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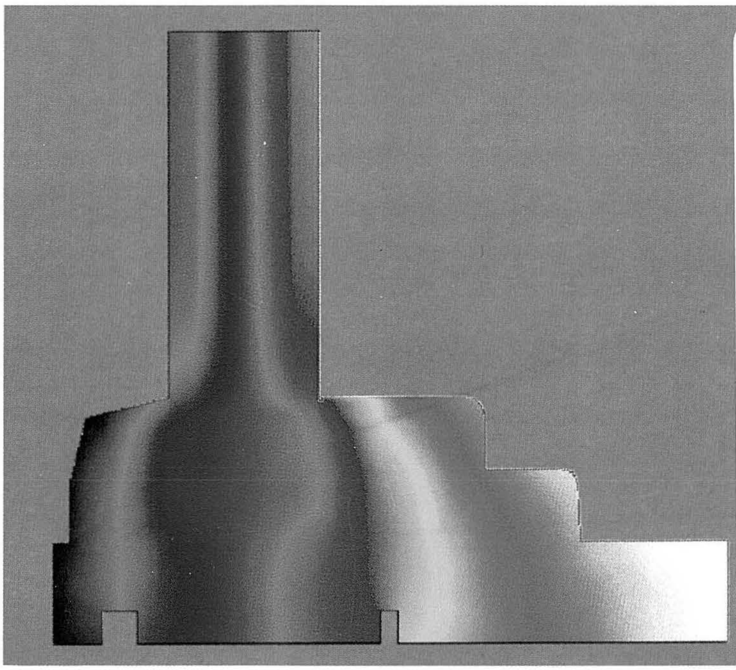
Building Technologies Program

1994 Annual Report



Energy & Environment Division
Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

LBL-36553
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April 1995

Cover: False-color visualization of temperature profile in a window section. The profile is calculated by THERM, a new heat-transfer engine being developed for WINDOW 5. (See Fig. 6 for a companion output figure with temperature contours.)

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Building Technologies Program
1994 Annual Report

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Report No. LBL-36553

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 comfort, amenity, health, and productivity in the building sector. We have focused our past efforts on two major building systems, windows and lighting, and on 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. In addition, we are now taking more of an integrated systems and life cycle perspective to create cost-effective solutions for more energy efficient, comfortable, and productive work and living environments.

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 to 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. These models are essential tools in any effort to formulate an integrated systems perspective on total building performance.

Despite important achievements in reducing building energy consumption over the past decade, significant additional savings are still possible. These will come from three complementary strategies: 1) developing advanced technologies that increase the savings potential for each building application; 2) integrating components into new building systems so that overall performance can be optimized while cost and risk can be minimized, and 3) developing advanced simulation and design tools so that building professionals can effectively select and apply existing technologies, thus extending market penetration of these technologies, and can create new design solutions that optimize overall building system performance.

Finally, all of these strategies must be embedded within a large 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 in buildings throughout the country. If the flow of heat and light through windows and skylights can be properly filtered and controlled with new advanced technologies, 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 also 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 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 the 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 daylighting scale models and new experimental facilities for measuring the photometry 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. Results of these analysis studies are being incorporated into new computer-based tools that use multimedia techniques and expert systems.

The ***Lighting Systems Group*** focuses its research on three areas: advanced light sources, impacts of lighting technologies on productivity and health, and building applications.

Our research on advanced light sources is concerned primarily with developing new technical concepts for efficiently converting electrical energy into visible light. The thrust of this research is the development of long-lived electrodeless lamps that use very high frequency (VHF) power to produce broadband white light, potentially without the use of mercury. One of the most promising light source developments, the sulfur lamp, was announced by DOE in October 1994. By applying our expertise in RF-operated sources to the new sulfur lamp we are helping to push forward the date when end-users will be able to take advantage of this exciting new light source.

The building applications research concentrates on technical approaches leading to major advances in fixture efficiency via improved optical design and better thermal management of fluorescent sources. We have developed several innovative, highly cost-effective approaches for improving fixture efficiency up to 20% that have recently been adopted by several major fixture manufacturers. Our study of advanced lighting distribution systems focuses on improving the efficiency of novel fixture designs that can exploit the technical attributes of the new sulfur lamp.

Our studies in the impacts area extend our research in electric lighting technologies to include consideration of how lighting affects human performance, productivity and well-being. Using specially designed experimental chambers where the lighting can be carefully controlled and manipulated, we have used sensitive instrumentation to measure human response to different lighting situations. We have collected data on how lamp spectral composition affects visual function and brightness perception. We are working with lamp manufacturers to assist them in the development of new lighting products that will take advantage of this new research to produce light that is more visually effective per unit of power consumed.

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 are continuing 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.

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Windows & Daylighting

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The energy-related cost of windows in the U.S. building stock exceeds $20 billion per year. Window performance also directly affects peak electrical demand in buildings; sizing of the heating, ventilating, and air-conditioning (HVAC) system; thermal and visual comfort of building occupants; and human health and productivity. With more intelligent use of existing technology and with development of new high-performance window materials, windows can be converted from energy liabilities to energy benefits.

