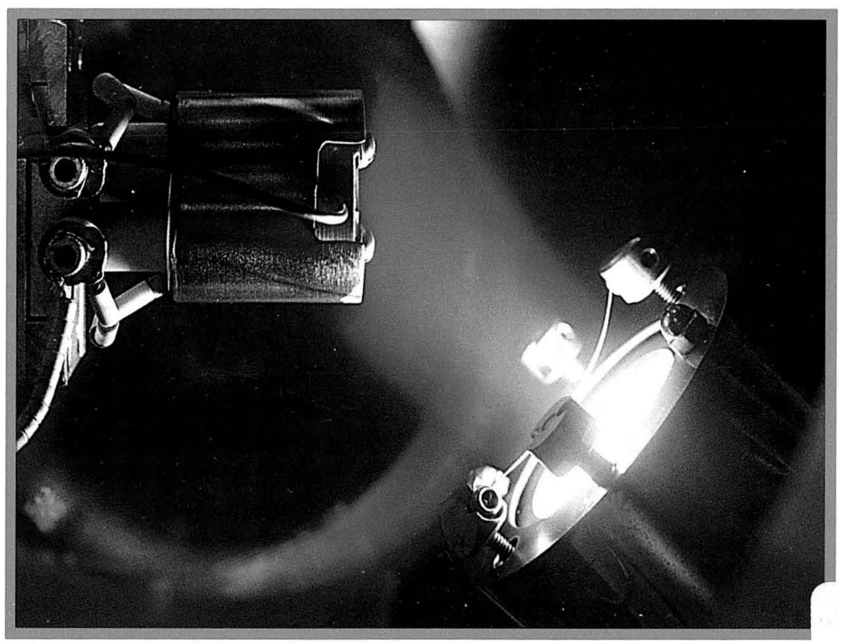
# Building Technologies Program

## 1993 Annual Report



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June 1994

*Shown on cover:* ion-assisted high-temperature deposition system for deposition of highly crystallized metallic compounds.

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# Building Technologies Program
# 1993 Annual Report

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Report No. LBL-35244

# 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 and associated greenhouse gas emissions 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. Finally, both of these strategies must be embedded within a larger set of implementation and "market pull" programs to translate potentials into realized savings.

The **Windows and Daylighting Group** focuses on the technical aspects of understanding and improving the energy-related performance of windows, and then deploying energy efficient windows throughout the country. 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 simulation models for predicting net fenestration performance in residential and commercial buildings. Simulation studies, field measurements in a mobile field test facility, and building monitoring

(cont.)

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## Introduction *cont.*

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 advanced 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 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 now developing an Energy Design Advisor using multimedia techniques and expert systems.

The **Lighting Systems Group** focuses its research on three areas: advanced light sources, building applications, and impacts of lighting technologies on performance 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 the allowed ISM (industrial, scientific, and medical) frequencies of 13.56, 27 and 40 MHz. We are investigating replacements for both fluorescent and high-intensity discharge (HID) lamps. These lamps promise more efficient conversion of electrical energy into visible light, longer lamp life and potentially the elimination of mercury.

The building applications research concentrates on technical approaches leading to major improvements in fixture efficiency via improved thermal management and better optical designs. We have developed several innovative, highly cost-effective approaches for improving fixture efficiency by 20% that are currently being adopted by several major fixture manufacturers. In addition, we are studying visual quality issues, primarily obtaining basic information on lighting and visual performance in order to provide an analytic basis for lighting recommendations. Our RADIANCE visualization program is in use by researchers and designers worldwide to support development of design solutions which minimize energy use while maximizing lighting quality.

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 primary contribution of the **Simulation Research 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, by utilities for design assistance, and by state and federal agencies for development of energy-efficiency standards. In collaboration with the Electric Power Research Institute, we have recently begun work on PowerDOE, a user-friendly version of DOE-2 that is easier and more cost effective to use.

This 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

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Approximately 20% of the energy consumed annually in the United States is used for space conditioning of residential and commercial buildings. About 25% of this amount is required to offset heat loss and gain through windows. In other words, 5% of U.S. energy consumption—the equivalent of 1.7 million barrels of oil per day—is related to the performance of windows. Fenestration performance also directly affects peak electric 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 and to collaborate with the building community to successfully deploy these technologies and strategies. We develop advanced technologies and create 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. Although our primary focus is improving energy efficiency, we seek solutions that also improve comfort, health, and amenity within buildings, and minimize undesired environmental impacts on a local, national, and international scale.

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 which are also available for use by industry. Our scientists, engineers, and architects collaborate with researchers in industry, academia, utilities, and government to accomplish our objectives.

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 actively participate in industrial, professional, and scientific meetings and societies (national and international) to ensure that our research results are widely disseminated. These interactions also provide feedback to our group to help guide future program design. Much of our R&D is well integrated with the deployment activities of the organizations and stakeholders that 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, to assist industry in the development of the next generation of energy-efficient window systems, and to help create and carry out deployment programs that will accelerate market penetration of promising technologies in the marketplace. To carry out this effort, we have organized our research into three major areas:

- Innovative Technology and Systems
  - —Advanced optical and thermal materials
  - —Advanced glazing systems and integrated fenestraton concepts
  - —New materials processing technologies
- Fenestration Performance
  - —Window rating systems
  - —Thermal analysis
  - —Daylighting analysis
  - —Field measurement of performance
- Building Applications and Design Tools
  - —Residential and nonresidential buildings
  - —Advanced design tools
  - —Deployment programs
  - —Market assessment

## Innovative Technology and Systems

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 and, by working closely with industrial partners, to accelerate market introduction of 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.

It takes time and a sustained effort to make significant changes in standard practice in the building industry, but our program has some notable success in the case of low-E coatings. 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 after six years of DOE-funded research, low-E coatings are used today in more than 35% of all residential windows.

Our next focus was the development of highly insulating superwindows which incorporate low-E technology and gas fills, and this effort 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 control of daylight and solar heat gain. Spectrally selective glazings preferentially transmit visible light while rejecting the near-infrared component of sunlight. "Cool glazings" based on silver combine a high visible transmittance with high infrared reflectance to minimize cooling load. Some metallic compounds are more durable than silver and have superior optical properties.

The key to achieving these superior optical properties is to induce a high degree of crystallinity in the coating materials. This has been done with a combination of high temperature and ion bombardment. In FY93 we concentrated on making durable spectrally selective coatings using techniques that could be adapted easily to the next generation of industrial sputter coaters. The high-temperature requirement was reduced to near-ambient temperatures and the ion source was operated successfully at sputtering pressures. Next year we will work with industry to adapt our ion-beam techniques for use with commercial coaters.

Almost all existing residences in California and elsewhere use clear glazing which admits high levels of solar gain. In FY93, with co-sponsorship from the California Institute for Energy Efficiency (CIEE), we showed that use of spectrally selective retrofits can significantly reduce energy costs and peak demand. This year we will investigate whether newly available retrofit films can have sufficiently long lifetimes to be cost-effective solutions.

### Low-Conductance Glazings and "Superwindows"

In climates with significant heating loads, highly insulating windows have long been recognized as a necessary component of virtually all residential and some commercial buildings. In the 1980's, when the industry was just beginning to market low-E gas-filled windows with R-values up to 4 hr-ft$^2$-F/Btu, we showed that windows with total R-values greater than 6 hr-ft$^2$-F/Btu installed in a north-facing wall in a typical residence in northern U.S. climates will transmit more useful solar gains than they lose in conduction. Thus, such superwindows would require less heating energy on a square foot basis than an insulated wall over a complete heating season. As a result of this finding, we began to develop the technology base for this next generation of highly insulating windows. Given the diversity of materials and designs used in the manufacturing of window products, our research in this area was focused on the development of new design concepts and the establishment of new tools necessary for the analysis of low-conductance glazings and superwindows.

Highlights of LBL research in this area over the past several years include a design concept for a superwindow which was quickly commercialized, utility co-supported field tests which validated performance claims, the development of a rating system which accurately characterizes the performance of highly insulating windows (see "Fenestration Performance—Window Rating and Labeling Systems"), and the establishment at LBL of an Infrared Thermography Laboratory for the diagnosis of two-dimensional heat transfer through insulated window frames and edges.

The first generation of commercially available superwindows use glazing with center glass heat loss of .2-.1 Btu/hr-ft$^2$-F but overall U-factors of only .3-.2 Btu/hr-ft$^2$-F. Glazing edge designs and sash/frame designs must be improved if the overall heat loss rate is to meet performance needs. We continued collaborative efforts with numerous window manufacturers who were interested in using our Infrared Thermography Laboratory to analyze the thermal bridging impacts of both current and redesigned frame and sash components (Fig. 1, next page). Superwindows may be developed more cost-effectively as part of an integrated window/wall system, rather than as a stand-alone component. A design concept for an integrated window and wall panel which includes recessed summer shading devices and night insulation was developed and discussed with industry representatives. During FY94, the design concept for this integrated window/wall system will be refined and proto-

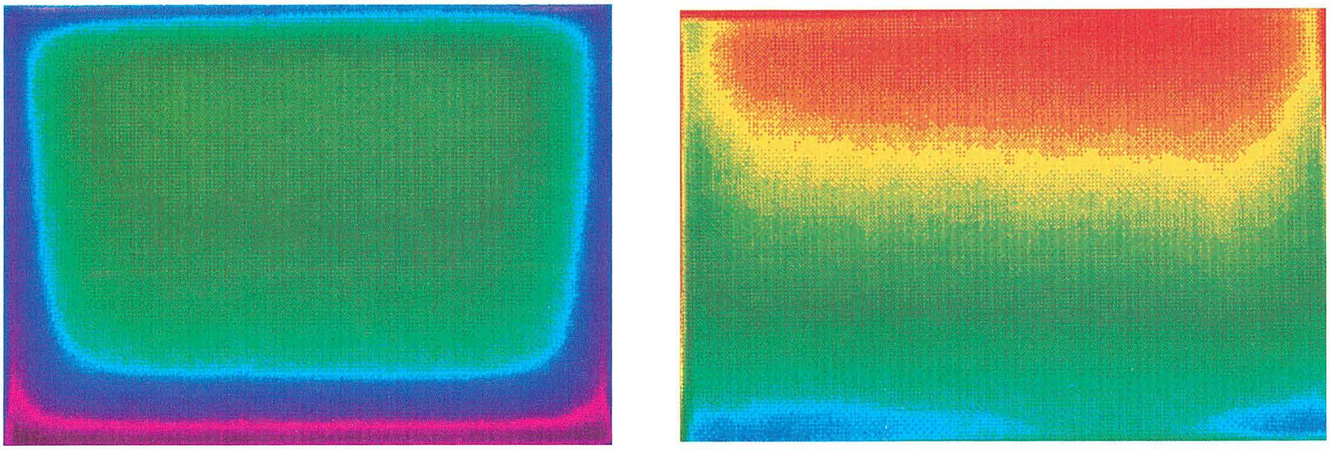

**Fig.1.** *Thermal effects of glazing spacers on edge-of-glass performance, analyzed using infrared thermography. In these infrared images of the warm side of two windows (double-glazed with identical frames exposed to simulated winter conditions), blue/green areas indicate colder temperatures and are thus poor insulators. The use of a prototype insulating spacer (right image) eliminates thermal bridging at the glazing edge, increasing edge-of-glass thermal performance and reducing condensation on the warm side of the window as compared to a window with a conventional aluminum spacer (left image).*

types built and tested.

