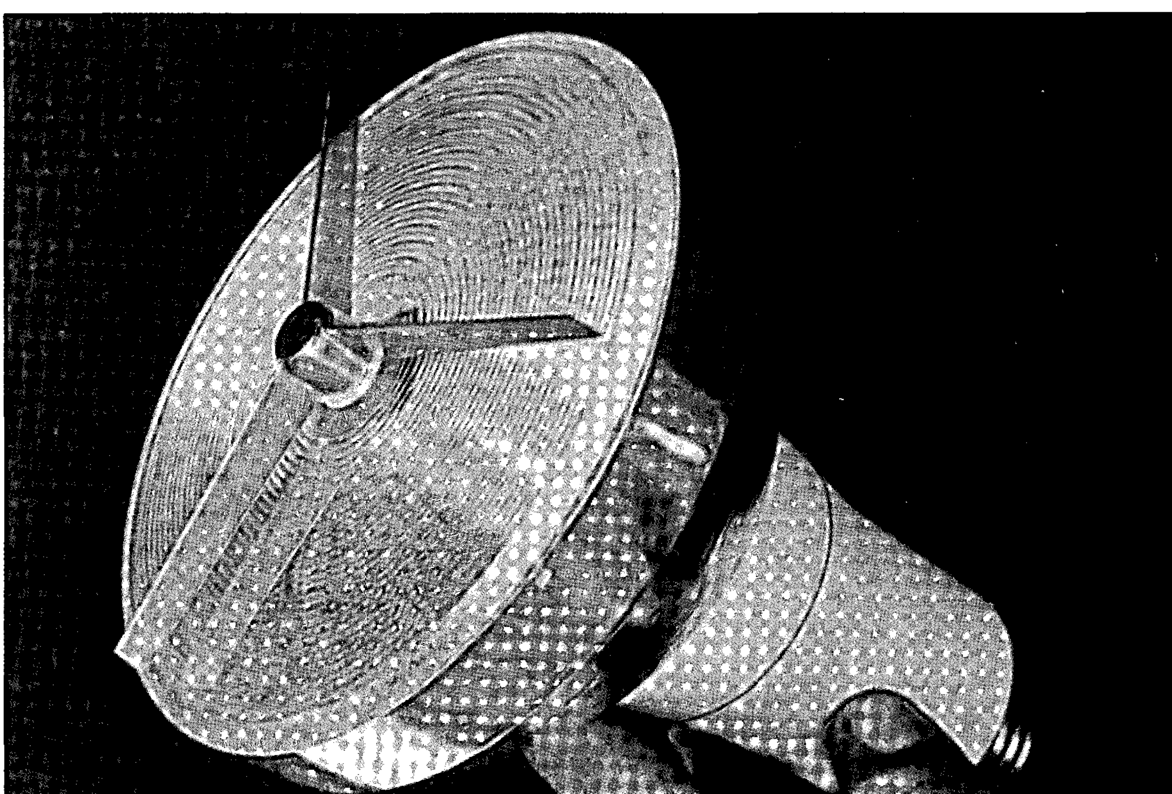

Figure 2. Compact fluorescent fixture shown with cooling fin attached. The fin allows the mercury coldspot to operate at about its optimum temperature, thereby maintaining lamp efficacy. Light loss from the fin is less than 3%. (CBB 900-8149)

tical. The algorithms for modeling light sources in Radiance were vastly improved, clearing a major bottleneck in the calculation, and we added support for X11, the new graphics display standard.

IMPACTS OF NEW LIGHTING TECHNOLOGIES ON PRODUCTIVITY AND HEALTH

Major benefits to lighting energy efficiency can accrue by directly studying human responses to find the type of lighting that provides the best visual effectiveness per watt of input power. Determination of visual effectiveness in terms of human subject responses requires a different approach than pure technology development, but it is an essential input to any such development since the end purpose of lighting is for human benefit.