The aim of the Windows and Daylighting Group is to develop tools and technologies necessary to accomplish this goal 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 fenestration concepts
  - New materials processing technologies
- **Fenestration Performance**
  - Window rating systems
  - Thermal analysis
  - Daylighting analysis
  - Field measurement of performance
- **Building Applications & Design Tools**
  - Residential and nonresidential buildings
  - Advanced design tools
  - Deployment programs
  - Market assessment

Innovative Technology and Systems

With the development and use of new high-performance glazing materials, buildings will consume significantly less energy than they currently require. The members of LBL's Windows and Daylighting group are therefore working to identify, characterize, and develop promising new optical materials for these applications. By working closely with industry, we hope to accelerate the introduction of advanced fenestration systems to the market. Our work involves coordinating scientific aspects of DOE-funded research projects at universities, private-sector firms, and other national laboratories.

Changing the standards of practice in the building industry takes strong, consistent effort over time. Despite the difficulties, our program has made significant gains in bringing low-emittance (low-E) coatings to the market. They were introduced commercially in 1982 after six years of DOE-funded research. By incorporating the coatings into conventional double-glazed windows, we produced a lighter, more compact unit with better thermal performance than that of triple-glazed windows. Today, low-E coatings are used in more than 40% of all residential windows.

We next turned our attention to the development of highly insulating "superwindows." These combine low-E technology and gas fills. Our cooperative efforts with industry have led to several commercially available products. The glazings have such low rates of heat transfer that they outperform even the best insulated walls in winter in any orientation and in any U.S. climate.

For cooling-dominated climates, we are developing improved spectrally selective coatings—modified low-E coatings that transmit daylight but reject near-infrared radiation. We develop improved coatings of this type and also help specifiers use them more effectively.

The majority of our recent work has been focused on developing "smart windows." These are windows that incorporate dynamic materials and devices, which have optical properties that respond to a changing environment. The resulting window systems have comprehensive energy management capabilities. These and other optical materials that can control incident daylight will allow the windows of the future to deliver net energy benefits to all buildings throughout the year in virtually any climate.

Spectrally Selective Coatings

We have been working to develop improved spectrally selective coatings for windows and to promote their use for energy efficiency. Spectrally selective coatings preferentially transmit visible light while rejecting the heat-bearing near-infrared component of sunlight. Although earlier research has shown that silver-based coatings make effective "cool glazings," we are exploring the use of other metallic compounds known to be more durable than silver and to have superior optical properties. This would extend the usefulness of "cool windows" to applications requiring more durable coatings.

Deposition with Ion-Beam Sources

In FY94, we used ion-beam sources to deposit durable coatings with superior properties onto glass. These coatings included oxide films with metallic properties and dielectric multilayers. The drawback of ion-beam sources for oxide deposition proved to be extreme slowness. We also tested another type of plasma source, developed at LBL, which had very high deposition rates (Fig. 1). We are planning to adapt both types of sources to industrial coating systems and conduct test runs with industrial partners of our durable cool glazings.

Retrofit Films

Almost all homes in California and elsewhere have clear glazing, which admits high levels of solar heat. In previous work, we showed that replacing existing residential windows with spectrally selective cool windows can significantly reduce energy costs and peak energy demand. The lowest cost retrofit strategy is to add a coated polymer film to the existing window. In FY94, with co-sponsorship from the California Institute for Energy Efficiency (CIEE), we began to investigate the potential lifetime of newly available retrofit films and to explore solutions for increasing that lifetime. If the results are positive, we will work with utilities and manufacturers to promote the conversion of homes to this cool window technology.

Superwindows

Highly insulating windows have long been considered important in virtually all residential and some commercial buildings that have a sizable heating load.

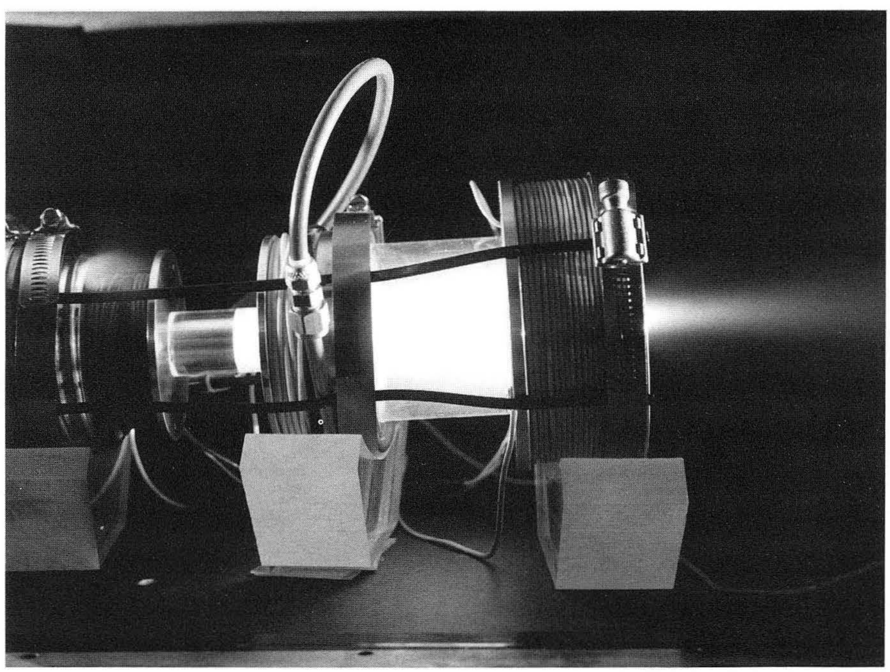

Figure 1. *Hollow-anode ion source for enhanced deposition of durable spectrally selective coatings. (BBC-944-1995)*