### Advanced Insulation Systems

In 1990, we realized that the same concepts used to design high-performance windows (low-emissivity coatings, low-conductivity gas-filled enclosures at normal atmospheric pressure) could be used to design a high-performance opaque insulation with a thermal resistance twice that of conventional CFC-blown foams. With funding from the California Institute for Energy Efficiency and the U.S. Department of Energy, we began to build and test opaque panels which utilized thin low-emissivity coated polymer layers to contain low-conductivity gasses. The primary applications for such gas-filled-panels (GFPs) are residential refrigerator/freezers (which currently use 7% of all electricity nationally). Innovative systems will require higher levels of insulation per unit thickness if refrigerator/freezer shell losses are to be lowered without changing the interior or exterior dimensions of the appliance.

Research over the past several years has focused on developing high-performance, cost-effective and durable gas-filled panels. Refrigerators are currently insulated with blown foams, which also give the appliance its structural rigidity. Until FY93, the development of GFPs was focused on GFP panels which could be imbedded within non-CFC-blown foams. Such an approach had its limits, since the panels did not cover the entire surface area. As a result, in FY93 we began to develop new structural designs for refrigerator shells and doors which allowed for a much higher GFP utilization and improved thermal performance. FY94 efforts are oriented toward working with industry to develop and test such prototypes.

Other applications for GFPs have also been identified and will be pursued in FY94. Since GFPs are very light in weight, we have received inquiries concerning their use in the transportation sector, where potential applications include airplane insulation, electric vehicle insulation, and refrigerated transport. An affiliate of the Mayo Clinic has licensed GFP technology (for which LBL has been granted patent rights) for the manufacture of medical shipping containers. Interest in using GFP insulation for buildings, particularly manufactured buildings and specialty building products (such as insulating shades), is also high.

### Optical Switching Devices

Electrochromic glazings have great potential to dynamically control the transmission of light and heat through windows in buildings, automobiles and aircraft. Electrochromic glazings are part of a family of chromogenic light control technologies including large-area dispersed liquid crystals, thermochromic and photochromic materials. These glazings are also known as "smart windows." Electrochromic devices represent the most versatile technology with the best combination of properties for switchable window applications. Electrochromic glazings can have a 10-80% visible light transmission change with moderately fast switching times and low d.c. power consumption. Because electrochromic glazings have memory, they will remain in the transparent or opaque state, and therefore only need power to make a change in transmission. Electrochromic technology can be coupled with smart control systems to maintain constant lighting levels, blending daylight with dimmable electric lighting, resulting in improved building energy efficiency. Energy simulations of office buildings indicate that smart windows can provide substantial energy savings and lower total cooling and peak utility loads. Other benefits include reduced HVAC system size and greater thermal and visual comfort. Our work focuses on the design, construction, and characterization of these glazings, and on industry partnerships to move these technologies to the marketplace.

Our electrochromic device development has concentrated on the development of devices based on oxides of tungsten, nickel, niobium, and iridium. The active components of the device are the electrochromic layer, the ion conductor, and the ion storage layer. All these layers must be electrochemically compatible, chemically stable in close contact with each other, and able to store and transport charge or ions reversibly for many cycles over long periods of time. We are developing all-inorganic devices as well as hybrid laminated devices incorporating polymer layers.

In 1993, we developed sputtering techniques to reproducibly coat glass with electrochromic tungsten and niobium oxides and now better understand the effect of the sputtering environment on the properties of these films. Comparing the properties of these sputtered films to films made by other techniques has helped us to understand and refine film properties. We have developed new techniques for the deposition of tantalum oxide ion conducting films using sol-gel deposition processes. The sol-gel process allows solid ceramics and glass layers to be made by low temperature processing. We have also used sol-gel coating techniques to improve the electrochemical efficiency of tungsten oxide. Film defects are very important to device operation for these all-inorganic devices. In FY94, we will strive to reduce the defects in these devices.

In our laminated device work, we have an ongoing collaboration with Dow Chemical involving the application of their proton fluoropolymer in electrochromic devices. A series of devices have been fabricated and tested with good performance results. This industrial collaboration will be expanded in FY94 with a Cooperative Research and Development Agreement (CRADA). Research continues on our LBL-developed lamination polymers as well, where we have continued to make successful devices with improved properties. We now have two patents pending for two families of organothiol polymers for use in electrochromic devices. We have been very active in pursuing efforts to license this polymer technology to industry. With the help of an industry gift from 3M Corporation we were able to make lithium containing polymers that cycled greater than 30,000 times. We have materials exchange agreements with several companies to develop new materials that allow ion storage and ion conductor layers to be made into a composite polymer. These new ion storage materials might permit a compact design with lower device fabrication cost, and they can tolerate film defects better than other thin-film designs. We have built several successful electrochromic devices using tungsten oxide electrodes laminated with a composite polymer ion conductor. A device of this type had a change in visible transmission properties over a range from 61 to 12%. The spectral response of this device is shown (Fig. 2). The device switches from transparent to a deep blue-gray with the application of -1.5V, and it bleaches with the application of +0.5V.

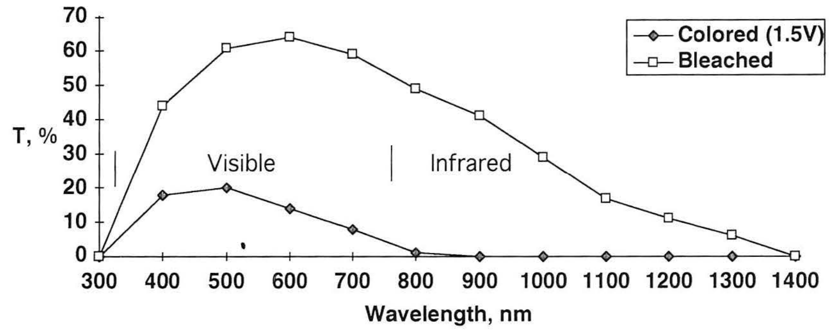


**Fig. 2.** *Spectral transmittance of polymer laminated electrochromic device. Both the bleached ($T_v$ = .61) and colored ($T_v$ = .12) conditions are shown. $T_v$ = visible transmittance.*

In FY93 we expanded our studies to better understand the performance of electrochromic devices in buildings. The electrochromics glazing library in the new DOE 2.1E program was expanded to include newly measured prototype data. Using this model, calculations of energy performance were made for realistic electrochromic windows in hot climates. These calculations will be extended to colder climates in FY94. Control algorithms will be refined and tested to identify strategies that provide optimum performance. We have also expanded our WINDOW 4.0 simulation program to take into account the wavelength dependent characteristics of glazing elements. This addition helps us to more accurately model the switchable characteristics of electrochromic windows with spectral switching properties.

Our activities in FY94 are directed at several goals. Our primary goal is to accelerate cooperative efforts with industry to develop commercially viable device prototypes, by improving materials properties and fabrication techniques, and to increase the cyclic durability of these candidate systems. The second goal is to better determine optimal smart window energy performance strategies and their proper use in buildings. Finally, we are working with U.S. and international researchers to develop test standards for electrochromic devices.

## Fenestration Performance

Effective use of fenestration to achieve a more energy-efficient building stock not only requires improved window systems and components, but also reliable information concerning their energy performance so that the designer can match fenestration systems to architectural needs. To achieve this, it is necessary to have the means to determine fenestration energy performance under a wide variety of conditions. Research in fenestration performance thus forms the bridge between new window technology and its effective application in buildings. 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. Our 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. The experience derived from these tests not only enables us to improve the accuracy of our predictions, but also allows us to predict the performance of new fenestration systems and novel architectural designs. Many new algorithms and data sets have been incorporated into hour-by-hour building energy simulation programs such as DOE 2.1, while others are directly applicable to window standard and labeling activities. The primary focus of our work has been to provide performance characterization procedures and related technical support to the National Fenestration Rating Council (NFRC) to assist in their development of window energy rating systems.

### Window Rating and Labeling Systems

The development of new energy-efficient window systems over the past decade has created a need for an accurate, fair, and cost-effective process to evaluate the thermal performance of all fenestration products. In 1989, the National Fenestration Rating Council was formed to bring together manufacturers, architects/engineers, builders, state regulators, utility incentive programs, and consumers to develop such a rating system. The Energy Policy Act (EPACT) of 1992 requires that an accurate and useable rating and labeling system be developed by 1995.

We have taken a lead role in working with NFRC's Technical Committee to develop and document procedures to rate window thermal properties and annual energy effects. LBL staff chair or are actively involved in all major subcommittees, and are responsible for coordinating the development of many NFRC procedures. NFRC's U-value, Solar Heat Gain, and draft Optical Property standards for simple windows are based on our WINDOW 4.0 computer program and its supporting research, while NFRC's Annual Energy Subcommittee has been using our RESFEN computer program in order to better understand issues relating to the annual energy effects of windows. LBL efforts in 1994 will focus on working with NFRC to improve the cost-effectiveness and accuracy of the procedures in general and to make them applicable to a wider range of products.

**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 computer program in order to provide a state-of-the-art public-domain tool to rate the thermal performance of existing (or proposed) window products. This program's most recent release, WINDOW 4.0, is referenced by NFRC's U-value and Solar Heat Gain Procedures and has more than 2000 users worldwide. Efforts during 1993 were aimed at developing version 4.1, to be released in early 1994, which is intended to make the program more compatible with the NFRC process. During 1994, we will accelerate our efforts to develop new features for WINDOW 5. These include a 2-D heat transfer module and algorithms for the analysis of specialty products (skylights, greenhouse windows, etc.). The entire user interface will be upgraded and we will explore the opportunities to directly link WINDOW to other software tools, including several being developed under international auspices.

**Optical Performance**

Characterization of the optical properties of window materials and systems provides feedback for materials development, input data for energy performance calculations, and product evaluations for rating and labeling activities. Most of this work is now coordinated through the Optical Properties Subcommittee of the NFRC. In FY93, we completed the NFRC procedure for determining emittance, which is needed to calculate both U-factor and Solar Heat Gain factor. This procedure was subsequently adopted by the American Society for Testing of Materials (ASTM) and will be adopted by the International Standards Organization as well. This marks a major step toward harmonization of U.S. and international window standards, reducing duplication of effort and promoting international trade.

A procedure for determining the solar optical properties of simple glazings was also drafted and will be completed in FY94. A group of measurement experts from industry met at LBL to discuss this procedure and to initiate a round-robin test. We are also participating in round-robin tests conducted by the International Energy Agency. With the addition of a variable angle spectroscopic ellipsometer and a large-diameter integrating sphere, we have assembled a complete facility for measurement of the spectral and angular optical properties of specular glazings. In FY93, at the request of applied-film manufacturers, we used this facility to determine the optical indices of laminating adhesives needed for development of a model of the optical properties of retrofit films. Next year we will complete this model and begin to incorporate it into the Window program. We also began to reprogram a computational model of slat-shading systems which will be compared to measurements on Venetian blinds.