Recent studies have shown that the more scotopic content compared to photopic content in a given lamp spectrum, the greater the effectiveness for making the pupil smaller. This is the basis for the more than 75% improvement in visual effectiveness per watt of the narrow band (5000°) fluorescent lamp compared to the warm white fluorescent lamp, even though they have equal traditional lumens per watt. Similarly, the supposed energy benefits of the HPS lamp as compared to the incandescent lamp are lost when compared on the basis of visual effectiveness. These two lamps would need about equal wattages to produce the same pupil size.

Table. Comparison of scotopic content and photopic content in lamp spectra.

Lamp Type	Lumens per Watt	Ratio of Scotopic to Photopic Lumens	Pupil Lumens* per Watt
Warm White Fluorescent	80	0.97	78
Cool White Fluorescent	79	1.47	106
Narrow Band (5000°) Fluorescent	83	1.96	139
Incandescent (125W)	18	1.4	23.4
High-Pressure Sodium (35W including ballast)	50	0.4	24.5

*Pupil lumen = $P(S/P)^{.78}$ where P and S are the photopic and scotopic lumens.

Spectral Effects

A powerful result demonstrating this concept was developed during the past year and is shown in the table above. This table is based on our results that determined the spectral determinants of pupil size and led to the 'pupil lumen' concept. It shows how varying the spectral composition that makes up essentially white light can lead to very large differences in visual effectiveness per watt as compared to the traditional and restricted measure of just lumens per watt. In this table visual effectiveness is specified by an objective measure, pupil size, which affects acuity and depth of focus. At typical building interior light levels, illumination is sufficiently large to be well above threshold conditions. In that case, smaller pupils are preferred because they allow for greater depth of field and improved acuity.

In terms of lighting energy efficiency benefits, this example shows that understanding how to apply visual effective lighting is the second most efficacious procedure for lighting energy benefits, with only the replacement of incandescent lamps by compact fluorescents providing a larger potential benefit.

Effects of Lamp Flicker on the Vision System

Because high-frequency lighting is more energy efficient than other types of lighting, supporting evidence that it is also beneficial to health and performance will serve to accelerate its market share. Recently, the British Medical Council reported on the reduction of incidence of headaches and eyestrain in a building in the UK where high-frequency lighting replaced the standard 50-Hz operation. Our past work on electroretinogram responses to oscillating light has provided a possible physiological basis for the British study.

During this past year, we have set up three additional studies to provide further support on the effects of light flicker on vision. In the first study two checkerboards, each consisting of a 20" × 20" array of high-power LED modules divided into two independent channels, are placed side by side. During trials in a two-alternative, spatial forced-choice detection experiment, one channel from each checkerboard is driven to produce a 20-Hz flicker simultaneously in the left and right displays, while the second channel from either the left or right checkerboard was switched between DC and an equal-average-luminance supra-CFF flicker ranging up to 141 Hz. The frequency of the supra-CFF source is always chosen to produce an interaction with a 1-Hz periodicity in the combined luminance envelope for the two sources. Subjects are asked to detect the interaction for a supra-CFF source up to at least 100 Hz, while control experiments (sub-CFF source switched off) are used to exclude artifactual explanations.

The second study of flicker would use the objective electrodiagnostic techniques of visually evoked responses to checkerboard alternation, where the frequency of alternation is sufficiently high so that flicker is not perceived. This study is an objective method for determining if flicker information is being received by the visual cortex and would further the hypothesis that subliminal flicker affects visual function.

A third study in progress during this past year examines the effect of flicker on saccadic eye movement accuracy in terms of the angular amount and frequency of secondary or corrective saccades that occur after a primary saccade has occurred. Saccadic eye movement is determined by using a special spectacle frame constructed in our laboratory during this past year with infrared sensors that can detect horizontal eye position. Target presentations would be provided under conditions of flickering light and steady light, with each subject acting as his/her own control. Light oscillations will vary from frequencies below CFF where the subject will be acutely aware of the presence of flicker, to supra CFF frequencies where subjects are not aware of flicker but where ERG responses have been obtained in our previous measurements.

We expect these studies to be completed during the next year.

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