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Building Technologies Program

1991 Annual Report

Energy & Environment Division

October 1992

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Building Technologies Program
1991 Annual Report

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Contents

Introduction

The objective of the Building Technologies program is to assist the U.S. building industry in achieving substantial reductions in building-sector energy use while improving the comfort, amenity, health, and productivity in the building sector. We focus our efforts on two major building systems, windows and lighting, and the simulation tools needed by researchers and designers to integrate the full range of energy efficiency solutions into achievable, cost effective design solutions for new and existing buildings.

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 every space in a building, lighting systems facilitate a variety of tasks associated with a wide range of visual requirements while defining the luminous qualities of the indoor environment. Window and lighting systems are thus essential components of any comprehensive building science program.

Building simulation models are key elements of any effort to improve the energy efficiency of the building sector. They are used directly by researchers (to better understand the relative benefits of technology options) and by government (to develop effective codes and standards). Simulation models form the technical basis for design tools that permit design professionals to fully evaluate the impact of design alternatives and ultimately to optimize their designs long before the first concrete is poured.

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) developing advanced technologies that increase the savings potential for each building application; and 2) developing advanced simulation and design tools so that building professionals can effectively apply existing technologies and extend the market penetration of these technologies.

The *Windows and Daylighting Group* focuses on the technical aspects of understanding and improving the energy-related performance of windows. If the flow of heat and light through windows and skylights can be properly filtered and controlled, these building elements can outperform any insulated wall or roof component and 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 group helped accelerate the development and market introduction of windows that incorporate 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 more than $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 the building applications and design tools area 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.

On the basis of the disciplines and facilities involved, research of the *Lighting Systems 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. The primary effort is devoted to the development of electrodeless lamps that operate at high frequency in the range of 50 to 5000 MHz. We are investigating replacements for both fluorescent and high-intensity discharge (HID) lamps. 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 improvements in fixture efficiency and effective use of lighting controls, and how these factors interact with a building's heating, ventilation, and air-conditioning (HVAC) system. In addition, we are studying lighting and visual quality issues. We have developed several innovative, highly cost-effective approaches that improve fixture efficiency, while our visual quality effort has concentrated on obtaining basic information needed to define the lighting conditions that enhance productivity in a cost-effective manner.

Our studies in the impacts area extend research in electric lighting to a broader range of human activities. In specially designed experimental rooms with controlled lighting conditions, human responses are measured objectively by sensitive instrumentation. We have obtained data on the effects of lamp spectral composition on visual function and on brightness perception, and are studying how these results can affect improvements in the energy efficiency of lighting design. Additional studies on glare and flicker as they relate to performance, especially in the automated workplace, are ongoing.

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 potential savings of $5 billion. The energy-efficient high-frequency surface wave lamp promises major reductions in lighting energy use without compromising light levels, while providing considerably longer lamp life.

The primary contribution of the *Building Energy Simulation Group* has been the development of DOE-2, a widely-used whole-building analysis program that calculates energy use and cost, given information about a building's climate, construction, operation, HVAC and lighting equipment, and utility rate schedule. DOE-2 is used by consulting engineers for design of energy-efficient buildings, by researchers for impact analysis of new heating, cooling and lighting technologies, and by state and federal agencies for development of energy-efficiency standards (such as the new DOE/ASHRAE Standard 90.1 for commercial buildings). In collaboration with the Electric Power Research Institute, we have recently begun work to make DOE-2 easier to use and to enhance its calculational capabilities.

Our group also carries out fundamental research into new techniques for simulating complex physical systems. The main result of this effort is an advanced simulation program, SPARK (Simulation Problem Analysis and Research Kernel), that allows users to quickly construct calculation models that are much more detailed than those in programs like DOE-2. SPARK users choose calculation components from a library and graphically link them together into networks that describe the building of interest. SPARK will allow researchers to explore the dynamic behavior of complex systems with an ease and accuracy unachievable with conventional software.

WINDOWS & DAYLIGHTING

S.E. Selkowitz, B. Andersson, D. Arasteh, F.A. Beck, C. Benton, D.L. DiBartolomeo, D. Dumortier, E.U. Finlayson, B.T. Griffith, R.J. Hitchcock, R.C. Kammerud, G. Kelley, E. Lee, J.H. Klems, C. Lampert, K. Papamichael, 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 advanced technologies and for creating procedures to predict and improve the thermal 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, academia, utilities, and government to accomplish our objective.

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. Much of our R&D activity is undertaken in close collaboration with the organizations that will ultimately utilize the results of our work to advance energy efficiency within the building community.

Our overall strategy is to develop the knowledge base needed to maximize the energy efficiency of existing technology and to assist industry in the development of the next generation of energy-efficient window systems. To carry out this effort, we have organized our research into three major areas:

- Advanced Materials and Concepts
  - optical and thermal materials
  - advanced systems and concepts
- Fenestration Performance
  - window rating systems
  - thermal analysis
  - daylighting analysis
  - field measurement of performance
- Building Applications and Design Tools
  - nonresidential buildings
  - residential buildings
  - design tools

ADVANCED MATERIALS

Significant reductions in energy consumption by buildings will result from the development and introduction of new high-performance glazing materials. Since the inception of our program, we have worked to identify, characterize, and develop promising new optical materials to assist industry in developing the next generation of advanced fenestration systems. We provide scientific coordination for DOE-funded research projects at universities, private-sector firms, and other national laboratories. We also work to transfer our research results to the private sector.

In 1976, development of low-emittance (low-E) coatings was a major objective of our program, 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 incorporates low-E technology, and 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 possessing 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 and accelerate the use of spectrally selective coatings for solar control and thermal insulation. These solar control coatings have a combination of high visible transmittance and low shading coefficient to minimize cooling load. Selectively coated glass and plastics now commercially available are based on the use of multilayer coatings incorporating silver. We have investigated classes of metallic compounds which are inherently more durable than these commonly used silver coatings and which in some cases possess even sharper wavelength selectivity. We are using several modes of ion-assisted sputter deposition to enhance the optical properties of these thin film materials, including a miniature ion implanter developed at LBL. Figure 1 shows the optical properties of a polycrystalline tungsten bronze deposited using both ion bombardment and substrate heating. The properties are nearly equal to the ideal properties of a single crystal of a similar material. We also compiled a comprehensive database of existing and experimental coated glazing products. A workshop on spectrally selective glazings was organized with assistance from utilities and manufacturers to be held in Spring 1992. Utility design assistance and rebate programs are an attractive vehicle to promote greater use of selective glazings, and this workshop is designed to facilitate greater interaction between utility planners and fenestration manufacturers.

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 highly 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 require less total heating energy than insulated walls over a complete heating season.

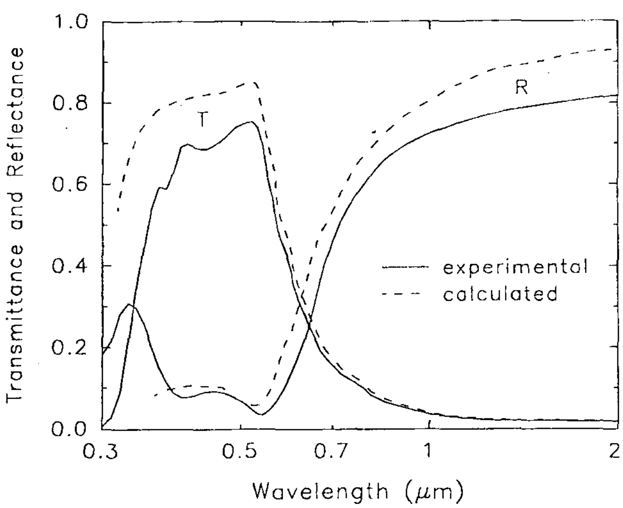


Figure 1 *Spectral transmittance and reflectance of a WO_3 film deposited at 459°C using ion-assisted sputtering compared to film properties calculated from single-crystal data.*

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 BPA super energy-efficient demonstration homes in Montana. These windows were designed to build on existing manufacturing processes and to utilize glazings 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 "super glazing;" an insulated glass unit with a center-of-glass R-value of 8 hr-ft^2-F/Btu. Two other manufacturers began to offer windows with "super glazings" for sale in 1991.

During winter 1989-1990 and winter 1990-1991, 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. Our data show that these glazing systems can perform as well as an insulated wall, although the total window, including the sash and frame, does not perform as well. These results suggested the need to concentrate on improving the thermal performance of sash and frame.

In 1991, we focused our attention on working with the window industry to develop higher performance edge and frame systems. Our Infrared Thermography Laboratory, established in 1990, was used to test prototype windows from approximately a dozen manufacturers. Test results were analyzed by LBL staff and were shared with each cooperating manufacturer (Figure 2). Our work demonstrates that significant thermal improvements can be made by combining design changes in existing edges and frames and by substituting new materials having lower thermal conductance. Improved frames, edges, and window/wall interfaces will be the focus of our research efforts for the next few years.

Advanced Insulation Systems

In 1990, as a spinoff from our superwindow research, we invented a new design for an energy-efficient, non-CFC 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 and focus primarily on replacing CFC blown foams in refrigerator/freezer appliances and in building components.

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.