**Solar Heat Gain**

Solar heat gain is the most complex and variable of the fenestration energy flows. Daylighting can provide energy benefits to a building year-round, but while sunlight can provide beneficial heating in winter, it may become detrimental to comfort or increase space conditioning loads in summer. Optimizing the solar gain from windows in relation to the associated building systems (e.g., lighting and HVAC controls) would provide a major opportunity for improving building energy efficiency. However, this is currently limited by the tools available for determining fenestration performance. At present, it is difficult to analyze correctly the performance tradeoffs for simple glazings, and in any case the degree to which simple glazings can optimize performance is limited. Complex fenestrations using sophisticated sun-control systems are virtually impossible to analyze using current tools. Our objective is to develop experimental facilities and analytical 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*

We have participated in a cooperative DOE/ASHRAE-sponsored project to develop a system for predicting the solar heat gain through complex fenestration systems. A mathematical method was developed, in which measurements made with the bidirectional scanner (see description below) of averaged properties for non-specular shading elements (e.g., shades, blinds) are combined with tabulated glass properties. The resulting figures for solar-optical transmission and absorption are then used to derive the system's solar heat gain coefficient (the fraction of incident solar energy that enters the building space). The figures used in this calculation for the inward-flowing fraction of the solar energy absorbed in each layer are derived from MoWiTT measurements (see Field Measurement of Fenestration Thermal Performance). The resulting calculation method is then validated by comparison to MoWiTT field measurements.

In mid-1992, we completed this analysis for the first of several candidate fenestration systems, a double-glazed window with an interior shade, and showed that the method produces a calculated solar heat gain coefficient in good agreement with MoWiTT measurements. During 1993, we completed measurements on additional shading systems, and began to extend the analysis to a number of combinations of glazings and shading systems to demonstrate the wide validity of the approach.

During 1994, we will complete this work and begin the process of utilizing this new method as a basis for develop-

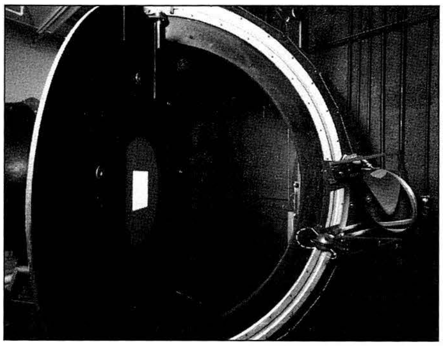

**Fig. 3.** *Bi-directional Scanning Radiometer/Photometer Facility. The detector assembly simultaneously measures radiance and luminance and moves along a semicircular track which in turn swings around a fixed axis to produce a scan of the entire outgoing hemisphere. The detector arm, shown here in position for a transmission measurement, also swings to the front of the sample plane at left for a reflection measurement. (CBB 900-8718)*

ing solar heat gain ratings for complex fenestration systems.

*Bidirectional Scanning Radiometer/ Photometer Facility*

We have built a large, automated scanning radiometer/photometer facility for measuring the average optical properties of non-specular and spatially heterogeneous layers of fenestration systems, such as venetian blinds (Fig. 3). It is designed to provide basic performance data both for solar heat gain and daylighting studies. In 1993, it was utilized primarily to develop a method of predicting the solar heat gain through complex glazing systems and to construct a data base of basic complex fenestration systems. In 1994, it will be used to support the development of voluntary window ratings (NFRC). It is also available to outside industry users.

## Daylighting

Lighting is one of the largest electrical loads in commercial buildings. An efficient daylighting design can displace 70% of the lighting energy requirements. The prediction of 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, continuously expanding modeling capabilities and improving calculation accuracy.

Our daylighting software, SUPERLITE, was selected as a primary analysis tool to be included in ADELINE (Fig. 4). ADELINE is the product of a multinational daylighting research effort undertaken by the International Energy Agency (IEA) as part of its Task XII efforts. ADELINE links a 3-D CAD program with both SUPERLITE and RADIANCE (see *Lighting Systems* section of this report) for the analysis of daylight and electric lighting system designs. ADELINE improves user interaction with our analysis tools by providing a DOS-based graphical user interface for both initial CAD input of a design and for graphical display of analysis results. During FY93, ADELINE reached the beta-test phase. Development of this collection of software will continue in FY94.

The modeling capabilities of the PC versions of SUPERLITE continue to be enhanced. SUPERLITE Version 2.0, available in late 1993, adds electric lighting analysis to the capabilities of Version 1.01. Version 3.0, expected to be available in 1994, will add complex fenestration systems and shading devices to the current daylighting analysis capabilities. The user documentation for SUPERLITE has been updated and, in the future, will be distributed on disk with the program.

We also continued the development of the IDC (Integration of Directional Coefficients) method for predicting the annual lighting energy performance of fenestration systems and spaces of arbitrary complexity. This method is based on a combination of scale-model photometry, for the determination of directional illuminance coefficients within architectural scale models, and computer-based analytical routines that utilize the measured coefficients to determine a set of daylight factors for use with the DOE-2 building energy simulation computer program. In this way, it can determine hour-by-hour daylight performance and energy impacts over an entire year. The illuminance predictions of the IDC method were successfully intervalidated

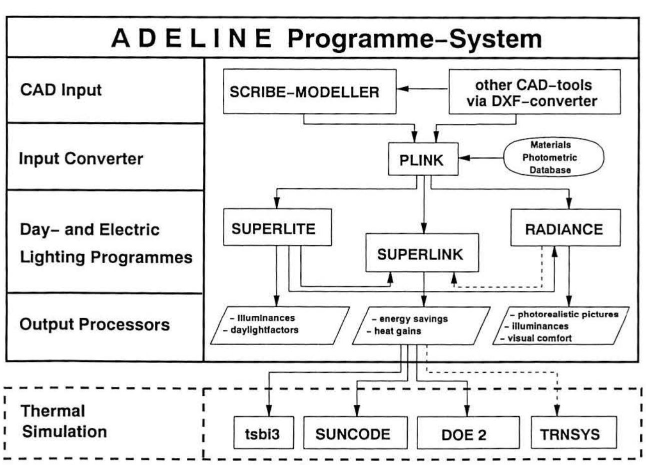


**Fig. 4.** *Diagram of the various modules integrated within, or linked to, ADELINE.*

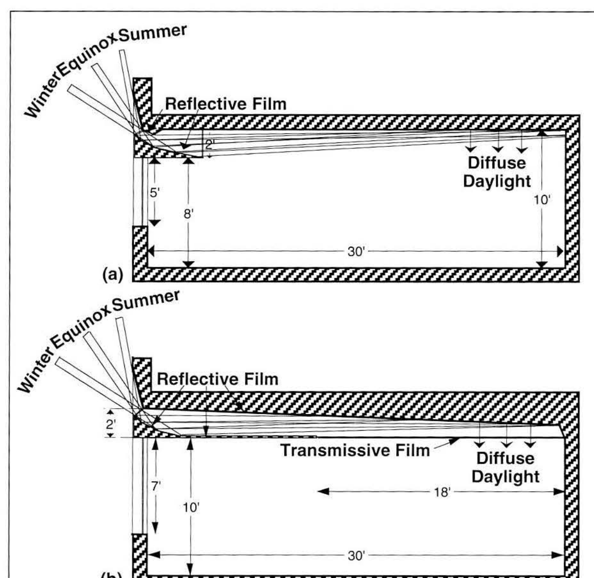


**Fig. 5.** *(a) Ray-tracing diagram for the south-facing light shelf prototype. The reflector shape is designed to redirect incoming direct sun to a target area on the ceiling plane at 7.6 m (25 ft) from the window. Solar altitude and azimuth varies throughout the year—we show the extreme range of solar altitudes in this diagram: December 21, March/September 21, and June 21. (b) South-facing light pipe prototype, which uses a similar reflector shape and optical daylight films as the light shelf to concentrate incoming daylight along the longitudinal axis of the pipe and minimize inter reflections along the pipe transport section.*

with the DOE-2, SUPERLITE, and RADIANCE daylighting algorithms for simple fenestration systems, and the method was used for the determination of the annual daylight performance of prototypical holographic glazings, venetian blinds, and complex light-shelves, light-pipes, and skylights (Fig. 5). Intervalidation of the IDC method with the RADIANCE ray-tracing program for complex fenestration systems is planned for 1994. Our longer term goal is to simplify this powerful-but-complex process so that it can be used more readily for practical design problems.

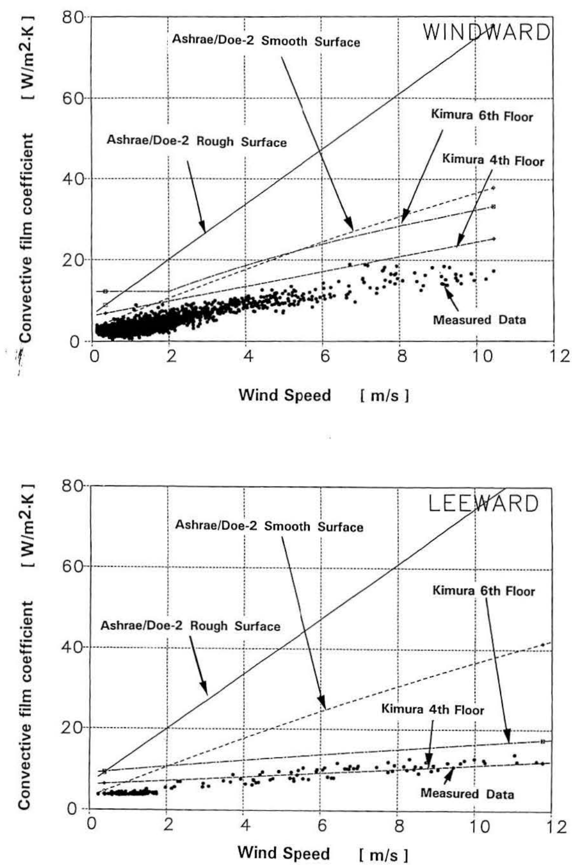


**Fig. 7.** *Measurements of Convective Exterior Film Heat Transfer Coefficients Compared with Commonly used Models. (a) Windward hemisphere, (b) Leeward hemisphere. Points indicate measured values. ASHRAE/DOE-2 and Kimura curves represent results from earlier studies.*

### Field Measurement of Fenestration Thermal Performance

The increasing variety and sophistication of fenestration products available, the move to develop energy labels for these products, and the development of programs to consider utility investments in improved end-use energy efficiency on the same basis as investments in new capacity, all augment the need to measure fenestration performance under field conditions. Measuring the performance of highly optimized window systems in a realistic way is a formidable task, requiring specialized, non-steady-state calorimetry on a scale never previously attempted.

To perform these measurements, the Mobile Window Thermal Test Facility (MoWiTT) was designed, built, and calibrated. In developing this facility (Fig. 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. We solved this problem by using a large-area heat flux sensor (developed as part of the project) and a very sophisticated measurement of the heat extracted from the calorimeter by its cooling system. The MoWiTT began operation in 1986 at a field-test site in Reno, Nevada.

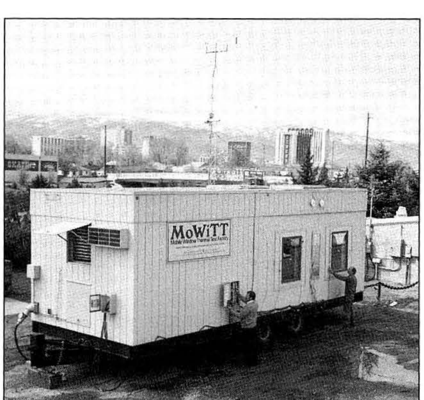


**Fig. 6.** *The MoWiTT facility at its field test site in Reno, NV. The windows are mounted in the two room-sized calorimeters of the facility. (CBB 923-3483)*

In 1993, we completed a multi-year study of the effective exterior heat transfer film coefficient experienced by windows under winter conditions at the MoWiTT test site and their dependence on the site-measured free-stream wind speed. This study (Fig. 7) showed that windows in low-rise structures (e.g., residences) experience much lower values of exterior film coefficient than predicted by the methods commonly used in building simulation programs. The formulas developed from our data were subsequently incorporated into version 2.1E of the DOE-2 program. The result of these measurements is to show that in low-rise buildings windows lose energy in wintertime at a somewhat lower rate than expected; however, the effect is systematically more important for thermally poorer windows (e.g., single glazing has a heat loss somewhere between what is expected for single and double glazing). The result of this systematic pattern is that energy *savings* from selecting a more thermally insulating window are lower for low-rise buildings than predicted from (pre-2.1E) DOE-2 calculations.