The building industry began marketing low-E, gas-filled windows with R values up to 4 hr-ft^2-F/Btu in the 1980s. At the same time, LBL researchers showed that, in a typical northern U.S. residence, windows with total R values greater than 6 hr-ft^2-F/Btu transmit more useful solar gains in winter even on a north elevation than they lose in conduction. These superwindows, therefore, would require less heating energy per square foot over a full heating season than would an insulated wall. This knowledge led us to develop the technology base for such highly insulating windows. Since the manufacturing of window products involves diverse materials and designs, we focused our research on developing new generic design concepts and establishing new tools that would allow manufacturers to analyze low-conductance glazings and alternative superwindow designs.

LBL advancements in the past several years include the development of a design concept for a superwindow, which was quickly commercialized, and participation in utility-supported field tests to validate window performance claims. We also developed a rating system to accurately characterize the performance of highly insulating windows. An infrared (IR) thermography laboratory has been established at LBL to study two-dimensional heat transfer through insulated window frames and edges (see Thermal Analysis). In FY93, we began design work on an integrated window/wall system that takes advantage of superwindow technology.

Our current work emphasizes collaboration with the U.S. fenestration and fenestration component industry to accelerate the development and cost-effective manufacturing of highly insulating windows. Given that there are many different ways to make windows and that consumers demand a variety of different products, the strategy is not so much to develop specific products but to use our expertise (our comprehensive knowledge of window heat transfer) and equipment (i.e., the IR laboratory and available simulation tools) to work with industry to make their product offerings as energy efficient as possible.

In FY94 we collaborated with Australian (University of Sydney) researchers on the development of an evacuated glazing system prototype, helping to identify the significance of two-dimensional thermal short circuits. The Australian team has developed a suitable technique for fabricating the glass-to-glass vacuum seal. The glazings have a typical center-of-glass conductance of 0.18 Btu/hr-ft^2 F but there is significant thermal loss at the edge. Our analytical and experimental studies quantified the performance of several design strategies for incorporating the evacuated glazing in a sash with reduced edge losses.

We also documented design specifics for the integrated window/wall system. The system with its recessed summer shading devices and night insulation replaces the conventional system shown in Fig. 2.

LBL continued to participate in the development of a national rating system for window thermal performance that accurately represents the benefits of superwindows (see Window Rating and Labeling Systems). The development of window thermal/optical simulation programs that accurately model superwindows also progressed (see WINDOW Computer Program).

In FY95, we will continue our work with Australian researchers to develop and test insulating edges for use with their evacuated glazing system and we will help U.S. window manufacturers evaluate this technology. We also plan to design, build, and test a prototype of our integrated window/wall system. In the coming year, we will present the prototype and discuss its design with industry. We will continue to ensure that superwindows are properly treated by a national rating system and in our own window thermal simulation programs.

Advanced Insulation

We realized in 1990 that we could design a high-performance opaque insulation with twice the thermal resistance of conventional CFC-blown foams by applying the same concepts used in high-performance windows. The result will be a more efficient, cost-effective insulated product. With financial support from the CIEE and the DOE, we began testing opaque panels composed of thin, low-emissivity coated polymer layers that hold low-conductivity gases. The primary use of these gas-filled panels (GFPs) is in residential refrigerator/