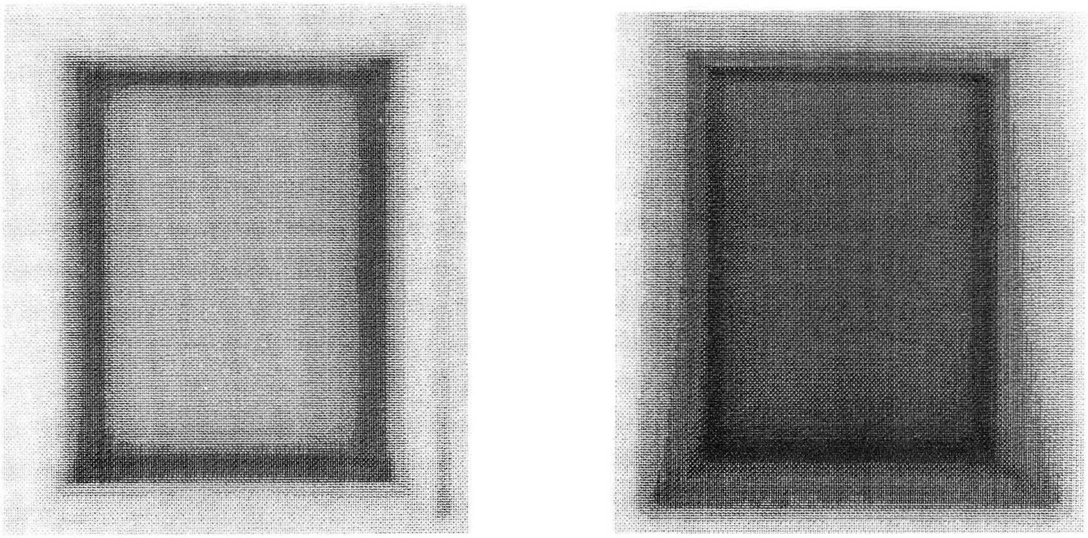


Figure 2 *Infrared image of the warm side of a superwindow (left) beside a conventional double-glazed window (right). The superwindow is a much better insulator, as can be seen from the warmer surface temperatures (light gray indicates warm surface temperatures, dark gray and black indicate cold surface temperatures). (XBB 923-1719)*

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-ft^2-F/Btu-in) for air-filled panels, 49.3 m-K/W (7.1 hr-ft^2-F/Btu-in) for argon-filled panels, and 86.8 m-K/W (12.5 hr-ft^2-F/Btu-in) for krypton-filled panels. Thus, air-filled panels perform as well as styrene foam, and argon-filled panels perform as well as CFC blown foams—a performance level twice that of fiberglass. Krypton-filled panels offer performance levels much higher 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 continued during 1991. We focused our efforts on collaborative efforts with industry to produce suitable gas-barrier materials and on developing stiffer baffles with minimal solid conduction.

Research efforts during 1992 are aimed at building prototype GFPs for use in conjunction with non-CFC blown foams in an EPA-sponsored advanced appliance demonstration project. For all applications, additional nonthermal testing (e.g., flame spread and smoke generation, acoustical resistance, and accelerated aging) is necessary to assess potential end uses.

Optical Switching Devices

Electrochromic devices can dynamically control the solar and visible light transmission of windows in buildings, automobiles, and aircraft. These devices are the most versatile and useful of the broad family of chromogenic technologies, including large-area liquid crystals and photochromic materials. Glazings using electrochromic coatings will have a wide dynamic switching range (e.g., 10-80% visible transmission), moderately fast switching times (1-20 seconds), and low power consumption. Electrochromic technology can be used with "smart" control systems to improve thermal and visual comfort, to maintain user-specified lighting levels, and to reduce building energy consumption. Energy simulation studies of office buildings indicate that this technology can provide substantial cost savings by reducing lighting, cooling, and peak electric demand. Other benefits include reduced HVAC system size, which can help offset the higher initial cost of this technology. Our objective is to create the technology base to reduce the technical and market risk to major industry investment. Our work focuses on the design, construction, and characterization of electrochromic devices, with a smaller supporting market conditioning effort.

During FY91, our computer simulation studies on the energy performance of switchable glazings have helped to define the necessary characteristics of advanced windows. We have developed our WINDOW 4.0 simulation program to include adjustable spectral characteristics useful for modeling chromogenic glazings. Our simulation work has demonstrated the advantage of reflective electrochromics over absorbing coatings, and has suggested that the performance of absorbing electrochromics can be substantially improved by adding a fixed spectrally selective coating to the window system. Data from earlier field tests of a 1 × 1-meter prototype electrochromic window in the MoWiTT test facility were analyzed and published.

Our materials research has concentrated on device development based on nickel oxide and tungsten oxide electrochromic materials. The major device components are the electrochromic layer, the ion conductor, and the ion storage layer. We have developed sputtering techniques to reproducibly coat glass with high-quality electrochromic nickel and tungsten oxide. In a collaboration with Southwall Technologies, we have adapted this process to coat polyester substrates. We have refined our electrochemical deposition techniques to produce a variety of chemically modified electrochromic electrodes with improved performance, such as nickel-cobalt and tungsten-molybdenum oxide.

We have made a significant development in polymeric ion-storage materials in collaboration with the Battery Group of the LBL Materials Sciences Division. We have developed and filed a patent application on a group of organodisulfide polymers that function as ion-storage materials that should result in better performance and lower device cost. A tungsten oxide device made using one of these polymers switched over a range of $T_{photopic}$ = 61–9% and T_{solar} = 47–5% with switching at a low 1.2V dc (Figure 3).

We constructed new electrochromic devices using nickel oxide, tungsten oxide, niobium oxide, and polymer ion conductors. One of our best devices was made of nickel oxide:cobalt/lithium polymer/tungsten oxide. This device exhibited integrated optical transmission properties of $T_{photopic}$ = 70–21% and T_{solar} = 52–14%. A second device, made of nickel oxide:cobalt/proton polymer/niobium oxide, had transmission properties of $T_{photopic}$ = 65–16% and T_{solar} = 45–15% (Figure 4).

In studies sponsored by the International Energy Agency (IEA), we have reported on characterization and test methods for electrochromic devices. This will help industry perform standard measurements on these devices. We also measured the performance characteristics of an Asahi Glass prototype electrochromic device.

Our research in FY92 is directed at improvement of polymeric ion-storage layers, which may result in a composite polymer design—eliminating one of the device layers. In collaboration with industry partners, we will continue to develop fabrication techniques for laminated devices and refine sputter deposited coatings on polyester. Energy modeling studies will continue with the new WINDOW 4.0 simulation program and DOE 2.1 building energy modeling program for studying the total building impacts of switchable windows in a variety of climates and building designs.

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 currently cost effective on the basis of their energy savings alone. Our objective has been to develop designs that use cost-effective optical technology to supply daylight to core building zones. Engineering analysis of several key optical elements and subsystems has been completed; the next step will be to fabricate and test a prototype system. Since DOE support is no longer being allocated for this effort, collaborative funding arrangements with industry and other sponsors will be sought in 1992 to carry out this phase of the program.

Automobile Glazings

Much of our group's expertise in the technology and performance of glazings for buildings is directly applicable to automobile windows. Reduction of the window solar load on automobile air conditioners would extend the range of electric vehicles, reduce the production of CFC refrigerants, reduce emissions, and save fuel. Reduction of window heating load could also extend the range of electric vehicles, which produce little waste heat and would thus use battery power to warm passengers in cold weather. We investigated applications of durable selective coatings, electrochromic coatings, and angle-selective coatings to automobile windows and also investigated the use of compact body insulation. Under a collaborative research agreement with Dow Chemical Co., we are jointly developing an electrochromic device using LBL sputtered coatings and Dow's polymer electrolyte. Devices were tested at Dow for thousands of cycles without deterioration. An upgraded heat-transfer model for automobiles was installed and tested. The model was used for a joint study with Airco Coating Technologies to model the effect of their advanced coatings on automobile windshields. We are assembling a group of automobile and glazing manufacturers to develop an industry standard climate control simulation model.

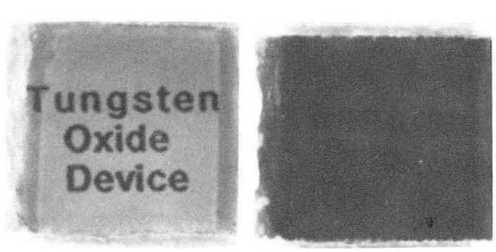
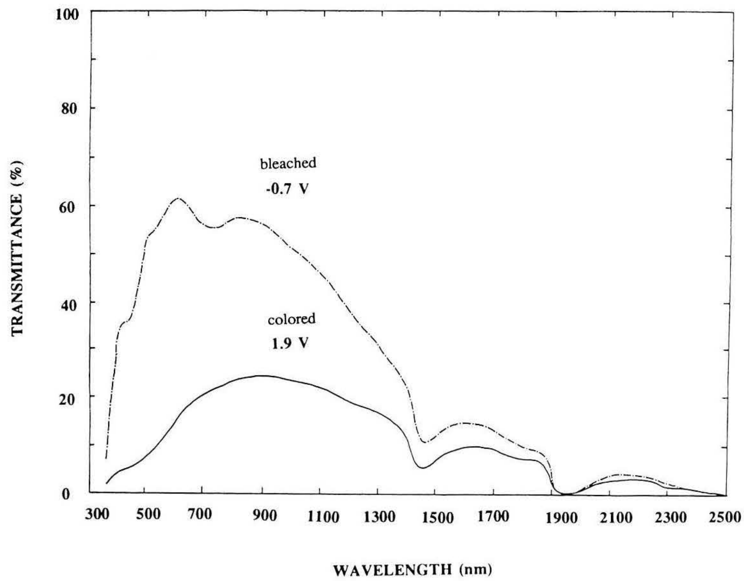


Figure 3 *The words printed behind it are clearly visible when an electrochromic device is switched to a high-transmission state. It becomes opaque when ions move into the electrochromic layer and react with tungsten oxide.*
(CBB 916-4871C)

Figure 4 *The solar spectral transmittance of an electrochromic device (nickel oxide/polymer/niobium oxide). Both the bleached and colored (deep bronze) states are shown. The device can be held at any intermediate level of coloration between these states. (XBL 917-1547)*



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. Beginning in 1986, we released the WINDOW program to aid in the evaluation of new product options and to serve as a standard for calculating window heat transfer properties. 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.