In 1993, we also began to use the MoWiTT to test solar heat gain calculation schemes under consideration as a basis for window performance ratings. We showed that incident angle effects are significant in the prediction of solar heat gain, and that the calculation of angular properties in WINDOW 4.0 agrees with measurements for uncoated windows. There is some disagreement for coated low-E windows, for which the calculation model at high angles of incidence is known to need improvement. We also studied the effect of spectrally selective windows on overall energy performance.

In 1994, we will continue our studies of selective glazings and continue to make empirical tests of the validity of currently used calculation models. We will also continue to test emergent window technology with fenestration industry and utility support. Industry is interested in field-test data from the MoWiTT to guide development of new products and designs, while utilities want to establish the benefits of including particular types of window improvements in their efficiency incentives programs.

# Building Applications and Design Tools

The development of new glazing materials and experimental determination of fenestration system performance must be complemented by efforts to apply this knowledge to the window selection tests faced by architects, engineers, and builders. Our objective in the applications area is to incorporate the knowledge gained from our basic science research efforts into tools that will aid the building design community to accurately and cost-effectively specify appropriate fenestration design solutions. We are developing tools for both the nonresidential and the residential building sectors and will increasingly be working with other national and regional groups to accelerate deployment of efficient window products in new and existing buildings.

### Nonresidential Building Simulation Studies

We continued our development of the COMFEN computer program, which calculates the incremental energy and cost performance of fenestration for a prototypical commercial building module. This year we concentrated on user interface issues in an object-oriented software environment and on validation of a simulation procedure which uses a reduced set of hour-by-hour weather data. We expect to release the initial beta test version of COMFEN during the coming year.

We have begun active participation in International Energy Agency/Solar Heating and Cooling (IEA/SHC) Task 18—Advanced Glazing Materials. Task 18 is a five-year task to support the appropriate development and use of advanced glazings in buildings with the aim of realizing significant energy and environmental benefits. Participants in Task 18 come from 13 different countries and include materials scientists, physicists, chemists, mechanical engineers, design engineers, architects, and representatives from industry. Task 18 is organized into two Subtask areas: Subtask A focuses primarily on analyses required to identify energy and environmental benefits and building applications of various potential glazing materials; Subtask B involves laboratory characterization of various glazings and daylighting component materials, including optical switching glazings, to provide the performance properties needed in Subtask A modeling.

### Envelope and Lighting Technologies to Reduce Electric Demand in Commercial Buildings

The full energy-saving potential of lighting and fenestration technologies for commercial buildings can be realized only when they are designed and packaged as *integrated systems*, supported by appropriate design tools. Beginning in 1991, we have been engaged in a multiyear project supported by the California Institute for Energy Efficiency (CIEE), with funding from major California utilities and co-support from DOE, to develop and promote advanced building systems integrating high-performance envelope and lighting technologies. Since the illumination and cooling of commercial buildings accounts for the largest portion of peak electrical demand, the promotion of such integrated systems can become a cost-effective, demand-side management option for utilities.

During the earlier first phase of our research, we developed methods for analyzing dynamic and optically complex envelope systems; assessed the impact of integrated systems on the growth of peak electric demand in California; initiated discussions with industry to commercialize integrated systems; and assisted several California utilities in demonstration projects implementing elements of our integrated designs.

In 1993, we completed the second phase of the program, developing and evaluating two integrated envelope and lighting system prototypes in a series of computer simulations, field tests, industry consultations, and real-world demonstrations. Our evaluation of the first prototype examined the value of anticipatory control algorithms versus simpler control strategies based on instantaneous measured data. Using the DOE-2 building energy simulation program, we compared an automated venetian blind system and two idealized electrochromic glazing systems. Results indicated that predictive control algorithms, while more complex to implement, allowed non-idealized systems such as the automated venetian blind to approach the performance of the idealized electrochromic system (Fig. 8). Using reduced-scale roof-top models and the Mobile Window Thermal Test Facility, we also determined the daylighting and thermal performance of the dynamic venetian blind system in real-time under variable weather conditions (Fig. 9, next page).

The design of the second prototype developed iteratively along two paths, exploring the use of a light shelf for south and east/west facing articulated facades, and a south facing light pipe

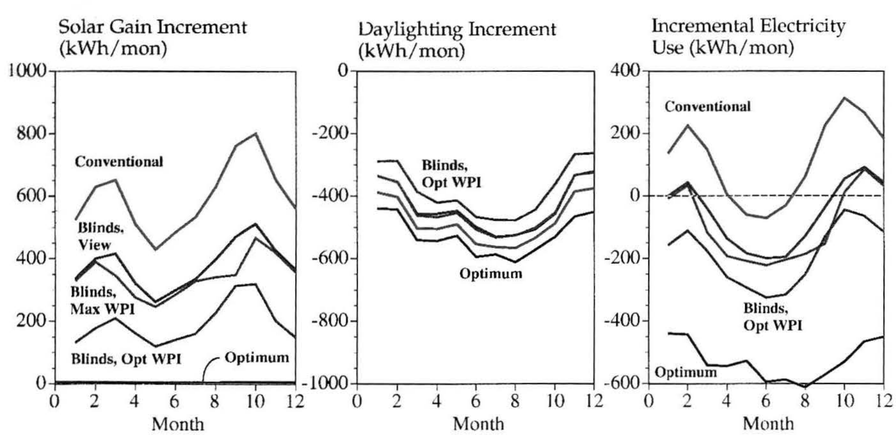


**Fig. 8.** *Monthly electricity consumption patterns of an automated venetian blind system operated by various control algorithms. The control algorithm "block direct sun and optimize workplane illuminance" (Opt WPI), is able to obtain near optimum energy performance (right) by minimizing the penalties due to solar gains (left), while achieving nearly the same daylighting performance as the other control algorithms (center).*

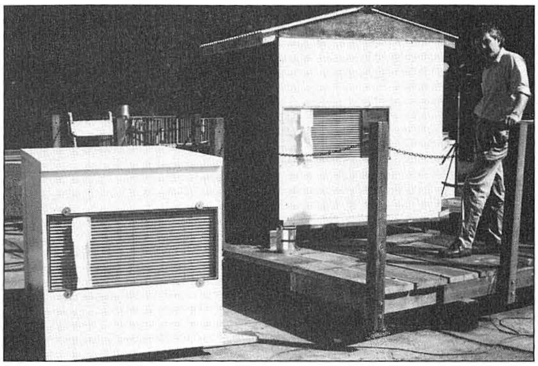

**Fig. 9.** *The daylighting reduced-scale model with an installed motorized venetian blind and electric lighting system is located on the right. The "slave" model to the left, to be used later for MoWiTT testing, is being checked to verify that its blind tilt angle mimics that of the "master" blind system. Note that both models have the same open tilt angle.*

designed to fit within the ceiling plenum of flush curtainwall facades (see Fig. 5). Our analysis indicated that these optically complex designs yielded good daylight distribution within the space with a high degree of light output efficiency for a correspondingly small window area. Demonstration plans for several of the integrated systems were developed with several utility-funded building programs to resolve real-world implementation problems with realistic complex site, building, and cost constraints.

In 1994, we will focus on demonstrating various integrated systems in an occupied, leased building, to evaluate energy performance and occupant comfort and productivity. We will also continue to assist real-world demonstration projects and collaborate with industry partners to commercialize variations of the integrated envelope and lighting systems.

### Residential Buildings

RESFEN is a computer-based tool to advise the designers, builders, and owners of residential buildings how best to specify cost-effective, energy-efficient windows. We anticipate that it will eventually be used by the National Fenestration Rating Council as its annual energy rating methodology. RESFEN calculates the 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. Version 1.3 was released in 1993, incorporating several major improvements made to the program. Next year we will create a graphical user interface to the RESFEN program so that it will function more effectively as an energy rating tool. Eventually, the RESFEN program will utilize an hour-by-hour calculation scheme similar to the DOE-2 program.

We completed a technical study on the analysis of cooling load/U-value interactions. This study was motivated by feedback from several RESFEN users who were concerned that the annual cooling load increased as the U-value was decreased. Our results showed that when comparing windows with identical orientation, size, and shading coefficient, higher U-value windows can yield lower annual cooling loads, but lower U-value windows yield lower peak cooling loads. This occurs because the window with the higher U-value conducts more heat from inside the residence to the outside during morning and evening hours, when the outside air temperature is often lower than the inside air temperature. A lower U-value window conducts less heat from outside to inside during summer afternoon peak cooling hours. Thermostat setpoint and other operational issues will also influence final results.

We completed prototyping a point-of-sale version of the RESFEN program that could be used by a homeowner selecting windows at a building supply store. This version is built into an interactive kiosk and is currently being evaluated in several local builder stores in the San Francisco Bay Area. Basic information about residential windows is provided on-line, as well as advice on selecting specific window products. Demonstrations of the kiosk were well received at several conferences and there appears to be a great deal of interest in such a decision support tool. Figure 10 shows one of the screens from the kiosk presentation.

Our electronic tools would also be supplemented with more traditional information resources. A Residential Window Design Guidelines handbook was reviewed during the year by several individuals in the architectural/window community and is nearing completion. The Guidelines include an overview and historical discussion of residential win-

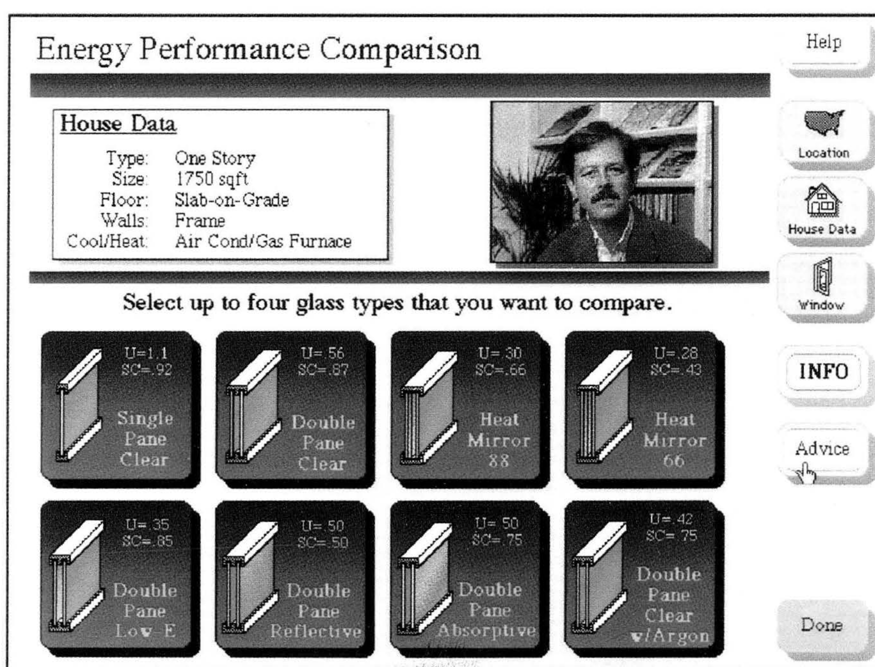


**Fig. 10.** *This illustration shows a screen from the RESFEN kiosk that is used for the selection of window orientation. The user in this example has asked for advice by selecting the ADVICE button along the right portion of the screen. The advice is given through the use of 20-second digital video clips in the upper right of the screen.*

dows; specific design recommendations regarding view, lighting, ventilation, insulation, solar heat gain, condensation, and acoustics; advice on material selection and installation, including glazing products and framing; and regional climate guidelines on energy performance. The Guidelines will be revised and published during the coming year.