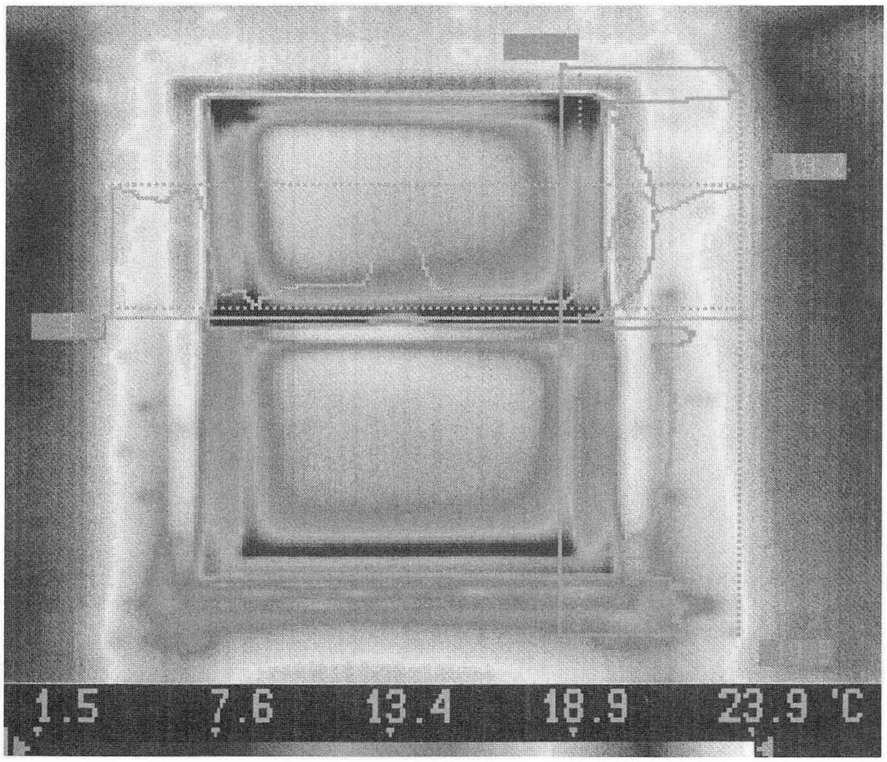

Figure 2. *Infrared image shows the warm side of a standard 2 × 4 wall with an energy-efficient double-hung window in the center. While the wall and center-of-glass areas are at constant warm temperatures (shown by red or yellow-red), other surfaces are colder (shown by blue, green, and violet), indicating thermal bridging through window frame and window framing materials. Current research focuses on the development of integrated window/wall systems which minimize two-dimensional framing effects and contain recessed night insulation and exterior summer shading devices.*

freezers, which account for 7% of electricity usage nationally. To avoid changing the interior or exterior dimensions of the appliance shell, new systems will need higher levels of insulation per unit thickness.

Efforts during previous years focused on the development and testing of prototype GFPs. Recent research, however, has shown that the thermal performance of a refrigerator/freezer shell is also a strong function of the structure used to contain the insulation. As a result, we built several prototype refrigerator/freezer door systems that utilize low-conductance structural polymer shells (as opposed to standard designs which use high-conductivity steel shells) (Fig. 3). Conventional steel shells, where foam is required for structure, allow for only about 50% coverage with GFPs by volume. In contrast, our polymer shells allowed for 95% coverage by volume with GFPs. We tested a typical top-mount refrigerator/freezer with these advanced doors in-house and also began testing at independent Environmental Protection Agency (EPA) and DOE laboratories.

Our basic research on GFP panel development this year included studies of the gas permeability of barrier materials, the use of alternative gases, and baffle design and construction.

In FY95, we expect to complete independent testing of the refrigerator/freezer doors, which we started in FY94. We will present our results to the refrigerator/freezer industry and to polymer manufacturers that would be capable of manufacturing such doors. We also plan to evaluate the possibility of using the same technology for the entire appliance cabinet.

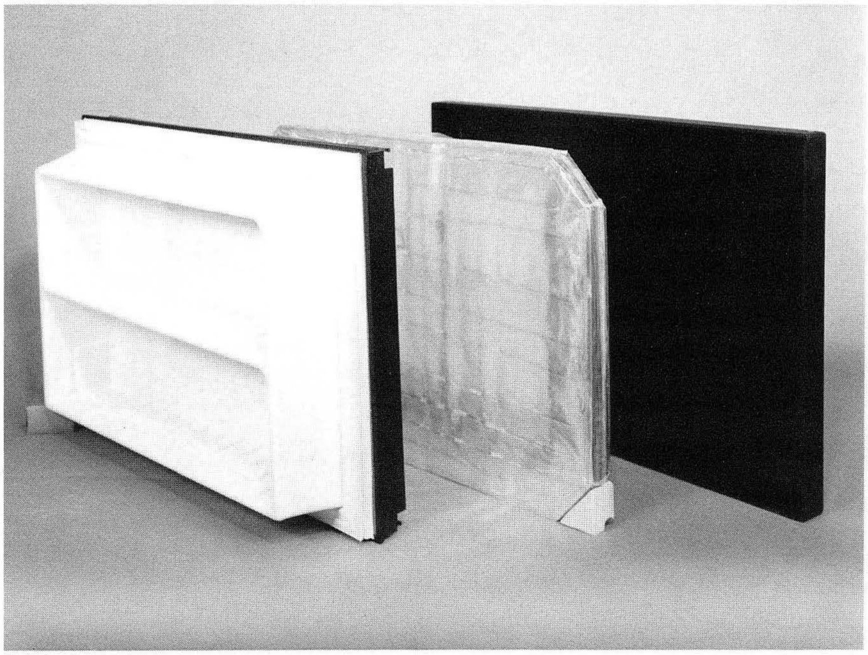

Figure 3. *Advanced gas-filled panel insulation is used in prototype polymer refrigerator doors to be tested at Oak Ridge National Laboratory. (BBC 947-4249)*

Electrochromic "Smart Windows"

Electrochromic glazings have great potential to improve the energy efficiency and occupant comfort afforded by architectural windows. These smart windows can dynamically control light transmission by windows in buildings, automobiles, and aircraft. Electrochromic glazings are the most significant members of a family of chromogenic light-control technologies that includes large-area dispersed liquid crystals, dispersed particle windows, and photochromic and thermochromic materials. Electrochromic devices represent the most versatile window technology of this type, exhibiting the best combination of switching properties for chromogenic window applications.

Electrochromic glazings typically have a change in visible light transmission from 10% to 70%, moderately fast switching times, and low dc power consumption. These glazings have memory, so they only need power to make a change in transmission. Electrochromic technology can be coupled with smart control systems to give constant lighting levels, blending artificial lighting with daylighting for improved building energy efficiency. Energy simulations of office buildings indicate that smart windows with lighting controls in arid climates can provide 30–40% energy savings over conventional windows. Savings are realized in cooling, lighting, and peak utility electric loads. Other benefits include smaller heating, ventilating, and air-conditioning (HVAC) systems and greater thermal and visual comfort. Our FY94 work focused on the fabrication and performance of electrochromic devices and comparison to international smart window developments.