This year we continued to focus on research issues relating to the spectral and angular dependencies of glazing materials. Construction of an experimental apparatus to measure these effects continued in 1991. A procedure to calculate the angular solar optical properties of uncoated glazing systems, given only their properties at normal incidence, and a multiband spectral model were incorporated into a draft version of WINDOW 4.0. WINDOW 4.0 will also include a simple model of solar heat gain through frames. Most importantly, this draft version of WINDOW is consistent with the rating procedure developed by the NFRC (see next section).

Window Rating and Labeling System

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 and document a procedure to rate window U-values. This procedure, drafted in 1990 and finalized in 1991, 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. To aid NFRC in the development of an Annual Energy Index, we developed a draft version of a PC program, RESFEN, which calculates seasonal and annual energy impacts of fenestration products in typical residences throughout the United States. We are involved with all technical issues relating to the development of these and other NFRC procedures (i.e., shading coefficient, visible transmittance, infiltration, and condensation resistance) and will continue our active involvement in NFRC's activities in 1992.

Studies of Daylight and Solar Heat Gain

Providing daylight to building interiors is one of the most important functions of windows and skylights, 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 that uses 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 for all sun, sky, and 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 5). 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 measured properties of component layers while correctly accounting for multiple reflections. During 1991, 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 1992. 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. In 1991 we completed a four-year program of measurements on common window configurations, 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.

Daylighting Analysis

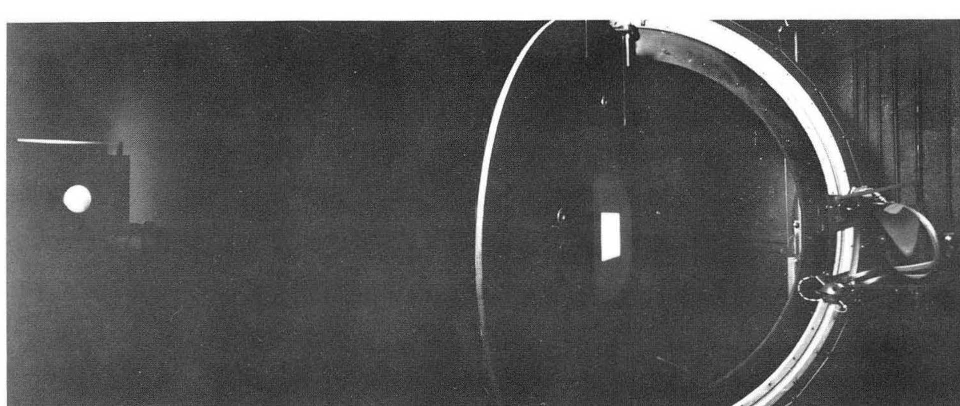
The prediction of lighting quantity and quality in the luminous environment is essential for energy-efficient daylighting design. Over the years, we have developed a range of daylighting analysis and design tools to expand our modeling capabilities and to improve calculational accuracy. Further improvements 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 IEA task group as the primary tool for a multinational daylighting research effort.

In 1991 we completed testing on a new version of SUPERLITE that models electric lighting. Further collaborative development work with the IEA group and with other university-based groups will improve the ease of use of the microcomputer version of the program and enhance its input/output capabilities. The ultimate goal of this work is a tool that can be used by designers to improve the use of energy efficient daylighting design strategies.

The Sky Simulator and Daylight Photometric Laboratory

Scale-model photometry of innovative fenestration systems 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

Figure 5 *A measurement of the bidirectional transmittance of a diffusing sun screen in progress on the scanning radiometer. (CBB 900-8720)*



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. Although the facility continues to be used for qualitative lighting studies, further research use of the sky simulator awaits upgrades to the lighting control and data acquisition systems of this facility.

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, and that fenestration systems that properly control summertime solar heat gain can provide large energy benefits for buildings that use daylight to displace electric lighting. Subsequent computer simulations 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 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 6), 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. Wesolved 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.

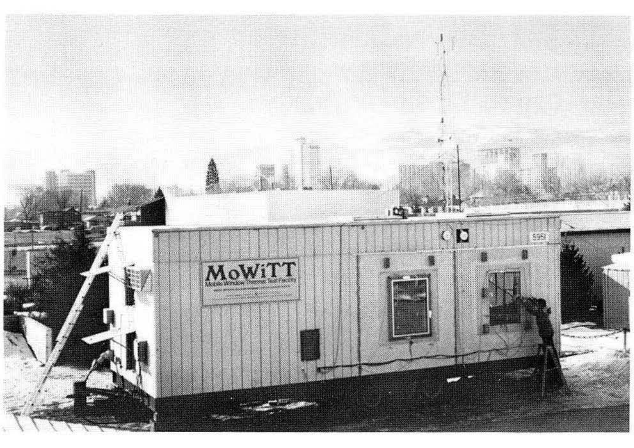


Figure 6 *The MoWiTT facility at its field test site in Reno, Nevada. Two sealed insulating glass units are mounted in the two calorimeters. (CBB 892-812-A)*

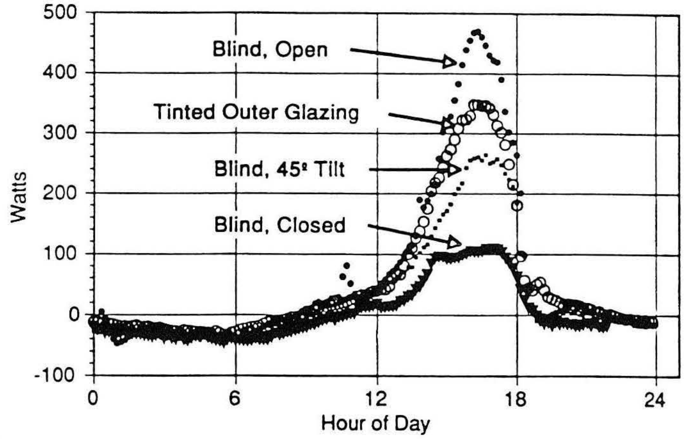


Figure 7 *Side-by-side measurements of two low-E double-glazed windows with different methods for solar heat gain and glare control are summarized in the four curves. One window (open circles) utilized a tinted outer glazing, whereas the other (remaining three curves) utilized a venetian blind between two clear glazings. The comparison demonstrates the greater range of performance available with an operable system.*

During 1991 we began to compare window design strategies for controlling summertime solar heat gain while admitting useful daylight (Figure 7), continuing the industry-supported study of emerging window technologies begun in 1990. We also completed a upgrade to the MoWiTT to increase its accuracy in measuring nighttime heat loss, a step made necessary by the increasingly high-performance "superwindows" beginning to appear in the marketplace.

In 1992 we will utilize the increased accuracy of MoWiTT to complete our studies of the winter performance of highly-insulating windows as part of a U.S.-Canadian joint research project. We will also continue our studies of solar heat gain and continue to test 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 measurements from the MoWiTT have the potential for removing uncertainties about window performance that have slowed progress in implementing energy efficient building design for the past decade.

BUILDING APPLICATIONS AND DESIGN TOOLS

The development of new glazing materials and experimental determination of fenestration system performance must be complemented by development of tools and design guidelines that will assist the building design community in the most cost effective utilization of window systems. Our objective in the Building Applications area is to apply the knowledge gained from our more basic research efforts to real world buildings and develop the tools and design data that are necessary to disseminate this information.

Nonresidential Building Simulation Studies

We completed the first draft of a Daylighting Handbook for Commercial Buildings. The handbook provides fenestration and daylighting design guidelines to architects, engineers, builders, and owners. The handbook represents the integration of our experience in promoting effective daylighting and results of prior collaborative efforts to develop tools to assist designers. Handbook topics include an overview and historical discussion of daylighting; light and its behavior; site location and context; building form including openings; lighting controls; and methods for evaluating energy and comfort performance .

We have begun creating the first version of a new microcomputer program, COMFEN. This program calculates the incremental energy and cost performance of fenestration options for a prototypical commercial building module. Users have the ability to vary fenestration size, U-value, shading coefficient, visible transmittance, desired lighting level, lighting power density, and daylighting strategy. The methodology is based on a regression analysis of many DOE-2 simulation runs and represents a companion product to the RESFEN program discussed below.

Envelope and Lighting Technologies to Reduce Electric Demand in Commercial Buildings

In 1991 we completed the first phase of this multiyear project, supported by the California Institute for Energy Efficiency (CIEE) with funding from major California utilities and co-support from DOE. California utilities have been leaders in the U.S. in promoting the use of new energy efficient building technologies. We are collaborating in this project with the Graduate School of Architecture and Urban Planning, University of California, Los Angeles.