### Advanced Design Tools: Building Design Support Environment

We began to explore new concepts for the development of advanced, computer-based building 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 properly address energy issues during the building design process. In collaboration with the Department of Architecture of the University of California at Berkeley, we developed a design theory that offers a comprehensive understanding of the very fundamental activities that contribute to design decisions and clearly defines the possibilities and the limitations of computer-aided design. Moreover, we have been continuously involved with the latest advances in computer technologies, developing state-of-the-art applications that incorporate hypertext, multimedia, and artificial intelligence techniques. In the meantime, the continuously decreasing cost of computing power has met our expectations for the availability of inexpensive computers that are powerful enough to allow for interactive use of the DOE-2 building energy simulation program.

In 1993, we completed development of a comprehensive plan and a demonstration prototype of the computer-based Building Design Support Environment (BDSE) that we have been designing over the past few years (Fig. 11). The objective of this prototype was to effectively communicate and test our ideas for the envisioned features and capabilities of the BDSE. Throughout 1993, we gave numerous demonstrations to a large variety of building industry parties, all of which were very enthusiastic and supportive of initiating actual development efforts. In 1994, with utility and DOE support, we will begin the initial development of the BDSE. The first use of the tool will be to support more effective implementation of utility Demand Side Management (DSM) programs. These development efforts will focus on the initial, schematic phases of building design and be tightly linked with the development of PowerDOE, the new user friendly version of the DOE-2 building energy simulation program.

### 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, including trade journal articles, network and utility-based television production, and exhibits, to reach a widely varied audience. 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.

In an effort to communicate with a variety of building industry audiences, both professional and consumer, we continued to focus on the uses of computer-based information systems and technologies. With limited resources for technology transfer, we explored video conferencing systems, CD-ROM publishing, and point-of-purchase consumer information marketing. These media can reach larger decision-making audiences with a lower cost-per-person investment.

Building on our multimedia development experience, we continued to explore new opportunities to develop prototype information projects. Several video memos were produced to demonstrate our advanced design tool and multimedia developments. We continue to talk with utility audiences about computer-based information in the belief that timely and entertaining professional education is critical to integrating new technologies and know-how into practice. The first multimedia kiosk for the U.S. Department of Energy, highlighting buildings research at five national laboratories, was completed. A debut at U.S. DOE headquarters in Washington, D.C., is planned for early 1994, with a follow-on tour of building industry conferences.

A Federal Laboratory Consortium Special Award for Excellence in Technology Transfer in 1993 was presented to Stephen Selkowitz and Dariush Arasteh for the development and transfer to the U.S. building industry of the technology base for "superwindows"—windows designed with better thermal performance than insulated walls.

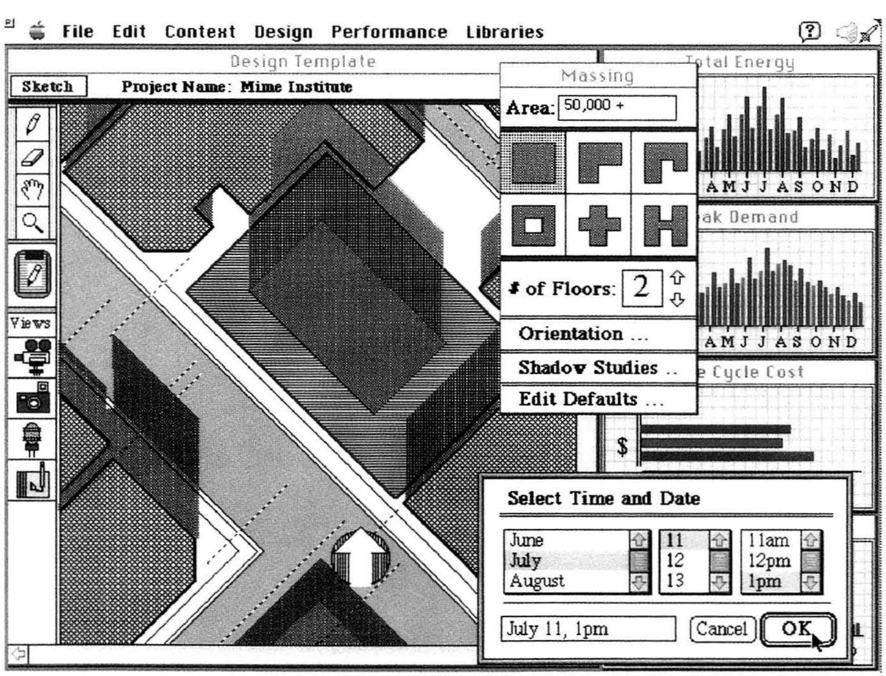


**Fig. 11.** *A screen from the Building Design Support Environment demonstration prototype illustrating a capability to examine shadows cast by the building form at any time of the year.*

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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 advanced building performance calculation tools—the Simulation Problem Analysis and Research Kernel (SPARK) and the PowerDOE program.

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.

The PowerDOE program is a substantially improved version of DOE-2 that is easier to use by the average designer and, by linking to SPARK, can simulate future HVAC technologies.

RESEM 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 Laboratory (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

DOE-2.1E, an enhanced version of DOE-2, was completed in a collaborative effort with Hirsch & Associates. Major new features aimed at meeting the simulation needs of the architectural and engineering research and design communities 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 thermal energy storage systems such as ice-on-coil, ice-harvester, brine, and ice slurry. Such systems reduce cooling energy cost 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. Included are the latest high-technology windows, such as those with low-emissivity coatings and gas fills to reduce heat loss. Also included is a set of experimental electrochromic glazings.

Other features in DOE-2.1E include improved outside air film conductance correlation with wind speed and direction (based on LBL MoWiTT measurements), add-on desiccant cooling, heat pump water heaters, new air-side and water-side economizer options, new heat pump defrost options, packaged variable-volume variable-temperature system, residential multizone variable-volume variable-temperature system, variable-speed electric heat pumps, gas heat pumps, a new water-source heat pump model, evaporatively cooled condensers, end-use metering, and an enhanced economics program that can simulate virtually any utility rate structure.

DOE-2.1E results were validated against test cell measurements (Fig. 1).

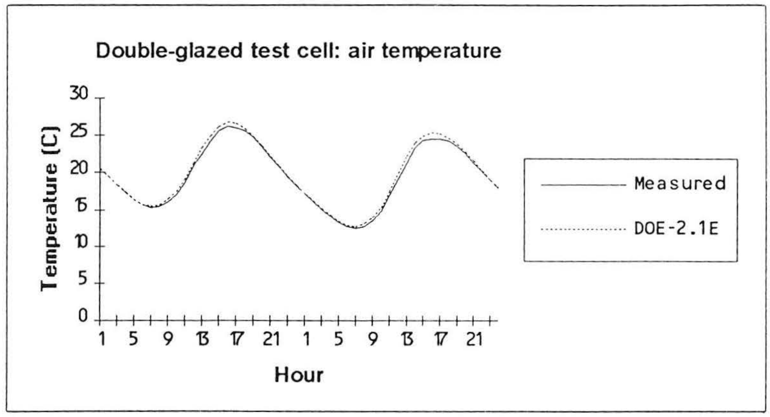


**Fig. 1.** *Comparison of DOE-2.1E predictions with IEA Annex 21 measurements of inside air temperature in a double-glazed test cell in England.*

## Simulation Problem Analysis and Research Kernel (SPARK)

SPARK 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 of building components and systems to aid in research and analysis of innovative technologies.

In 1993, we successfully tested the new "strong component" feature in SPARK which reduces solution time by decomposing large problems into smaller ones. Work continued on the SPARK interactive editor with which users graphically assemble networks that represent the physical problem to be solved. A PC version of the SPARK kernel was developed. The NEUTRAN program was extended to allow it to translate from Neutral Model Format—an emerging standard for expressing component models—to SPARK. SPARK simulation results were shown to compare well with the predictions of two other object-oriented simulation programs (the French programs ALLAN and ZOOM), establishing confidence in the SPARK approach. The first draft of a SPARK user manual was written.

In 1994 a beta-test version of SPARK will be released.

## PowerDOE Program

The PowerDOE program is under joint development by the Simulation Research Group and Hirsch & Associates, with support from the Department of Energy, the Electric Power Research Institute, and utilities. It is a major extension of DOE-2 that is easier to use and 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; and at utilities, for support of demand-side management and marketing efforts.

In 1993 work began on the PowerDOE user interface (Fig. 2) and on modifications to DOE-2 to allow it to work interactively with the interface. Phase I of PowerDOE will be released in the spring of 1995.

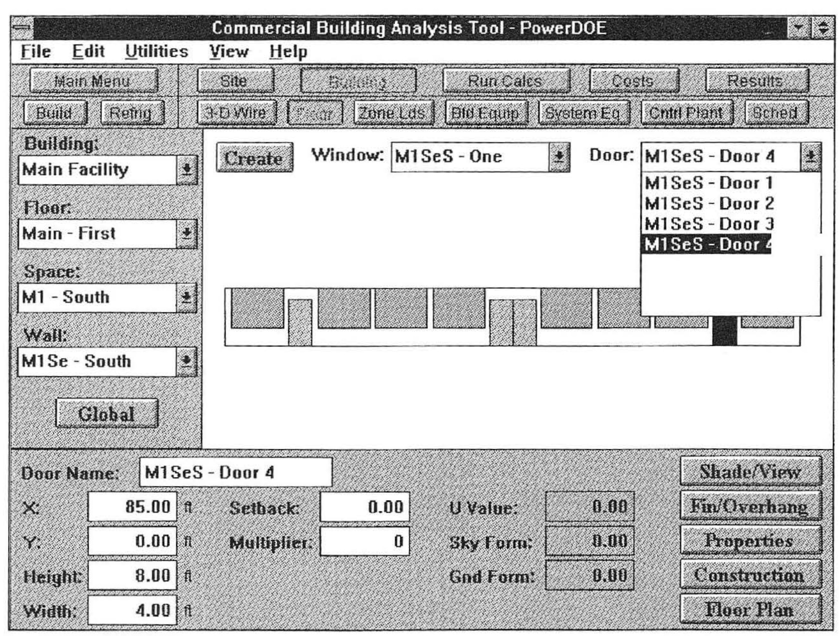


**Fig. 2.** *Sample PowerDOE input screens. The interactive interface provides graphical feedback on placement of building envelope elements, such as walls and windows, in plan and elevation views.*

## Alternative Cooling Strategies

### Radiant Cooling

Work began using SPARK to develop RADCOOL, a model for hydronic radiant cooling systems. These systems are expected to be less energy intensive than traditional systems because the cooling is delivered by chilled water, which has low pumping energy, rather than air, which has high fan energy. Currently there are no programs, including DOE-2, that can accurately model radiant cooling. RADCOOL will be used to analyze the performance and cost-benefits of radiant cooling in different California climates.