In FY94, our continuing in-depth studies on the modeling of switchable glazing energy performance helped to better quantify the energy efficiency of switchable windows. We used our WINDOW 4.0 window simulation program to model the detailed optical properties of a range of electrochromic windows with real and hypothetical properties. The use of measured electrochromic window characteristics helps us to more realistically model these windows. We used the DOE 2.1 building energy model to calculate the expected energy savings over conventional windows and investigated the effect of alternative daylight control strategies. We found that even greater energy savings could be obtained by using predictive algorithms to optimize cooling control. We have just begun to explore the issue of increased visual and thermal comfort. In FY95 we will do more performance modeling to investigate comfort issues and control systems, and we will extend our studies to examine performance in residences.

Our electrochromic device development concentrated on a lithium coloring device based on tungsten oxide as the active electrode. The device structure consisted of an active electrode beside an ion conductor next to an ion storage electrode, all laminated between 2 pieces of conductive glass. This device was made with doped and chemically modified a-PEO (polyethylene oxide) as the ion conductor. The counterelectrode was of lithium nickel oxide. Finished devices first cycled between 53% and 3% luminous transmittance, and after 7,000 cycles the devices switched between 55% and 10%. Figure 4 shows an example device with three conditions of coloration. We tested devices to 80°C before we noticed bubble formation. To give higher stability, we will process the polymer to exclude the lower molecular weight products; this should solve the bubbling problem. This and other device improvements will be made in FY95.

We studied the various material layers to improve the overall device properties. We used reactive sputtering to make niobium oxide films. Such films have shown promise as possible substitutes for tungsten oxide. Niobium oxide is more chemically stable than tungsten oxide. For this electrode, we were able to obtain a 40% change in visible transmittance. We also studied sol-gel processing to make ion conductors and ion storage electrodes. Sol-gel is a unique process that allows solid ceramics and glass layers to be made by low-temperature processing. The goal of the sol-gel work was to develop processes that were potentially less capital intensive than conventional coating processes and thus reduce coating costs. We successfully made lithium niobate ion conductors as a substitute for a-PEO. We were also able to make niobium oxide as an active electrode by sol-gel deposition. In addition, we used a thin tantalum oxide sol-gel coating to improve the electrochemical efficiency and chemical stability of tungsten oxide.

During FY94, we continued our ongoing collaboration with Dow Chemical on the application of their proton fluoropolymer in tungsten oxide devices. We helped Dow evaluate some of the more basic materials science issues concerning the layers used in their device.

Our research in FY95 will be directed at creating larger electrochromic devices with improved cyclic durability and optical performance. We also intend to better quantify the energy efficiency and human factors properties of electrochromic windows. DOE will launch a cost-shared initiative with industry in FY95 to develop prototype windows for niche markets in three to five years. We expect to apply our materials and device development expertise to help industry meet those goals.

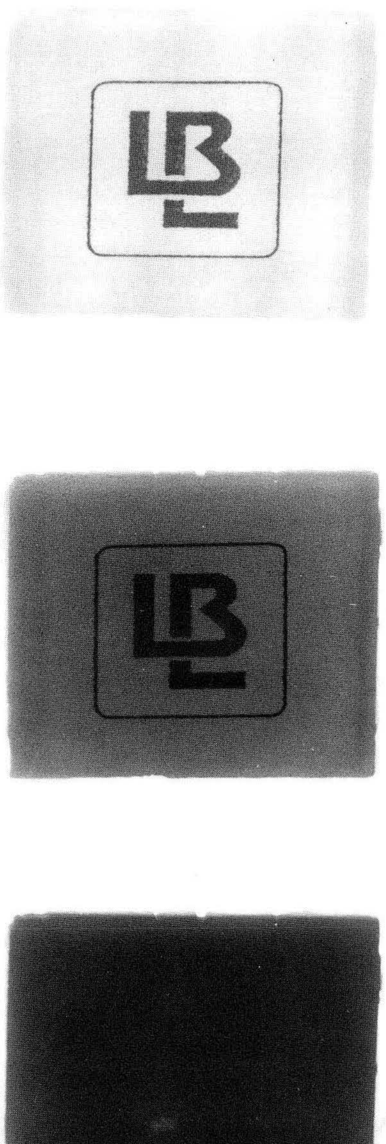

Figure 4. *LBL electrochromic window. Shown are the bleached condition, intermediate coloration, and fully colored (top to bottom). The window is constructed of thin films of tungsten oxide and lithium nickel oxide laminated with a polymer ion conductor. The visible transmittance range is* $T_v = 0.68\text{-}0.10$ *and solar transmittance range is* $T_s = 0.47\text{-}0.07$.

Fenestration Performance

Achieving greater energy efficiency in buildings through improvements in window technology involves more than developing new components and systems. Obtaining reliable information about their energy performance is equally important. With such data, a designer can match fenestration systems to architectural needs. To make this possible, one must be able to determine window energy performance under various conditions. Assessment of fenestration performance forms a vital link between development of new technology and its effective use in buildings.