The focus of this project is to develop and promote advanced integrated building systems incorporating high-performance envelope and lighting elements. The largest components of peak demand in most California commercial buildings can be traced to the fenestration and illumination systems, which typically impose large electrical loads for cooling and lighting. Reducing or eliminating these loads can be a cost-effective, demand-side management option for utilities. While the performance of lighting and envelope systems has improved in recent years, designers confronted with a large array of new technologies have not been successful in creating designs that achieve optimal energy performance results. The full potential of existing and emerging technologies will be realized only when they are commercially available in a form that maximizes performance and facilitates widespread application. Technologies designed and packaged as *integrated systems* and supported by appropriate tools to assist in design, specification, and assurance of performance will exert a far greater impact in the building community.

Project goals include development of integrated envelope/lighting systems that enhance comfort and productivity while significantly reducing energy use and peak demand. The project seeks to encourage industry to adopt and commercialize these technologies, and to stimulate architects and engineers to specify them. Demonstration projects are an integral vehicle to verify performance claims, generate interest, and reduce risks. Improved design tools will also be included at a later phase.

Several task areas comprised the first phase of the project: development of performance targets and estimates of savings potentials, design and analysis of the preliminary envelope/lighting system, and technology demonstrations. In 1991, computer modeling of advanced envelope/lighting technologies projected a potential 38% reduction of lighting and cooling energy by the year 1995 and a 73% reduction by 2005; projected peak demand would be reduced by 22% in 1995 and by 40% in 2005 (Figure 8). Optimal whole-building performance "targets" were derived for the years 1995 and 2005. We reviewed a large number of underexploited individual technologies as candidate components for integrated systems, compiling a substantial compendium which has proven useful to outsiders as well as serving project needs. We began participation with utilities in two short-term demonstration projects wherein we hope to further explore our initial concepts for integrated systems in real buildings.

International Collaboration on Atrium Research

Large numbers of atria are being built in the United States and overseas. Most of these atria are not particularly energy efficient; in fact, most atria waste significant amounts of energy. Design guidelines addressing the energy implications of atrium design decisions are urgently needed to convert atria to energy-efficient design strategies. Developing such guidelines will help designers understand the energy implications of design decisions and will guide them in making those decisions. It will also provide information on the comfort conditions to be expected in such spaces, allowing designers to match energy systems to the function (and comfort requirements) of a given space.

For several years, LBL has been evaluating and analyzing the performance of solar commercial buildings as part of the U.S. contribution to the IEA Task XI and the U.S./U.K. Bilateral Agreement. The work for Task XI has emphasized simulation analysis and evaluation of both energy use and occupant comfort in selected atrium buildings, as well as synthesis and interpretation of the results of the monitoring and analysis of a range of atrium buildings.

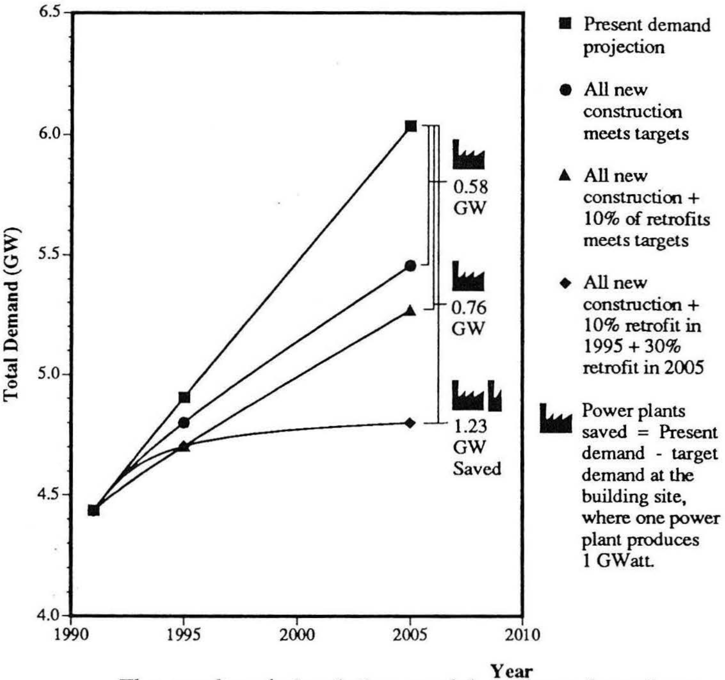


Figure 8 *Total potential demand reduction for commercial office buildings in California if new and retrofit construction met lighting and building envelope performance targets for 1995 and 2005 derived in the first phase of this study.*

The results of simulation model analyses have been incorporated into the Atrium Chapter of the Source Book, the main project deliverable for IEA Task XI. The first draft of this chapter was prepared (by LBL and others) during 1990 and has undergone extensive review by the multinational Task XI participants during 1991.

Our technical contributions to this activity include novel use of the BLAST building simulation program to accurately model an atrium building (Dumortier et al.). A detailed description of the model of the ELA University building in Trondheim, Norway and its calibration are included. Simulation results for key atrium design strategies in Trondheim and in five other American and European locations are presented. Design recommendations based on energy performance and comfort analysis are outlined for each key atrium design strategy and summarized in the report's conclusion.

Residential Buildings

We completed the first draft of a Residential Window Design Handbook. The handbook provides fenestration design guidelines for architects, builders, and homeowners. Topics include an overview and historical discussion of residential windows; specific design recommendations regarding view, lighting, ventilation, insulation, solar heat gain, condensation, and acoustics; material selection and installation guidelines, including glazing products and framing; and regional climate guidelines on energy performance.

We completed two versions of RESFEN, a new microcomputer program that calculates the seasonal and annual incremental energy and cost performance of fenestration for several residential building models. Users have the ability to vary window size, window type, U-value, shading coefficient, infiltration levels, and interior and exterior shading systems. The simplified methodology will serve as a prototype for a fenestration energy rating procedure currently being evaluated by the National Fenestration Rating Council.

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 addressing energy-related design issues and considering new, energy-efficient technologies. We began to explore new concepts for computer-based architectural design tools several years ago, after observing that energy efficiency remains a low priority in standard building design practice, mainly because of lack of time and expertise to predict the energy-related performance of buildings. Our initial image of an intelligent and integrated package that would contain the required expertise and automate the energy-related performance prediction has since been developed into an experimental prototype, the BDSE. This integrated computer-based environment uses various new computer technologies, such as hypertext, multimedia, and expert systems, in order to more effectively reach and engage building designers (Figure 9).

During the past year, we developed an approach for expert systems for design that distinguish between those design tasks that can be effectively delegated to a computer and those value-oriented decisions that must be made by the designer. This work formed the base of a theoretical model of the design process which allows for the representation of the specifiable design knowledge and the automation of the design tasks that can be effectively delegated to the computer.

One of the first products of our BDSE development efforts is a demonstration prototype which will be used to test and validate our theoretical model for integrating energy issues into the design process. The BDSE prototype addresses the design of windows and electric lighting in office buildings, considering energy requirements, comfort, and cost. It is designed to record all design decisions, provide information on how to satisfy specific design criteria, and to determine the performance effects of design modifications. Moreover, it will automatically record the designer's preferences with respect to performance acceptability, thus "learning" through use. All of these functions are accomplished through integrated use of data-, issue-, and rule-based systems, under a multimedia user interface that allows access to electronic handbooks, product catalogs, and case studies. By the end of FY92 we expect to have an operating prototype of this system. Our activities in this area also contribute to the Advanced Energy Design and Operation Technology (AEDOT) project supported by DOE.

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 popular press and trade journal articles, network and utility-based television production, and exhibits. We continue to develop more effective approaches to technology transfer by experimenting with new electronic and optical media. Our primary audiences include other national and international 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 1991.

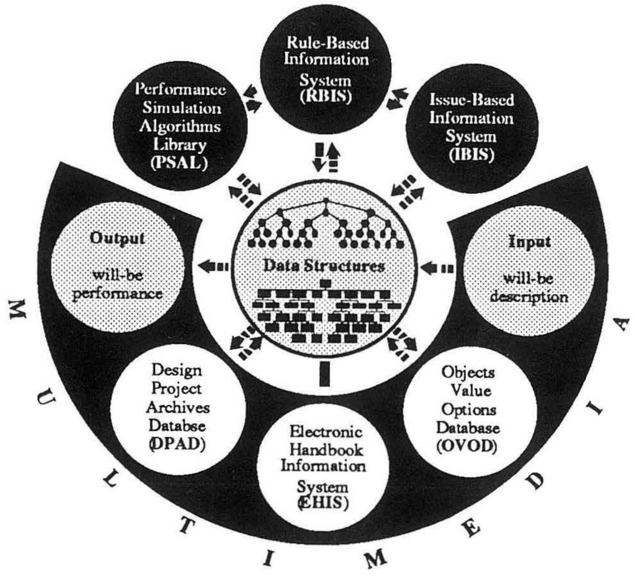


Figure 9 *The components and structure of the computer-based Building Design Support Environment.*

In 1991, we hosted several long-term visitors from Norway and Romania. 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, created for Southern California Edison's Customer Technology Application Center (CTAC), was adapted for traveling exhibitions. 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.

Building on our multimedia development experience, we continued to explore new information and technology transfer delivery systems. Believing that timely and entertaining professional education is critical to integrating new technologies and know-how into practice, we experimented with voice control of the computer, use of computer "agents" to facilitate communication among users, and data glove control for virtual reality tours of computerized graphic design environments.

We believe that these advances in computer-based information systems will ultimately provide a cost-effective means of reaching key decision makers in the area of building design and will motivate them to design projects that more aggressively address energy.

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LIGHTING SYSTEMS

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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 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 affect productivity and visual functions; and determination that lamps providing scotopically rich spectra can supply major energy savings in a highly cost-effective manner.