### Alternatives to Compressor Cooling

Work began on modifications to DOE-2 for improved analysis of forced ventilation, natural ventilation, and evaporative cooling. This work is part of a multi-institutional California Institute for Energy Efficiency (CIEE) project to lower residential electrical demand by finding cost-effective alternatives to compressor-driven air conditioning.

## 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, automated specification of energy-efficient strategies for improving the overall performance of a building, and a variety of criteria for evaluating the relative performance of alternative building designs.

LBL provided support during early design tool planning in the selection of the tool's hardware platform and software development environment and programming tools. We implemented the first functional prototype of an interface specified by NREL for use as a demonstration for the project sponsors.

Current LBL support efforts, which will continue on into 1994, relate to the building design issue of daylighting. We have, to date, provided algorithms for evaluating simple daylighting energy-efficient strategies that can be applied to building designs (vertical glazing and skylights). We have also provided user interface prototypes for describing these strategies (Fig. 3).

During FY 1993, we began the development of algorithms for evaluating more complex fenestration system (CFS) types for daylighting, including specular light shelves and geometrically complex roof monitors. During FY 1994 we will complete development of these CFS algorithms.

Also during FY 1994 we will develop algorithms for the description and evaluation of electric lighting systems in a manner that is consistent with the daylighting system description and evaluation. We will also explore methods for automating the specification of an appropriately integrated daylight and electric lighting system strategy for the building under design.

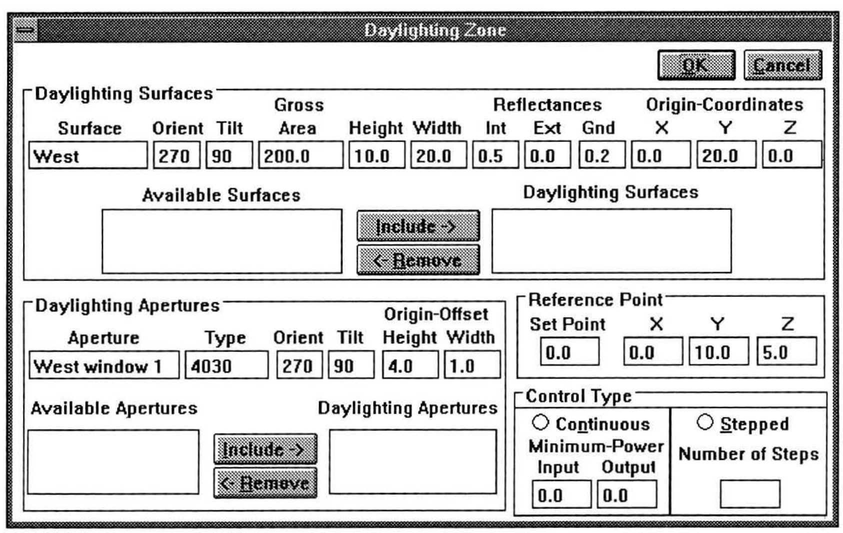


**Fig. 3.** *Prototype user interface for describing a daylighting system.*


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# Lighting Systems

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Lighting for buildings, housing, signage, and streets accounts for 25% of all electrical energy consumed annually in the United States. New, efficient lighting technologies and strategies have the potential to reduce lighting energy use from 515 BkWh to 260 BkWh—a savings of $20 billion annually—while increasing productivity and comfort. These savings would allow for the forecasted doubling of commercial floor space by the year 2020 without an increase in the total annual energy budget. By avoiding the need for additional power plants, these savings would free $100 billion of capital to be used for other purposes.

To help achieve this more energy-efficient economy, the LBL lighting research program combines research activities with an emphasis on technology transfer, assuring that the technology base and concepts developed at the laboratory are transferred to the lighting community in a timely manner. 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 much-needed information on the performance of energy-efficient lighting systems and concepts.

A major thrust of the lighting program is the development of more energy-efficient light sources that operate at very high frequencies (VHF) without electrodes. This approach will improve efficiency, equipment longevity, and environmental quality. In addition, the program is developing comprehensive strategies to optimize the benefits of these new light sources by working with industry to produce highly efficient lighting distribution systems that could replace general lighting in many applications. The program develops innovative technical solutions that enable lighting fixture (luminaire) manufacturers to incorporate better thermal management, thereby improving the performance of their compact fluorescent and full-size fluorescent product lines. Our efforts in this area are assisted by the application of the RADIANCE computer simulation system, which was developed at LBL to produce highly realistic and accurate images of lighted spaces. RADIANCE is also being transitioned to the private sector through licensing agreements to provide end-users with a state-of-the-art tool for producing energy-efficient lighting designs and evaluating lighting quality. In its study of the relation between lighting variables and visual function, the Lighting Systems program is identifying visual responses to lighting conditions—research results that can lead to innovative new lighting products that improve both energy efficiency and human productivity. This interdisciplinary program encourages innovation in the industry and accelerates the societal benefits obtainable from a more cost-effective and energy-efficient lighting economy.

Since its inception in 1976, the LBL Lighting Systems program has produced more than 175 reports and publications documenting research on: solid-state ballasts, operation of gas-discharge lamps at high frequency, scotopically enhanced lighting, energy-efficient fixtures, lighting control systems, and visibility and human productivity. In addition to its research activities, the internationally recognized staff is actively involved in a variety of professional, technical, and governmental activities.

Our strategy is:

- to assist industry in the development of the next generation of energy-efficient light sources and luminaires;
- to develop techniques for manipulating lighting spectral content and distribution to improve visual performance and comfort; and
- to accelerate the deployment of new and emerging efficient lighting technologies into the commercial and residential sectors.

To carry out this program, our research is organized into three major project areas: advanced light sources, impacts on visual performance, and building applications.

## Advanced Light Sources

The advanced light source project develops new, highly efficient lamp technologies and light sources. At present, the most efficient white light source in general use—the electronically-ballasted fluorescent lamp—has a luminous efficacy of approximately 90 lumens per watt; that is, every watt of power used by the lamp produces 90 lumens of light. Although this is 25% more efficient than the fluorescent lamp of 15 years ago, and much more efficient than typical incandescent lamps (17 lpw), still greater efficacies are possible. Theoretically, pure white light can be produced at 220 lumens per watt and a "whitish" light at over 350 lumens per watt. Thus, the lamp physics allows for much more efficient light sources, possibly without the use of mercury. Currently, all efficient white light sources use mercury, which is undergoing increased environmental scrutiny because of its toxicity. The advanced lamp technology program is developing the engineering science that will help achieve a target lamp efficacy of 150 lumens per watt within the present decade.

Our 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 allows the use of compounds that have desirable light spectra and gas fills that do not require mercury. Presently, the use of these materials in HID lamps is excluded because they would harm the electrodes, which are required for operation at low frequencies. An efficient mercury-free electrodeless lamp that could be dimmed without observable spectral changes and provide instant restrike would herald a new age of light sources. It would improve energy-efficiency and have the optical characteristics desired by lighting designers while containing minimal toxic materials.

Our present research on fluorescent lamp improvements focuses on three major energy-loss mechanisms: electrode losses; energy loss by lamp phosphors in their conversion of ultraviolet (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 challenge is to find an efficient method for coupling the RF energy into the lamp without causing new losses.

Besides the light source itself, the other important component of the lamp is the electronic power supply, which must convert incoming wall plug power to the high-frequency power required by electrodeless light sources. Because of the total absence of commercially available, efficient power supplies operating at power levels and frequencies needed for our light sources, we are also embarking on a program to accelerate the development of the necessary power conditioning equipment. The physical nature of the coupling between the light source and the power supply requires the research to be highly interactive between the power supply and the light source. Concepts such as the Type-E Amplifier, which provides a method for high-frequency switching of voltage at zero current, and current switching at zero voltage, are under consideration.

### Electrodeless HID (High-Intensity Discharge) Lamp

A major disadvantage to fluorescent lamps is their low luminosity. A lamp with lower luminosity delivers less luminous flux per unit surface area than a source with high luminosity (such as an incandescing filament). Sources with lower luminosity are less desirable in applications where good optical control is necessary. High-intensity discharge (HID) lamps can fulfill this need. Three types of HID sources are in common use today—metal halide, mercury vapor and high-pressure sodium—but only metal halide is considered to have good color rendition. If the ignition period of metal halide lamps could be greatly shortened and the color inconsistency between lamps reduced, metal halide sources could have much wider application than they currently enjoy.

Electrodeless operation of HID lamps can potentially solve the slow ignition problem with these lamps as well as affording the opportunity to increase source efficiency by the use of novel light emitting elements. With electrodeless operation, light-enhancing gasses that would attack the electrodes in conventional HID lamps can be seriously considered. The electrodeless HID approach also offers the opportunity to employ mercury-free lamp fills. One of the most promising approaches appears to be the sulfur lamp. Originally developed and patented by Fusion Systems, the sulfur lamp has been used for producing highly intense sources of ultraviolet radiation, especially useful in the electronics and packaging industries.

To apply LBL expertise on RF operation of HID lamps to the sulfur lamp, an agreement was concluded between Fusion Systems and LBL allowing for exchange of technology and concepts and providing for protection of intellectual property rights relative to the sulfur lamp technology.

With the above option agreement in place, we made significant progress in FY93 in bringing the sulfur lamp concept closer to commercialization. Adapting our RF technology to the sulfur lamp, we were able to demonstrate consistent and reliable RF operation of the sulfur lamp at low power (approximately 100 watts input) over a wide range of frequencies. By developing a coupling method for efficiently transferring RF power into the sulfur bulb, we were able to demonstrate efficacies of approximately 150 lumens per RF watt. We were further able to demonstrate that the spectral output of the sulfur lamp, which is broad band in nature, could be altered and tuned by varying lamp parameters.

This significant work has established the technical foundation for the development and production of a new light source with an efficacy far higher than that currently achieved by any other white light source. Furthermore, the successful operation of the sulfur lamp at RF frequencies paves the way to the development of highly efficient power supplies that can operate in allowed radio frequency bands.

In the next year, we intend to fund

the further development of the sulfur lamp concept and advance it toward commercialization.

### Operation of Tungsten-Oxybromide Lamps at Radio Frequencies

Tungsten-oxybromide has the potential to be the basis of a new generation of lamps that would offer many of the advantages of incandescent lighting (such as a light that is broad band in nature) while operating at much higher efficacies. Research on tungsten-oxybromide has been pioneered by Phillips Lighting in Europe.

LBL obtained tungsten-oxybromide (with a 0.4% deviation from the ideal bromine content) and used it to construct several lamps for testing under RF operation. This was a much cleaner mix than was used in our initial work on tungsten oxybromide. By using this clean mix, and adding a vacuum annealing step to our lamp fabrication process, we were able to ignite lamps consistently and stably at 42.959 MHz with 120 watts input.

### RF Operation of Low-Pressure Gas Discharge Lamps

In last year's annual report, we reported that RF operation (100 MHz to 250 MHz) of a medium-length (15-inch) fluorescent lamp system improved efficiency by only 5% as compared to operation at 25 kHz (the operating frequency of most currently used electronic ballasts). While the energy benefits of an RF lamp may be marginal compared to an electronically-ballasted lamp, the lamp life could be significantly longer than a conventional fluorescent. Because RF lamps do not require electrodes, lamp lifetimes should be 60,000 hours—three times longer than present fluorescent lamp life (20,000 hr). With RF operation, ultimate lifetime will depend on the longevity of the electronic ballast package and the lumen maintenance characteristics of the phosphor rather than the lamp electrodes.