Our work in this area aims to assess fenestration components and whole systems over the entire range of operating conditions that may exist in any climate or building type. We are developing and refining analytical models and techniques for determining heat transfer and solar optical properties of window systems; we are validating them in field test facilities and in occupied buildings. This experience helps us to improve the accuracy of our predictions. In addition, it lets us predict the performance of new window systems and architectural designs. Hour-by-hour building energy simulation programs, like DOE-2.1, comprise many new algorithms and data sets. Our window standard and labeling activities take advantage of other data. Providing the National Fenestration Rating Council (NFRC) with performance characterization procedures and technical support has been the main thrust of this program. This assistance helps the NFRC in the development of its window energy rating systems.

Window Rating and Labeling Systems

As highly efficient window systems have evolved during the past decade, the need for better ways to assess the thermal performance of these systems has grown. A single fair, accurate, and inexpensive rating and labeling system that could be used to compare all types of fenestration would have many benefits. Consumers, architects, and engineers would have access to reliable information, and utilities would be assured of real energy savings. State energy offices would be spared the need to develop their own rating systems, and manufacturers would have to meet only a single standard.

The National Fenestration Rating Council (NFRC) was founded in 1989 to answer this need. The council brings together manufacturers, architects, engineers, builders, state regulators, utility incentive programs, and consumers. To meet the requirements of the Energy Policy Act (EPACT) of 1992, the council hopes to complete the development of a basic window rating and labeling system in 1995 (Fig. 5).

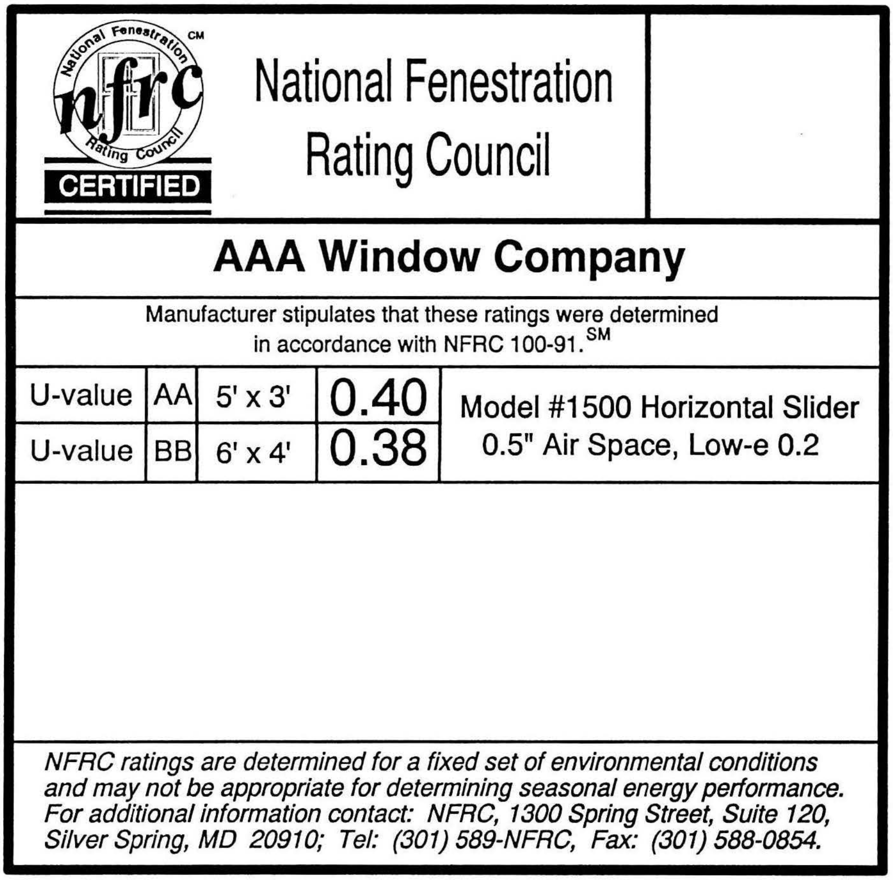

Figure 5. *Sample NFRC label showing U-value data for two standard window sizes.*

Researchers at LBL are assisting the NFRC in this task. LBL staff members chair or are actively involved in all the council's major subcommittees and are responsible for coordinating the development of many NFRC procedures. Several NFRC standards for simple windows are based on our WINDOW computer program and its supporting research, and the Annual Energy Subcommittee has used our RESFEN computer program to study issues relating to the annual energy effects of windows.

In 1994, we worked with NFRC to improve the accuracy and cost-effectiveness of the U-value procedure, which NFRC implemented in 1991, and to extend it to opaque doors. We also worked to finalize NFRC procedures for determining solar heat gain and infiltration for simple window systems. Continuing efforts were made to educate manufacturers about how an annual energy rating system for residential buildings would work.

In 1995, we expect to finish the implementation of the solar heat gain and infiltration procedures. We will expand our efforts to improve the accuracy of the U-factor and solar heat gain procedures for complex products (i.e., skylights and other projecting windows). Work is also planned to help NFRC complete a draft of the first annual energy rating methodology for residential windows. We will strive to make sure that it is consistent with the work of other groups (i.e., ASHRAE) that are developing other related annual energy estimating methodologies.