Our program is now actively pursuing the development of more efficient light sources through technical concepts employing a variety of ingenious methods for operating lamps at very high frequency without electrodes, which improves both efficiency and longevity. In addition, the program is developing comprehensive strategies to optimize the benefits obtained by combining our new technical approaches that improve the efficacy of fixtures together with lighting control systems. 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 155 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 1991—and those planned for 1992—by each of our three major efforts: advanced light sources, building applications, and impacts on productivity.

ADVANCED LIGHT SOURCES

The work on advanced light sources promotes development of new highly efficient lamp technology and light sources. To understand what can be accomplished in this area, consider that the most efficacious four-foot fluorescent lamp, operated at a medium high frequency possible with today's technology (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 present decade.

In the area of fluorescent lamps, our present candidates for efficiency improvements include three major energy-loss mechanisms: 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.

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 working on a phosphor chemistry project 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 allow us to use 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 characteristics desired by lighting designers.

Besides the light source itself, the second most important component of the lamp is the electronic power supply which must convert incoming building power to the high-frequency power required by the electrodeless light sources. Because of the total absence of commercially available, efficient power supplies operating at the power level and frequency needed for our light sources, we have established a working relationship with a small electronics firm, Design Automation, Inc. (DAI), of Boston, Massachusetts, to develop the necessary power supply and amplifier. The physical nature of the coupling between the light source and the power supply means that the research is highly interactive between the power supply and the light source. DAI has developed and holds patents on a concept referred to as the Type E-Amplifier, which provides a method for high-frequency switching of voltage at zero current and current at zero voltage. In the following paragraphs, we discuss several successful stages in this development process. Figure 10 shows our present prototype amplifier.

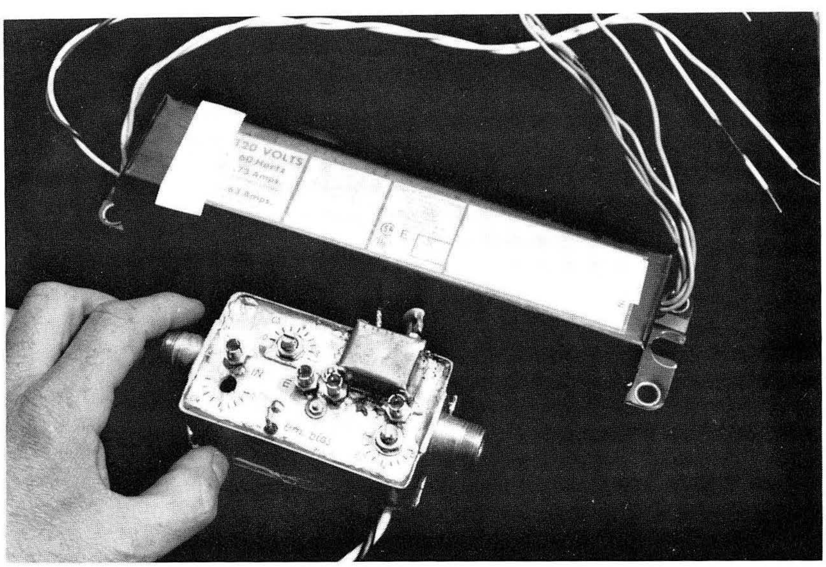

Figure 10 *The current type-E amplifier is shown with a conventional fluorescent lamp ballast. The prototype displayed uses only one transistor and is considerably lighter in weight than present high-frequency solid-state ballasts. (XBB 922-887).*

TM-Mode Fluorescent Lamp

During FY 1991, we focused considerable effort on developing the high-frequency power supply for the low-pressure electrodeless fluorescent lamp. This lamp is excited through a cavity coupler in the wave guide mode referred to as transverse magnetic or TM mode. Operating at 215 MHz and at a typical commercial power level of 13 watts, our prototype Type-E amplifier successfully started and delivered steady power to the lamp and coupler combination. The amplifier was about 80% efficient according to our measurements and was completely stable. The overall efficacy improvement over the conventional 60 Hz operation was 38% at the rated power level.

Two important theoretical developments were accomplished during this past year: 1) a calculational procedure for determining the steady state impedance of the TM mode lamp-coupler combination from measurements obtained from the application of a network analyzer device, and 2) an approximate theoretical basis for the actual steady state impedance. These developments are essential for the design of impedance matchers that would allow lower frequency operation. Achieving lower frequency operation (possibly in ISM bands) has advantages for both simpler electronic components and easing requirements on electromagnetic emissions. Maintaining the high efficacy improvement while operating at lower frequencies will be a prime consideration for the FY 1992 effort.

HID (High-Intensity-Discharge) Lamp

During the past year, we made significant improvements in coupling high-frequency power efficiently into an argon-mercury electrodeless HID lamp. Operating at 35 watts, a small lamp of about 2 inches in length is ignited to full power in about 1 minute of time. This is an order of magnitude quicker than can be achieved with conventional electroded HID lamps. During the next year, we expect to achieve the light output of a 100 W incandescent with about 20-25 watts of electrodeless HID power. Because present compact fluorescent lamps do not achieve the lumen output of the higher wattage incandescent lamps while maintaining their small size, there is a significant opportunity for our concept to fulfill the need for a highly efficient replacement.

The original approach for the TM mode electrodeless HID was to use the RF couplers and impedance matchers developed for the low-pressure discharges to operate a TM mode argon-mercury HID. With some RF coupler modifications, this worked well and TM mode electrodeless argon-mercury HID's have been operated from 35-100 watts. However, the original RF couplers and impedance matchers were designed to operate in the frequency range 200-500 MHz in conjunction with a low-pressure discharge tube. The high-pressure discharge tubes are typically 100 times smaller than a typical low-pressure discharge tube; thus, with all other things more or less equal, they must be operated at higher frequencies than their low-pressure counterparts. Their frequency range of operation was 600-800 MHz. After a thorough investigation of the plasma and spectral properties of these discharges, we determined that there was a 10% energy loss in the RF coupling to the plasma. This is not totally surprising as the RF couplers and impedance matchers used were designed for 200-500 MHz operation, and not for 600-800 MHz operation. During 1992, we will work to reduce or eliminate this inefficiency by modifying the HID RF coupler with a focus on lower frequency operation. In combination with these modifications, we will evaluate the efficiency of these discharges at different power levels.

Mercury Concerns

A brief technical analysis was prepared in response to concerns about a potential negative environmental impact related to replacing the energy-inefficient incandescent lamp with the much more efficient compact fluorescent lamp, which contains minute amounts of mercury, a toxic substance. The brief report deals with the trade-off between mercury releases during the burning of coal for electricity generation and the mercury used in compact fluorescent lamps. Our rough analysis indicates that there would be far more mercury released by the coal-generated electricity wasted in powering the inefficient incandescent lamp.

Multi-Photon Phosphors

Both theoretical calculations and experimental measurements were carried out in order to explore a number of phosphor systems for multiple photon emission (MPE). Many proposed schemes which have appeared in the literature would theoretically lead to MPE. The processes we have considered 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 be activators and/or sensitizers. The third process involves multiplication of electron hole pairs due to the Auger process, which affects the electronic states of the valence and conduction bands.

Of the three processes, the cascade and interband processes have been shown experimentally. Previously, 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.

During the past year, continued effort at GTE Lighting was devoted to the search for small-band (2.5 eV to 4 eV) hosts and possible dopants to allow the IBA process to occur. Based on calculations and subsequent band gap measurements, some promising candidates included categories of sulfides, titanates, antimonates, and thiosilicates. Dopants were selected from alkaline earth and rare earth elements, and about 30 candidates were seen as viable (i.e., they showed reasonable luminescence under 365-nm and/or 254-nm excitation). We chose the best candidates in terms of brightness; along with the previously identified phosphors ($Ba_2TiP_2O_9$; Y_2O_3:Eu; Zn_2SiO_4:Mn and YBO_4:Eu), these were studied at the Brookhaven National Synchrotron Light Source (NSLS). Data analysis should be completed early in FY 1992.

Our theoretical studies have indicated the possibility of yet another concept for multi-photon emission, namely, Impurity Assisted Interband Auger (IAIBA). The data taken at

NSLS should provide some confirmation of this proposed process.

The multi-photon phosphor Zn_2SiO_4:Mn was applied to a lamp wall, and the lamp was run in a low-pressure/ fluorescent mode to examine the visible light output directly. The discharge was operated with a rare gas fill, without mercury, and performed well. However, the light output was disappointingly small, which was eventually traced to phosphor degradation occurring during the actual coating and finishing process. We hope to correct this problem next year and expect to demonstrate light outputs close to our calculated values.

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 simulated scenes that 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. These R&D efforts are coordinated with substantial technology transfer activities with the fixture industry in order to assure rapid acceptance of our concepts into the market.

Energy-Efficient Luminaires and Thermal Control Devices

Several approaches have been developed for improving the thermal performance of fluorescent fixtures. These techniques have been successfully applied to a number of fixture systems, notably full-size and compact fluorescent fixtures.

For the four-foot fluorescent luminaires, two main concepts have been explored: convective cooling and the thermal bridge. The thermal bridge employs a liquid heat sink and a conductive metal bridge with cooling fins external to the fixture shell.

Methods to improve the performance of compact fluorescent fixtures have been focused on convective cooling, the liquid heat sink, and a metal spring bridge with dissipating fins. Lamp burning position (base up or base down) was found to be a key determinant of system efficacy.