## Impacts of New Lighting Technologies on Productivity and Health

We can achieve major benefits to lighting energy efficiency by studying human responses. Determination of visual effectiveness in terms of human subject responses requires an understanding of how lighting affects performance. This knowledge is essential to technology development, especially considering that the end purpose of lighting is for human benefit.

### Spectral Effects (with Abratech Corporation)

We have shown in previous years that the rod photoreceptors of the eye (responsible for night vision) have significant effects on vision functions at light levels typical of building interiors. These studies showed that, in adult subjects 20-40 years of age, under conditions of full-field lighting, pupil size is predominantly determined by the response of the rods (which is characterized by the scotopic function) rather than the response of the cones (which is characterized by the photopic function and is the basis of standard photometry). Other studies showed that brightness perception of whitish light also depends on the scotopic content of the viewed illumination, but not quite as strongly as does pupil size. We have discovered evidence that scotopically enhanced surround lighting produces 1) smaller pupil sizes, 2) a perception of increased brightness, 3) increased visual acuity, and 4) decreased disability glare. These results suggest that scotopically enhanced light sources need less photopic luminance to achieve given levels of visual performance, visual clarity, and brightness perception with reduced glare. By taking advantage of these effects, scotopically enhanced lighting can be operated at a significantly lower wattage without negatively affecting visual performance or brightness perception.

Our initial studies showed that two light sources (one with a scotopically rich spectral power distribution and the other scotopically deficient), providing the same level of photopic luminance of whitish light, will elicit both different pupil sizes and different perceptions of brightness. At the National IESNA meeting in San Diego, more than 100 attendees viewed the illuminants in the booth, and the vast majority of them judged the scotopically enhanced illuminant as brighter, although it produced about 20% less photopic luminance on the viewed wall.

After demonstrating lighting effects on pupil size and brightness perception, we expanded our studies to examine the effects of light spectra on visual acuity. Our hypothesis was that the smaller pupil size which results from scotopically enhanced lighting would result in improved visual acuity. We studied this question in a laboratory situation in which surround lighting was manipulated while the luminance of the visual task was unchanged. In three studies of adults 20-40 years of age, we have consistently demonstrated improved recognition of low contrast stimuli with scotopically enhanced surround lighting as compared with scotopically deficient surround lighting. We have also extended these findings to include older individuals (62-67 years of age).

Recently we have begun collaborative work with GE Lighting, which has produced a variety of scotopically enhanced fluorescent lamps for LBL to evaluate. In our first study, we compared their most scotopically enhanced lamp, the JP90, with a standard warm white lamp. This study confirmed our earlier results and demonstrations, which indicated that our findings are generalizable to lamps that can be produced commercially, and could be the basis for energy-efficient, scotopically-enhanced fluorescent lighting for general use.

In preparation for the future studies described below, we have developed instrumentation for studying visual acuity based on a word reading task. The instrumentation, which can be used in a simulated office environment, monitors both pupil size and eye position while the subject reads material, seated in a relaxed position. Reading speed, as measured by eye position, remains relatively constant as the reading material becomes gradually smaller until a critical size is reached, at which point reading speed dramatically decreases (when the words are so small as to be blurred). We plan to test whether scotopically enhanced lighting will improve vision as measured by this test.

Finally, we have begun a new series of investigations to examine the effects of surround spectra on disability glare. We believe that scotopically enhanced surround lighting may decrease disability glare for two reasons: 1) smaller pupils allow less surround light (which is the source of disability glare) to enter the eye, and 2) if the surround light is photopically deficient, the veil produced via light scatter in the eye will have a reduced effect on foveal (photopic) vision. If confirmed, this would demonstrate that scotopically-enhanced lighting can help alleviate glare—a significant factor in reduced productivity that is especially prevalent in the aging work force.

**Research on Discomfort Glare (with UCB Department of Optometry)**

A second area of importance in relating how lighting affects visual performance concerns discomfort glare. Control of discomfort glare is a significant concern for lighting users and designers. Improved energy-efficient light sources have higher luminance surfaces than their less efficient predecessors. In addition, glare is frequently reported by VDT users as detrimental to visual performance.

We have recently reported a new objective method for assessing discomfort glare by using electromyography. Although the discomfort sensation caused by glare can be qualitatively assessed by subjective methods, no one had yet found a reliable objective correlate of discomfort glare. In order to find such a correlate, we have examined electrical activity associated with the major sphincter muscle that surrounds the eye, viz. the *orbicularis oculi.* We have made electromyographic (EMG) recordings using small silver chloride electrodes applied to the skin above the muscles, and we have measured electrical potentials while lighting glare conditions have been changed. EMG responses were subjected to Fourier analysis, and the power frequency spectrum was determined with appropriate digital filtering used to eliminate power line artifacts. For individual subjects, we found increases in the EMG activity and subjective discomfort with increased glare luminance. On the basis of these results, we are able to conclude that the EMG technique is a valid objective means of assessing discomfort glare.

Currently there is a total absence of information on the spectral dependence of discomfort glare. This dependence is important because we are claiming energy-efficiency benefits of increasing the scotopic content of lighting. If scotopic spectral content increases glare effects, it would have serious negative implications with regard to scotopically enhanced lighting. To investigate the influence of scotopic content on discomfort glare, 10 subjects were studied using two glare sources. The two sources were matched for photopic luminance, but had markedly different scotopic luminances due to their spectra. Discomfort glare was assessed using both objective and subjective techniques. The objective method uses the measured EMG response as described above. For the subjective method, subjects indicated the level of discomfort by means of a questionnaire. When glare sources were equated for photopic luminance, the color of the glare source made no significant difference to the objective or subjective glare indices. When glare sources were equated for scotopic luminance, there were substantial differences in both glare indices. We are thus able to conclude that discomfort glare is related to the photopic luminance of the source.

In the coming year, we plan to examine how the equipment used to record EMG response can be simplified and made into a field instrument for direct evaluation of discomfort glare in the workplace.

## Building Applications

To achieve real energy savings with new energy-efficient lighting technologies, methods must be developed to assist the lighting community in applying these technologies and concepts in everyday design. Our building applications research covers a broad range of technical support activities ranging from the development of advanced lighting design tools to novel methods for increasing the efficiency of fluorescent luminaires. We aim to develop, analyze, and assess new and emerging energy-efficient lighting technologies and to characterize their technical performance. This information is in turn used to develop analytical methods to accurately model the energy-efficiency, cost-effectiveness, performance, and level of satisfaction with the lighting. We are active participants in ongoing efforts by the Illuminating Engineering Society (IES) to establish quantifiable relationships between visual performance and physically measurable lighting attributes such as illuminance level, luminance distribution, contrast, and glare. As part of this effort, we have developed the RADIANCE visualization and simulation program, which allows illuminated spaces to be accurately modeled and visualized in exquisite detail. Using simulated scenes that are visually indistinguishable from real photographs, we can model effects of changes in the illumination systems with regard to visual performance and, potentially, satisfaction and comfort. Validation of luminance values produced by these simulations requires physical measurements of luminances in complex environments. To measure luminance distributions in the field, we have developed video capture systems that record detailed luminance data from interior settings.

In perhaps our most successful interaction with lighting manufacturers to date, we have developed and demonstrated thermal management strategies that largely eliminate the light losses associated with fluorescent lamps operating at elevated temperatures. Convective venting of compact fluorescent lamp (CFL) fixtures—an idea pioneered by LBL three years ago—was adopted by several major fixture manufacturers in 1993.

**Energy-Efficient Fixtures**

Research at LBL over the past few years has clearly shown the importance of considering how ambient temperature affects fluorescent lamp performance. We have shown that the warmer ambient temperature of most interior fixture environments not only reduces the lumen output to about 20% below maximum, but also reduces system efficacy. We have developed two general approaches for improving the thermal performance of fluorescent fixtures: convective venting and thermal bridging.

These techniques have been successfully applied to a number of fixture systems, notably the full-size (4-ft lamp) and CFL fixtures, and are now being used by several major fixture manufacturers.

Convective venting strategies have proven particularly attractive to manufacturers of compact fluorescent downlights. Convective venting is the simple technique of strategically placing slots in the fixture reflector to allow air to flow through the lamp compartment. This airflow, which occurs naturally without external means, has the effect of reducing the lamp wall temperature to its optimum point where light output and efficacy are maximum. For many multi-lamp fixtures, this results in 20% more lumens being emitted from a vented fixture than from an unvented one. This provides manufacturers with a competitive advantage, since lumen output is often a limiting factor in CFL downlight applications. In addition to producing 20% more light, a fixture with convective venting is also about 10% more efficacious (lumens per watt) than an unvented fixture. That is, if an unvented fixture emits 50 lumens for every input watt, a convectively vented fixture will produce 55 lumens per input watt. In new construction, this efficacy advantage allows vented CFL downlights to provide the same illuminance as unvented downlights, at 10% lower power density. Increased lumen output means fewer vented fixtures are needed, reducing initial costs.

We completed several thermally efficient fixture prototypes this year. By helping fixture manufacturers to solve generic thermal control problems in their product lines, we have helped reduce the time between inception of the thermal control concept and its implementation by industry. We completed work on the induction venting CFL downlight prototypes. Depending on the specific lamp shape, number of lamps, and orientation, either back venting, front venting, or both are used to increase air flow through the lamp compartment, cooling the lamp to the optimum operating temperature. A prototype of a thermally efficient, indirect lensed fixture was also demonstrated. This fixture uses a spot cooler with heat dissipating fins concealed within the fixture body. Although this requires a slightly larger heat fin to obtain the desired cooling effect, the technique is responsive to the manufacturers' requirement that the thermal control device not be visible from the outside.

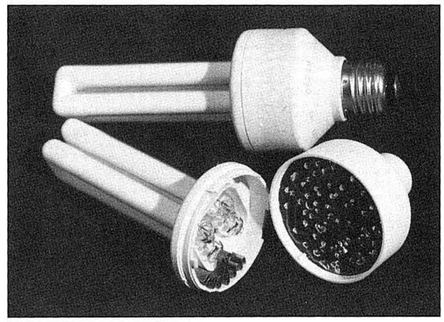

**Fig. 1.** *Thermally efficient compact fluorescent lamp broken down to show the inside of the ballast shroud. Note the heat sink on the lamp tubulation which cools the tip sufficiently to improve base-down performance to approximately the same level as base up operation.*

Our research has shown that a screw-based CFL, operated base-down (as in a typical table lamp), produces 20% fewer lumens than the same lamp burned base-up. This represents a disincentive to use CFLs, since base-down applications are common in the home, and low lumen output has been identified in other research as a significant market barrier. Using a thermal bridge that is installed within the ballast shroud, we have demonstrated a CFL that produces the same lumens regardless of burning position. As shown in Fig.1, the heat sink fits over the lamp tubulation that juts into the ballast shroud. The heat sink itself is inexpensive and easy to manufacture and install.

As part of the joint DOE/CEC ETAP project (California Energy Commission's Energy Technology Advancement Program), we completed several building demonstrations of thermally efficient fluorescent luminaires. At the National Institute of Standards and Testing (NIST) environmental facility, spot coolers were installed in 2′ × 4′ troffers and their performance measured relative to a control condition. We also concluded a demonstration of convectively vented CFL downlights at the Ventura County Courthouse. Next year, we will complete an additional three demonstrations, which will include indirect and direct pendant-mounted fixtures using internal thermal bridges.