WINDOW Computer Program

In the mid 1980s, we developed a computer program to evaluate the thermal performance of window systems. This program, WINDOW, calculates thermal performance properties such as U-values, shading coefficients, solar heat gain coefficients, and various optical properties. It has been used by manufacturers in the design development process; by the American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE) to calculate tables of representative U-values for the 1989 and 1993 editions of the Handbook of Fundamentals; and most recently and most significantly, by the NFRC to develop certified ratings for fenestration product U-factors and solar heat gain coefficients (see Window Rating and Labeling Systems).

Our goal is to ensure that the WINDOW software meets the needs of the fenestration industry and market in determining product thermal performance parameters. It will provide information for both design development and consistent product rating. We continually strive to improve upon program capabilities so that advanced products can be designed and rated accurately. Such improvements include adding databases and capabilities to evaluate component performance. We also hope to improve the program's ease of use so that it reaches a wider audience.

This year, we released an upgraded version of WINDOW 4, version 4.1. This upgrade incorporates many procedural changes and was intended to meet the needs of the NFRC's recently implemented U-value rating system. We began development of a two-dimensional, finite element analysis (FEA) heat transfer module for WINDOW. The current version of the program uses a one-dimensional algorithm to evaluate glazing system heat transfer and then uses data from the Canadian FRAME program to evaluate two-dimensional frame/sash effects. The new Thermal Resistance Modeler (THERM) module will allow the user to directly import CAD drawings or scanned images of window frame/sash profiles and easily model their true geometry (Fig. 6). This code is being developed in collaboration with colleagues at the University of Massachusetts. Much of the effort has focused on obtaining an automeshing code so that no input from the user on mesh levels is required. This is necessary if the program is to be used by the window industry as well as by heat transfer experts. Planning continued on the development of WINDOW 5.0 which will feature a new window-based user interface, new databases, and links to other software modules.

Next year, we will release the two-dimensional FEA heat transfer module as a stand-alone tool. Its output will be usable by WINDOW 4.1 to calculate total product properties. The module will also be capable of analyzing two-dimensional heat transfer effects through other building components. A beta version of WINDOW 5.0 will be completed.

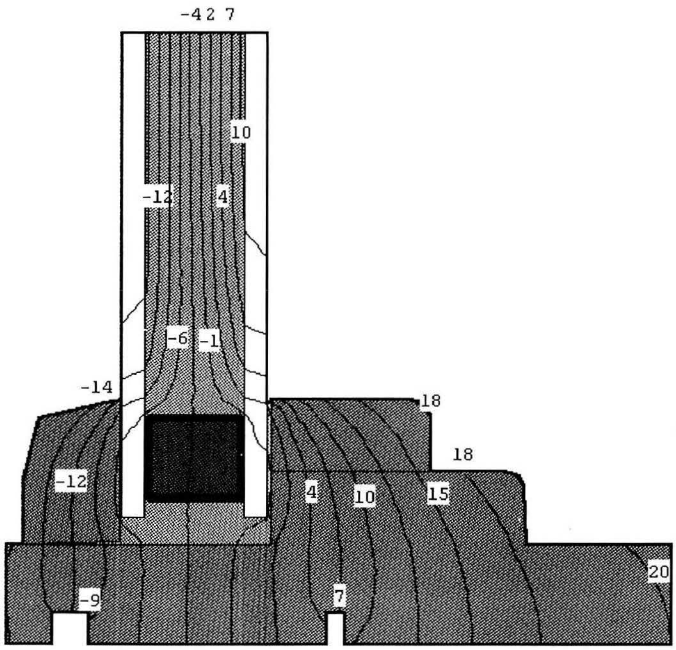

Figure 6. *Sample output screen from THERM showing temperature contours at edge of window. (For false-color visualization, see cover photo.)*

Thermal Analysis

Advanced optical coatings, gas fills, and insulating edges and frames are being used in more and more windows, leading to a proliferation of available window configurations. Methods of thermal analysis for windows have had to keep up with the fast pace of change. We are advancing the thermal analysis field by developing computer tools and experimental facilities to evaluate thermal effects (i.e., conduction, convection, and radiation) in fenestration products.

Our efforts in this area focus on improving the WINDOW program's treatment of heat transfer. This year, we concentrated on developing THERM, the FEA engine for WINDOW (see WINDOW Computer Program). We also upgraded the measurement capabilities of our IR thermography laboratory. This facility helps manufacturers examine specific high-performance fenestration products they have under development. It uses infrared imaging to visualize and quantify the thermal strengths and weaknesses of window systems. Prototype windows are mounted in a chamber so that one side is exposed to room-temperature air and the other is exposed to cold air. With the upgrade, we have more precise control of warm- and cold-side temperatures and air flow. Thus, our thermography results can be better compared to those obtained with standard hot-boxes used to measure total product U-values.

In 1995, we will conduct preliminary research on adding convective and three-dimensional heat transfer capabilities to the THERM module. We also plan to finish improvements to the IR thermography laboratory. The upgraded laboratory will be used to develop a database of two-dimensional and three-dimensional effects for comparison with THERM and other computer programs. This will help us to prioritize future improvements to THERM.

Optical Performance

Standard procedures for determining the optical properties of window materials are vital in any effort to improve energy efficiency. Consistent, reliable characterization provides feedback for developing new materials, data for calculating energy performance, and the basis for rating and labeling.