The feasibility of techniques to improve thermal performance has been demonstrated, and industry has shown strong interest and support for this work. We have been collaborating with fixture manufacturers and utilities to keep them abreast of the latest developments and encourage technology transfer. One manufacturer has already licensed our CFL fixture concept using the metal spring bridge. However, these technologies need to be further researched and refined before advanced prototypes can be presented to industry.

In 1992, we plan a major effort to improve the efficacy of recessed open downlights by implementing new concepts developed for convective cooling. We will measure performance responses to different approaches and conduct photometric studies to assess any optical losses associated with the convective strategies. We will begin cooperative efforts with industrial partners to apply the thermal bridge concept to standard linear fluorescent systems.

Expert System for Specifying Energy-Efficient Lighting Equipment

A prototype analysis tool for analyzing the energy performance, luminous output, and cost-effectiveness of existing fluorescent lighting systems and proposed retrofits was completed in FY 1991. The prototype was implemented as a template for the popular Excel spreadsheet program (Microsoft Corporation) and is code named LEAR (Lighting Energy Analysis for Retrofits). It runs on both IBM-PC compatibles and on the Macintosh computer. At present, the program is restricted to analyzing relamping, re-ballasting, and de-lamping of 4-foot fluorescent luminaires. We completed a draft of the user documentation for the current LEAR.

We extracted thermal performance data for fluorescent luminaires from GE's LEAP program, Lithonia's SPEC-L program, and from data published by Philips. These data have allowed us to develop a simple reference table of fixture ambient temperatures for many commonly encountered lamp/ballast/fixture combinations. This table has been incorporated into LEAR. However, the model is purely empirical and does not allow predictions of operating temperatures for cases not included in the table. This will require a more general thermal model that we intend to develop during the coming year.

We conducted a meeting of lighting experts at the IES Annual Conference in Montreal in August 1991 to review and critique the algorithms and methodology used in the LEAR program and to solicit opinions as to how LEAR could be improved and generalized.

We have collaborated with National Renewable Energy Laboratory (NREL) in the development of the Federal Lighting eXpert System (FLEX) program that is being developed to support the FEMP Relighting program. We translated the core algorithms and databases in LEAR into the C programming language for inclusion into FLEX.

Quality Illumination and Performance

A resurgence of interest in the possible benefits of polarized light produced by light fixtures led to a new analysis of these potential benefits for vertical tasks. Our analysis has led to the following conclusions.

Current commercially available polarizing panels are designed for situations where the light requirements are determined by horizontal orientated visual tasks. As a general guideline, the designer should consider polarized lighting for horizontal tasks which are glossy, and where most of the area of the task is viewed at an angle, instead of head-on. Examples of glossy tasks involve reading or studying magazines and other coated or shiny papers, photographs, paper printed with shiny inks or written on with pencil, and glass or metal surfaces. Computerized visibility calculations for a reference pencil task appear to indicate that on the whole these tasks will generally reach the same visibility at lower light levels with a polarized lighting system than they will with an unpolarized lighting system.

Vertical polarization does not improve the visibility of tasks that are tilted substantially up from the horizontal and away from the line of sight. It also does not improve the visibility for very matte tasks or very small tasks that are viewed normal to the surface. Since polarizing panels are less efficient than a high-efficiency panel in raw light output, they are not recommended for these latter situations. The panels are not economical if this design calls for a higher power level than it would with standard fixtures.

Continual effort on the concept of critical size and performance as it relates to lighting has shown the need to consider both the detection and resolution aspects of reading tasks. Incorporating resolution corrections to the data analysis has greatly improved the quality of the fit and has allowed for a very good homology in contrast and luminance as a function of size for most subjects. This analysis is expected to be completed during FY 1992, and a paper discussing the results and applications for use in field testing for the adequacy of illumination levels will be presented at the national IES meeting in August of 1992.

Computer Imaging

We have made the hemispherical goniometer more operational by analyzing the accuracy of reflectance measurements. These reflectance measurements are used to determine the bidirectional reflectances of various materials which are essential empirical inputs to the database for the Radiance program calculations. We have completed reports describing the spectral characteristics of the luminance camera and accuracy analysis of the camera/goniometer system. Validation and measurement on a variety of specific materials will be accomplished during FY 1992.

We have continued to distribute Radiance to interested users over the last year. The users are generally from academic institutions where the lack of user interface presents few problems; a few users work in commercial lighting design or A/E firms.

In February 1991, we conducted a workshop on Radiance at LBL that was attended by 25 national and international users.

NEW LIGHTING TECHNOLOGIES: IMPACTS ON PRODUCTIVITY AND HEALTH

We can achieve major benefits to lighting energy efficiency by studying human responses to 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 is an essential input to any such development, considering that the end purpose of lighting is for human benefit.

Spectral Effects (Human Response to Electric Lighting, UCSF)

In a series of studies done over the past three years, we have shown that the rod photoreceptors of the eye have significant effects on vision functions at light levels typical of building interiors. These studies (for conditions of full-field of view and adults 20-40 years of age) showed that pupil size was predominantly determined by the scotopic spectral content of the ambient illumination and also that brightness perception of whitish light depended strongly on the scotopic content of the viewed illumination. Thus, two general lighting illuminants providing the same level of photopic luminance of whitish light, but with different spectral distributions, will elicit both different pupil sizes and different perceptions of brightness. The illuminant with the greater scotopic luminance will yield a smaller pupil and will be perceived as brighter.

During the past year, we examined the question of whether spectrally induced pupil size differences affect the recognition of Landolt C orientation with the hypothesis that smaller pupils will yield improved performance. We tested this proposition by comparing two illuminants providing the same surround photopic luminance but with different scotopic luminances. The scotopically richer surround illumination yields smaller pupils and the better performance. The small Landolt C task is viewed on a CRT in binocular vision with a constant luminance unaffected by the surround illumination. Figure 11 shows the experimental setup.

The results of our study demonstrated that scotopically richer light yields smaller pupils at a fixed photopic luminance, which results in better performance on the Landolt C orientation task even though task retinal illuminance is smaller. This determination supports the suggestion that energy savings can be obtained by taking advantage of the visual scotopic sensitivity. If an equal level of scotopic luminance is achieved by increasing the scotopic spectral output obtained at a lower energy, visual performance would remain unaffected and savings would accrue. Additional studies demonstrating this effect are planned for 1992.

Discomfort Glare (Lighting Ergonomics, UCB)

A second area of importance in relating how lighting affects visual performance concerns discomfort glare. Because the trend in moving to the smaller size and more

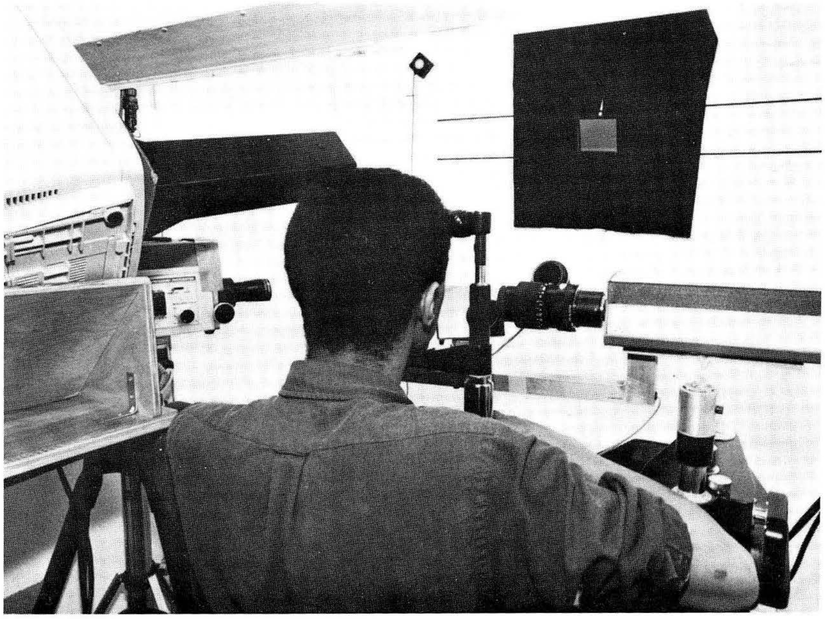

Figure 11 *Rear-view photo of subject in test room, with head on pupilometer chin rest while viewing the task. Task is displayed on CRT situated at left of and slightly behind the observer. Task is viewed via a front surface mirror situated in the middle of the black curtain. The CRT surface is covered with matte black except for the viewing tube. Simultaneous recording of pupil size and Landolt C orientation is performed. (ZBB 916-4500)*

efficient light sources will increase glare response, a better understanding of possible negative user concerns is needed. Although it is relatively easy to perceive and report discomfort sensations caused by an offending light source of high luminance, no one has yet found a reliable objective correlate of discomfort glare. In the 1960's, Hopkinson speculated that changes in pupil behavior could serve as an objective indicator of discomfort glare, and Fry et al (1965-1991) have claimed to have detected glare-induced changes in the power spectrum of the involuntary pupillary oscillations commonly known as hippus. In our laboratory, we find that the power spectrum of the hippus oscillations determined under conditions of discomfort glare is no different than the power spectrum of the hippus present under large luminous fields arranged to give the equivalent pupil size, but without creating discomfort sensations.

In order to find an objectively measured correlate of discomfort glare, we have conducted a pilot study and examined electrophysiological activity associated with the two major facial muscles that surround the eye, viz the orbicularis oculi and the corrugator supercilii. We have made electromyographic (EMG) recordings using small silver/silver chloride electrodes applied to the skin above these muscles and measured electrical potentials while lighting conditions have been changed. Intensities were varied over a range extending both above and below BCD (border between comfort and discomfort).