As our research into improved thermal management is being successfully transferred to industry, we are shifting the focus of our work to improving the optical performance of fixtures. This work is proceeding along two fronts: the first is directed at improving the luminaire efficiency for modern CFLs (especially the T-5 fluorescent lamp); the second seeks to develop efficient optical systems for distributing light from the next generation of high output light sources.

In FY93, we developed a study describing the physical characteristics of reflectors for T-5 fluorescent fixtures that are based on non-imaging concentrators (compound parabolic concentrators).

If highly efficient, high-output sources (such as the sulfur lamp and the electrodeless HID sources described earlier) are to find widespread application, it will be necessary to develop lighting distribution systems that are able to efficiently transport light from the source to the area where the light is needed. We are studying a variety of approaches, including light pipes, improved reflectors and refractors, fiber-optics, and silvered tubes as ways to distribute light throughout a building space. As an exploratory exercise, we worked with TIR (of Vancouver, Canada) and 3-M to produce a prototype 4-way light pipe system that could effectively meet the lighting needs of four workstations using one 20,000 lumen source. We have installed the light pipe system into the newly completed fixtures laboratory and are setting up to measure its luminous performance (Fig. 2). After installation, a series of measurements will be made with a

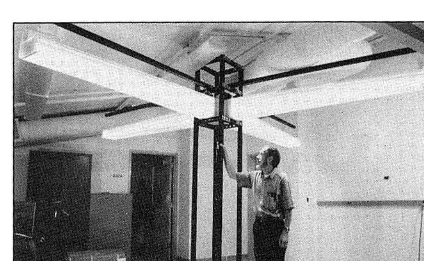

**Fig. 2.** *Researcher examines a 4-way light pipe prototype system. This system uses the light from one centrally located 250-watt metal halide lamp and distributes light uniformly down the four arms of the fixture.*

conventional 250-watt metal halide source to determine the system's optical efficiency (OE) and the luminaire efficacy factor (LEF = lamp/ballast system efficacy × OE). This derivation will help to characterize the efficacy of the advanced lighting distribution system (ALDS) in supplying illumination in realistic building applications and will provide a basis for comparing the to other competing systems. The 4-way light pipe will be modeled using OptiCad, and the simulation results compared to physical measurements.

Finally, we are providing equipment, design assistance, and analysis to the building staff and design group of the National Air and Space Museum and at the DOE Forrestal Building in Washington D.C. with respect to demonstrations of sulfur-lamp/light pipe systems at these facilities. The Lighting Group staff will continue to assist in these demonstrations by performing photometric measurements and analyses of the spaces after the equipment is installed.

### Quality Illumination and Performance

One of the major activities of the Illumination Engineering Society of North America (IESNA) is the development of light level recommendations. Although not prepared as a legal standard, the recommendations of the IESNA are often the de facto standard. As such, their light-level recommendations have major implications for lighting energy consumption in the U.S. The present recommendations have been in place for more than a decade, and the IESNA is tasking its technical committees to issue new and revised recommendations. A major reason for this action is that the present recommendations are based on consensus opinion of a body of expert practitioners and have no clearly defined analytic basis. The principal technical committee undertaking the revision has proposed that the new recommendations be based on the experiments and models of visual performance.

Over the past years, we have been involved in the analysis of visual performance and have concluded that a major flaw in the IESNA recommendations is their failure to take into account the economic aspects of light level. To this end we have been incorporating straightforward benefit/cost analysis in the modeling of visual performances and have derived consequences for light level recommendations. During the past year, we have developed a method for finding optimum light levels based on identifying the point at which the economic value of performance benefits to workers, due to increased lighting, is incrementally less than the cost of the added energy and equipment. This analytic procedure can be applied to all models of visual performance. Our methodology, when applied to the model of visual performance used by the IESNA in their proposed revisions, yields values for light level recommendations that are very different from theirs. Differences between the IESNA numbers and our values can be greater than an order of magnitude, with the IESNA recommendation generally being higher. These results were presented at the 1992 annual national meeting of the IESNA.

Our work is the first to explicitly combine both the benefits and costs of lighting to derive a light level recommendation. These results will have a major impact on energy use for lighting. We expect to actively pursue further interactions with the IESNA on this issue during FY94.

In addition to introducing economics into the IESNA light level issue, we have completed an extensive study of 16 subjects who read words as a visual performance task. We determined how performance (reading speed) relates to light level and contrast, with the size of the letters as the critical parameter. The model developed to support the data represents a major refinement over past models and should replace earlier models with less predictive power.

More importantly, this study has led us to the development of a simple instrument that can be taken into the field to test whether a particular worker has an adequate light level for a particular task. The instrument has been built, and we have tested it in an office building as part of our lighting quality work under the auspices of Caltrans (the transportation agency for the State of California).

### Study of Lighting Quality at a Caltrans Office Building

Under contract to Caltrans, we conducted a series of physical measurements, expert surveys, and occupant questionnaires in an effort to assess the lighting quality in a Caltrans office building in Marysville, CA. One of our goals was to examine whether simplified measurements of illuminance and luminance could be used to predict occupant satisfaction with the workplace environment. In fact, the occupant survey revealed that a significant number of employees in the space lit with parabolic-type fixtures rated the lighting quality of their work areas relatively poorly compared to occupant ratings for a similar space lit with wraparound type fixtures. While we were unable to obtain sufficient objective data to demonstrate the point at a statistically significant level, we found that the presence of reflected ceiling lights in computer screens (as ascertained by our visual inspections) did correlate with occupant dissatisfaction with the lighting. At a lower, but still significant confidence level, the occupants' overall impression of lighting quality was also correlated to the absence of veiling reflections in computer screens. Since the presence or absence of veiling reflections can be easily checked by non-experts, our findings should be helpful in improving the quality of lighting audits. But we were disappointed in not finding correlations to the more traditional variables available to lighting designers and auditors (such as illuminance and calculated visual comfort probability). This in part may reflect the fact that designers take illuminance levels and glare into account in their designs. Regardless, our findings revealed that simple adherence to accepted standards of illuminance and glare does not guarantee satisfactory lighting in modern office spaces.

### Computer Imaging

With most of the development of the RADIANCE computer simulation program completed, the emphasis of this year's work was preparing RADIANCE for transfer to the private sector. Effort was also devoted to using RADIANCE for solving various real-world design problems.

We completed an interface for RADIANCE that provides default values for most program options given a user-inputted parameter for rendering quality. Thus the user can request a "low" quality rendering, for example, and the program will select the options that best reflect that quality of rendering. This interface significantly reduces the work required for third-party developers of commercial lighting software to incorporate RADIANCE into their existing products and increases the probability that RADIANCE will have widespread application as a tool for energy-efficient lighting design.

We are making the RADIANCE simulation engine available to a broad sector of the architectural and illumination engineering community by licensing RADIANCE 2.3 to private-sector software developers. As necessary, we will assist private-sector developers in the codevelopment of interfaces to allow RADIANCE to run with successful lighting and architectural design packages.

## Environmental Impacts of Mercury in Lighting

We completed a study on the effects of mercury in light sources on the environment and the biosphere. Among other things, this study showed that incandescent lamps, even though they contain no mercury, cause twice as much mercury to be released into the atmosphere as conventional fluorescent sources (Fig. 3). Because incandescent lamps are so much less efficient than light sources that contain mercury, additional fossil fuels (which contain trace amounts of mercury) must be burned to generate the additional electrical energy required to produce the less efficient light. The release of mercury into the atmosphere via the smokestacks of power plants presents a shorter path to the biosphere than discarded lamps in a landfill.

## "Greening of the White House" Initiative

Because of our deep understanding of new lighting technologies and our experience in assessing lighting quality in buildings, we were asked to be members of an interagency team charged with performing an energy and environmental audit of the White House complex. This audit was requested as part of the Greening of the White House Initiative announced by President Clinton in April 1993. Working with other members of the interagency team, we performed a lighting audit of the Old Executive Office Building (OEOB) and the White House Residence, as part of the larger energy and environmental audit conducted in June 1993 (Fig. 4). Along with other LBL staff, we participated in the Greening of the White House Workshop—an intensive three-day design charrette drawing on the knowledge of 100 experts from all parts of the country to provide recommendations to the Office of Environmental Policy on how to improve the energy efficiency of the White House complex.

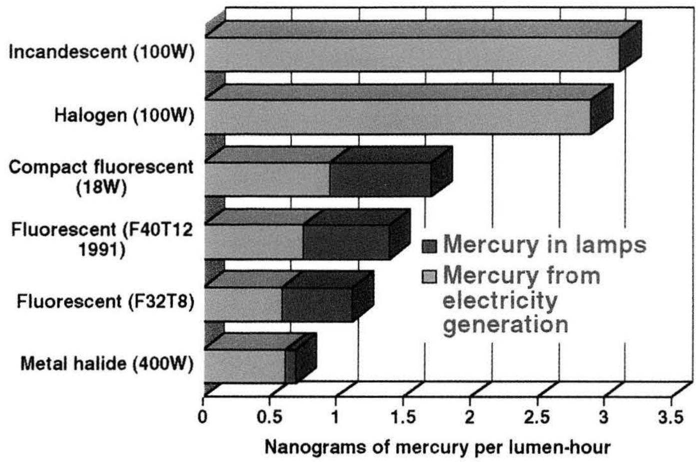


**Fig. 3.** *Graph shows the amount of mercury introduced into the environment as a consequence of using light sources of varying efficiency. Although incandescent lamps contain no mercury, their use actually causes more mercury to be introduced into the environment (via the burning of coal) than do more efficient sources that contain mercury.*

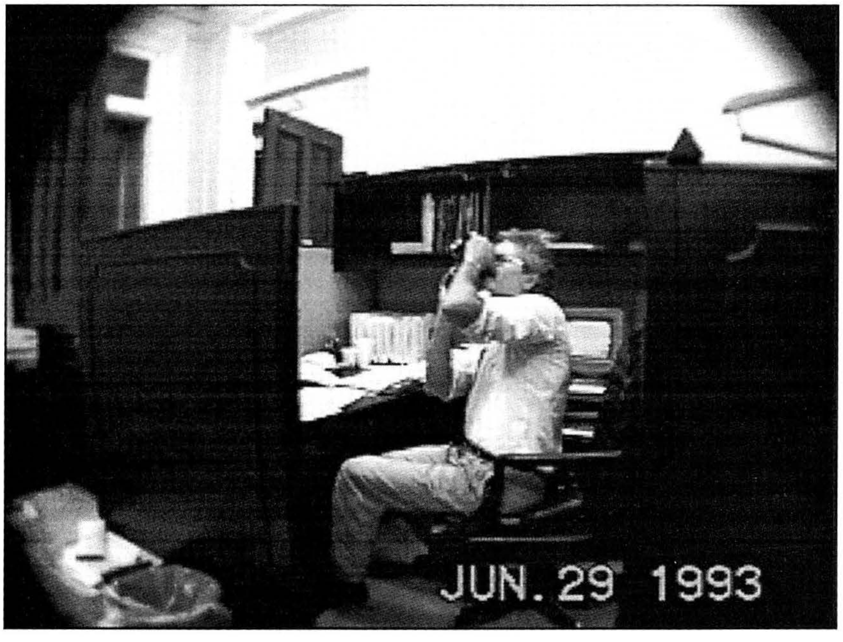


**Fig. 4.** *Researcher measuring luminance of a ceiling fixture in Old Executive Office Building. This video still was obtained during the June 1993 energy audit of the White House complex.*

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