For a given adapting luminance, the power spectrum of the EMG response remains essentially unchanged from baseline until the intensity of the glare source reaches BCD. Thereafter, the measured EMG response increases monotonically with increasing luminance of the glare source.

For the coming year, we plan experiments using our EMG methods to verify that EMG responses correlate with the known subjective properties of BCD (e.g., dependence on surround luminance). In addition, we plan to examine the influence of the glare source's color on discomfort glare. We will also conduct more precise experiments to determine whether the EMG changes at intensity levels that are still below BCD.

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BUILDING ENERGY SIMULATION

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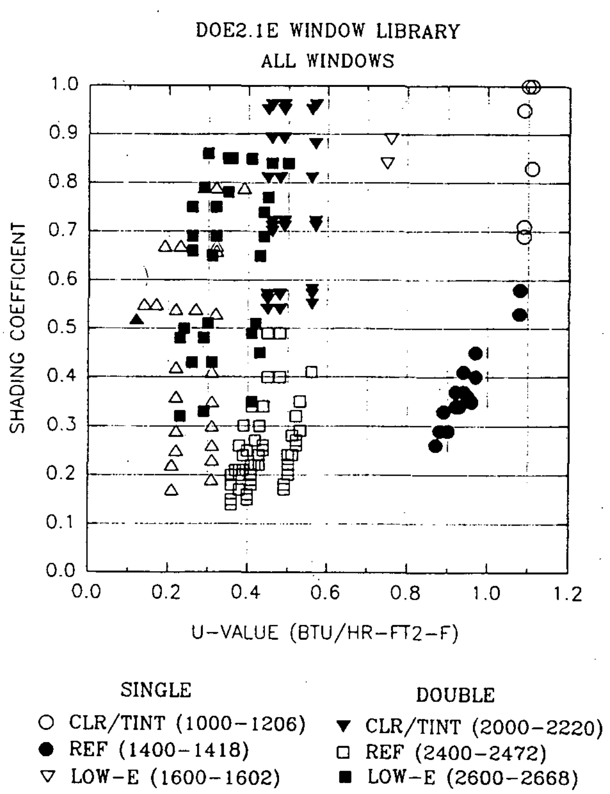
Our simulation research effort develops accurate, well-validated computer programs to assist in the design of energy-efficient and cost-effective buildings. This work includes development and maintenance of current generation energy analysis programs, DOE-2 and the Retrofit Energy Savings Estimation Model (RESEM), and development of the Simulation Problem Analysis and Research Kernel (SPARK) and DOE-3 advanced building performance calculation tools.

DOE-2 is a public-domain computer program that performs an hour-by-hour simulation of a building's expected energy use and energy cost given a description of the building's climate, architecture, materials, operating schedules, and HVAC equipment. DOE-2 is widely used in the United States and in 42 other countries to design energy-efficient buildings, to analyze the impact of new technologies, and to develop energy conservation standards.

SPARK is a modular simulation environment designed for developing customized models for analysis of complex building energy components and systems.

DOE-3 is a substantially improved version of the DOE-2 program that is easier to use by the average designer, can simulate future HVAC technologies, and provides expert-system-based design guidance.



RESEM, the Retrofit Energy Savings Estimation Model, is a PC-based, interactive tool developed for the DOE Institutional Conservation Program to provide reliable estimates of energy savings due to energy conservation retrofits in institutional buildings.

We are also collaborating with the National Renewable Energy Labortory (NREL) and the Passive Solar Industries Council in the development of a computerized tool that will provide design guidance for the optimal utilization of passive solar technologies in small commercial buildings.

DOE-2

With the assistance of Hirsch & Associates, we continued work on DOE-2.1E with joint funding from Southern California Edison Co., Pacific Gas and Electric Co., the Electric Power Research Institute, the Gas Research Institute, and the DOE Office of Building Technologies. Major new features in DOE-2.1E include:

- *Evaporative cooling.* Models were developed for stand-alone evaporative cooling systems and evaporative cooling units integrated with conventional HVAC systems. This feature will allow cost-benefit analysis of evaporative cooling as an alternative to vapor-compression cooling systems.
- *Ice storage.* Modifications to the DOE-2 PLANT program allow simulation of a variety of cool storage systems such as ice-on-coil, ice-harvester, brine, and ice slurry. Such systems have the potential for reducing cooling costs by allowing ice to be made at night, when electricity rates are low.
- *Switchable glazing.* This feature allows simulation of "smart" windows whose solar-optical properties can change according to environmental conditions. An example is electrochromic glass that can be switched from clear to reflective by changing the applied voltage in response to a control variable such as incident solar radiation. Switchable glazing has the potential for providing better solar control than conventional glazings, with resultant lower cooling loads.
- *Glazing library.* A new window library has been assembled containing about 200 glazings (Figure 12). Included are

Figure 12 *Shading coefficient vs. center-of-glass U-value for all glazings in the DOE-2.1E window library. The lowest U-value (0.12 Btu/hr-ft²-F) corresponds to a super-window developed by the LBL Windows and Daylighting Group. Key: CLR/TINT is clear or tinted glass; REF is glass with a reflective coating. LOW-E is glass with a low-emissivity coating. SINGLE, DOUBLE, TRIPLE and QUAD refer to the number of panes. Numbers in parentheses give the identification number used to specify the glazing in DOE-2.*

the latest high-technology windows such as those with low-emissivity coatings and gas fills. The library was created using the WINDOW 4.0 computer program in a collaborative effort with the Windows and Daylighting Group. In addition, the WINDOW 4.0 glazing heat transfer model was integrated into DOE-2, yielding a more accurate calculation of conduction and solar gain through windows.

Other features in DOE-2.1E include add-on desiccant cooling, heat pump water heaters, new air-side and water-side economizer options, new heat pump defrost options, variable-speed heat pumps (electric and gas), a new water-source heat pump model, and an enhanced economics program.

To help new users learn DOE-2 more quickly, the *DOE-2 Basics* manual was published. This manual covers only the most commonly used features of the program.

Simulation Problem Analysis and Research Kernel (SPARK)

SPARK (formerly called the Energy Kernel System) allows users to quickly build models of complex physical systems by linking calculation modules from a library. SPARK is aimed at simulation experts who need to create detailed models to aid in buildings research and analysis of innovative technologies.

Figure 13 shows the overall organization of SPARK. The user interacts with the program in four basic ways: defining objects (e.g., component models); defining simulation problems by linking objects; specifying run-time data (e.g., coefficients and time-varying data); and specifying desired output. The objects are defined in text files, either as mathematical equations or as component models in Neutral Model Format. These files are processed symbolically with programs written in Macsyma, producing C language functions and objects that are stored in libraries. Problems are defined by interconnecting objects into networks using an interactive graphical editor, producing a problem specification file in the Network Specification Language (NSL). The nucleus or "kernel" works from the NSL description and generates internal data structures based on graphs. Matching and reduction algorithms are employed with these graphs to automatically devise an efficient solution algorithm, producing an executable program for a particular problem. The executable program reads constant and time-varying data from files, then produces the solution at each time step by iteratively solving the set of coupled, non-linear differential equations corresponding to the problem network. The output processor reads the result file and generates graphical displays according to interactive user requests.

In 1991, an alpha-test version of SPARK, without the graphical editor, was made available for use by other groups at LBL. This version was tested on two complex problems: radiant cooling of rooms and aerosol transport in ducts. Work continued on the SPARK graphical editor, and techniques were developed for choosing the starting values in a simulation and for enhancing convergence during rapid change of input values. The 2-D partial differential equation simulation generator was extended to solve dynamic problems. The SPARK/Macsyma interface (which allows users to express calculation objects symbolically, thus relieving the user from having to write and debug computer code) was extended to generate dynamic macro objects. A cooling tower object was created for the SPARK library.

DOE-3

DOE-3 will be a major extension of DOE-2 that is easier to use, provides built-in design guidance, and, by incorporating SPARK techniques, allows models for new HVAC technologies to be quickly built up from component modules. This program is aimed at a broad range of users: *at the average architect/engineer*, for rapid design of energy-efficient buildings; *at researchers*, for impact analysis of new technologies and development of future energy standards;

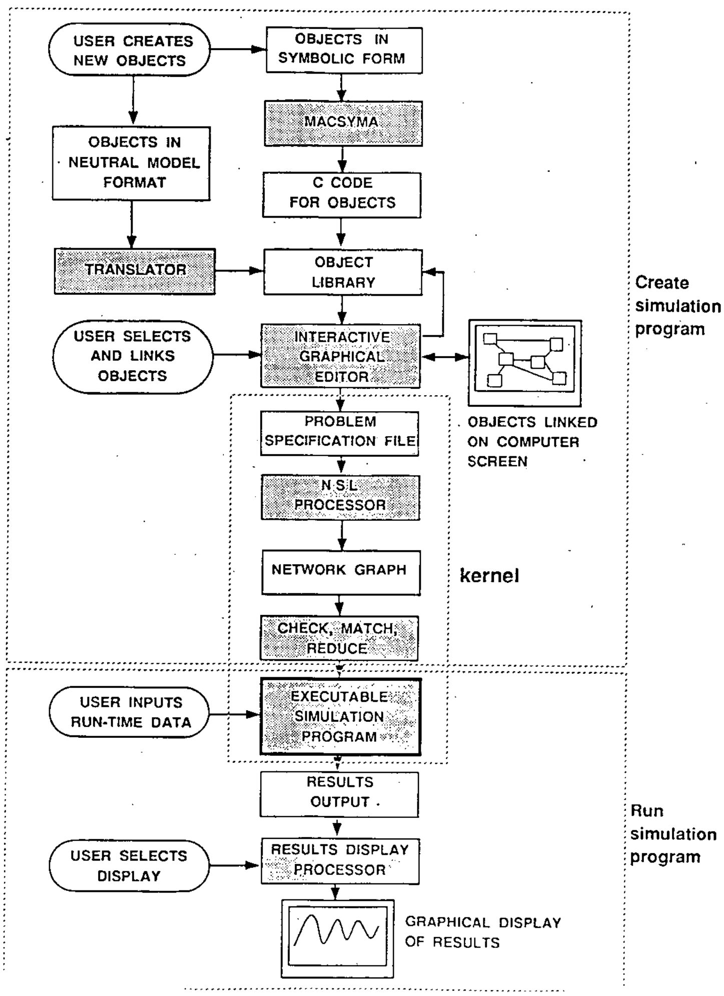


Figure 13 *Configuration of the Simulation Problem Analysis and Research Kernel (SPARK), which allows users to easily configure and execute simulation models of complex building systems. Shaded boxes are programs; unshaded boxes are files. Ovals show user actions.*

and *at utilities*, for support of demand-side management and marketing efforts.

In 1991, negotiations began with the Electric Power Research Institute (EPRI) for joint EPRI/DOE development of DOE-3. The new program will be built upon the current version of DOE-2, with substantial enhancements, including features brought over from micro-AXCESS, the current EPRI program.

The tasks in this three-year joint effort include:

- Improve the DOE-2 calculation engine: integrate SPARK and its object library into DOE-2 to simplify modeling of new technologies; combine the loads, terminal system, and primary system calculation into a single time step; apportion energy use by load component; add library of system controller functions; upgrade coil and compressor models; improve HVAC sizing methodology; enhance output reports and options; add useful features, such as individual energy use meters, from micro-AXCESS.
- Develop a new user interface that is interactive and menu-driven; satisfies different levels of user proficiency, novice to expert; provides on-line help and graphical results display; accesses library of buildings, spaces, schedules, and HVAC configurations; can automatically generate building description from type, vintage, area, number of floors, etc.; and communicates with the Energy Design Advisor.
- Develop the Energy Design Advisor, which provides expert-system modules for design guidance. This will be done in collaboration with the LBL Windows and Daylighting Group.
- Connect to CAD: develop an interface to popular CAD packages, such as AutoCAD, in order to simplify accurate architectural description of buildings.
- Provide enhanced program support in order to handle the greatly increased number of users expected for DOE-3. Support will include program maintenance, newsletter, training courses, hot line, electronic bulletin board, referral to modeling consultants, and documentation maintenance.

In 1992, we will continue to maintain and support the DOE-2 program and to publish the quarterly *DOE-2 User News*. The DOE-2.1E version of the program will be completed and released to the public. SPARK development will continue, with emphasis on completion of the graphical user interface, expansion of the library of calculation objects, and writing of user documentation in preparation for a beta-test release of SPARK to selected outside users. Work will begin on DOE-3.

Retrofit Energy Savings Estimation Model (RESEM)

We developed the building-specific Retrofit Energy Savings Estimation Model (RESEM) for the DOE Institutional Conservation Program (ICP) in order to improve the quality of savings estimates. For maximum accuracy and validity, pre-and post-retrofit energy use—and thus savings—are directly based on utility billing data. RESEM is a user-friendly tool that allows state and regional ICP staff to use readily available information to determine the energy and cost savings due to ICP-supported retrofits for a single building.

Highlights of the operational computer tool include the user interface, which uses dynamic menus and pop-up windows for specialized data entry. The overall menu structure is designed to lead the user easily through the complex savings analysis sequence. Built-in, simplified simulation capabilities used in the savings analysis have been shown to compare favorably to more detailed hourly simulation programs such as DOE-2, and are quite fast, requiring less than 5 seconds (on a 386-class PC) to simulate a typical building. Additionally, automatic features such as complete-default building generation and "push button" retrofit descriptions have worked quite well in early use experience, saving the user time and effort in describing the buildings and the retrofit measures.

In 1988 and 1989, we designed and implemented most of the tool, yielding an operational prototype. In 1990, we completed the primary software implementation of the tool and shifted our focus from software development to initial field testing and the development of supporting materials. A limited beta-test was carried out using several state energy and DOE operations offices. Formal demonstrations of RESEM were made at two conferences of national energy program managers and numerous informal demonstrations were given to interested parties. Technical papers describing the capabilities and methods used in RESEM were completed and presented.

In 1991, final work on the RESEM program that incorporated feedback from earlier testing and user comments was finished. The early technical software documentation was expanded into a comprehensive end-user reference manual and made ready for general dissemination. Work on an extensive weather data library covering in excess of 200 locations was also completed. Product announcements and presentations were made to introduce RESEM to potential end users, and additional technical papers were presented.

Energy Design Tool for Small Commercial Buildings

A DOE-funded industry/laboratory collaboration between the Passive Solar Industries Council (PSIC) and the National Renewable Energy Laboratory (NREL) was initiated in 1990 to develop design guidelines for energy-efficient small commercial and institutional buildings. A key element of this project is the development of a computerized tool which provides an interactive environment in which to explore the energy impacts of various building design decisions. LBL is providing technical support in the development of this design tool.

The design tool is being developed to operate on an IBM-compatible PC under the MS-DOS and Windows operating system. This tool is meant to go well beyond the type of energy evaluation programs which are currently available. Innovative features include the initial generation of a complete building simulation model from minimal input data, intuitive access to and modification of the design details of the building, intelligent guidance in the selection and specification of energy-efficient measures for improving the overall performance of a building, and a variety of criteria for evaluating the relative performance of alternative building designs. An especially critical aspect of the tool is the user interface which provides access to the inherently complex details and tasks related to building design.

In 1991, LBL provided support during early design tool planning in the selection of the tool's hardware platform and software development environment and programming tools. Our initial efforts focused on the importance of the tool's user interface. We implemented the first functional prototype of an interface specified by NREL for use as a demonstration for the project sponsors (Figure 14). The design tool will provide capabilities for describing, implementing and evaluating a variety of daylighting energy-efficient strategies that can be applied to building designs. We have explored a number of approaches to first specifying an appropriate daylighting strategy for the building under design, and then accurately evaluating the consequences of applying this strategy. The effort this year has laid the groundwork for the implementation in 1992 of both the user interface and the underlying analysis capabilities necessary to integrate daylighting into this design tool.

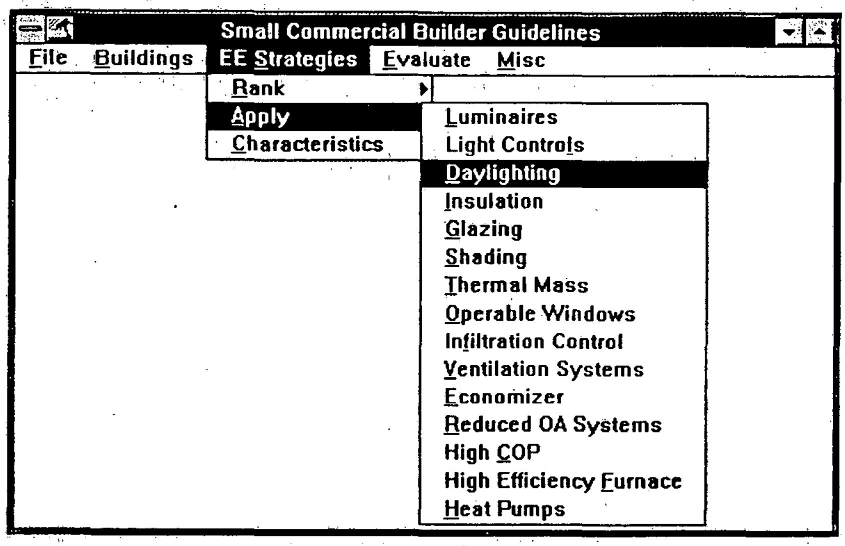


Figure 14 *Pull-down menu selection for applying a daylighting strategy to the current building design.*

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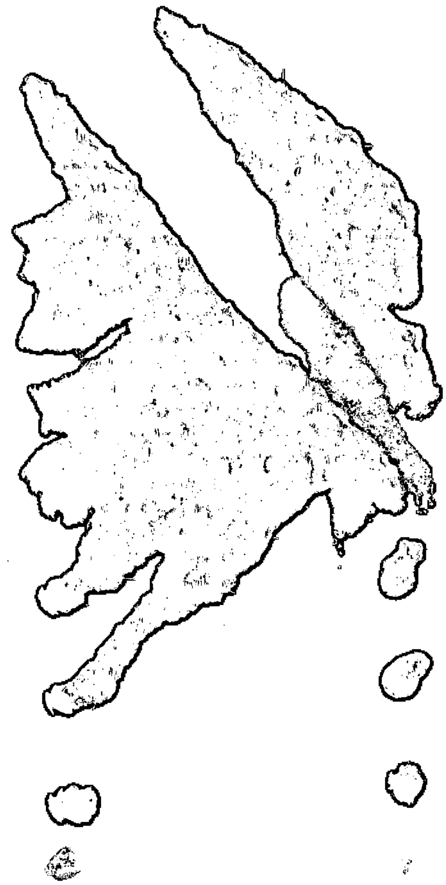

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