Procedures for Determining Optical Properties

In FY94, we completed a procedure for determining several solar optical properties of glasses and coatings. This procedure was thoroughly tested through the NFRC and the International Energy Agency.

To implement this procedure and one we had developed earlier for determining emittance, we drafted a plan for verifying data supplied by manufacturers. Efforts to harmonize these procedures with national and international standards organizations have been generally successful. At the request of the manufacturers, who must measure the optical properties of their products, we developed two methods to simplify and reduce the costs of these measurements. One method allows the properties of glazings with applied films (Fig. 7) to be calculated from the measured properties

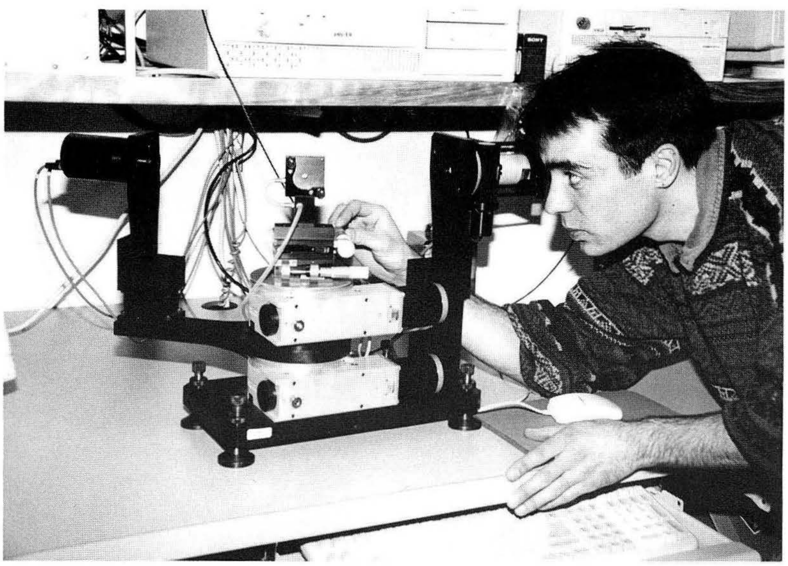

Figure 7. *Measurement of optical properties of an applied film using variable-angle spectroscopic ellipsometry.*

of the components. The other method allows the properties of products of different thicknesses to be calculated from the measured properties of one product in the series. We have written a computer program to execute these methods, and it is now under testing.

Now that procedures for determining optical properties of simple glazing materials and windows are completed (or at least under way), the next step is to develop analogous procedures for complex glazings and shading systems. In FY94, we took the first steps toward designing and constructing an apparatus for quick and accurate measurement of the spectral and directional optical properties of component materials. We also began work on a general computer model for complex window systems.

Solar Heat Gain

The fraction of the incident solar energy let into a building by a window (called the solar heat gain coefficient) contributes greatly to the window's energy impact on the building. Our work is concerned with developing accurate and efficient ways of determining this important window property.

Properties of Window Systems

Two properties of a window system, its transmission and absorption, control the admission of incident solar energy. But only a part of the energy absorbed by the window reaches the building's interior. For this reason, a third property, termed the inward-flowing fraction, must also be considered. Because energy absorbed by the window flows inward by the ordinary processes of heat transfer, the usual method of directly measuring the solar heat gain coefficient has been to use a calorimeter. This is both slow and inaccurate. Much more rapid and accurate methods of measuring transmission and absorption alone are available, and they could be used if one could separately determine the inward-flowing fraction. Finding a good way to do so is the research challenge.

Simple Windows

While these observations are true of windows in general, the problem is essentially solved for simple windows consisting of plane-parallel, specular glazings. For these, reliable methods of calculating the inward-flowing fraction exist, transmission and absorption can be measured on small glazing samples by available spectrophotometric equipment, and the solar heat gain coefficient can be calculated with a high degree of confidence. Therefore, our work in this area now centers around developing user-friendly calculation programs, systematizing the data and the assumptions used in the calculations, checking the calculation results, and encouraging the formation of organizations (such as NFRC) and the use of industry practices that utilize the calculations in consistent ways. This is an ongoing effort. In FY94, we made substantial progress in systematizing data and standardizing procedures.

Complex Windows

For complex glazing systems—windows that are not both geometrically and optically simple—the current methods for measuring the inward-flowing fraction have been inadequate. Such windows include those with blinds, shades, drapes, or sun screens (in short, all windows that have features allowing control of privacy, solar gain, or daylighting). In FY94, we finalized several years' work on the development of a new method and demonstrated that it could be used for complex glazing systems (Fig. 8). This method employs an automated gonioradiometer ("scanner") to determine the optical properties of glazing-system layers. The scanner averages over relatively large sample areas, such as the many slats of a venetian blind. The layer data are then combined by calculation to yield the performance of the glazing system. Inward-flowing fraction values, determined by standard calorimetric measurements for particular geometries, are used. (The calorimetric measurements were obtained systematically by using the MoWiTT facility, described under Field Measurements of Fenestration System Performance.) In FY95, we plan to apply this method to making economical determinations of solar heat gain for a wide variety of complex systems.

Daylighting

Lighting accounts for a huge share of the electrical energy consumed in commercial buildings. But energy-efficient daylighting (substituting daylight for electrical lighting) can eliminate 70% of this consumption. To achieve energy-efficient daylighting design, one must be

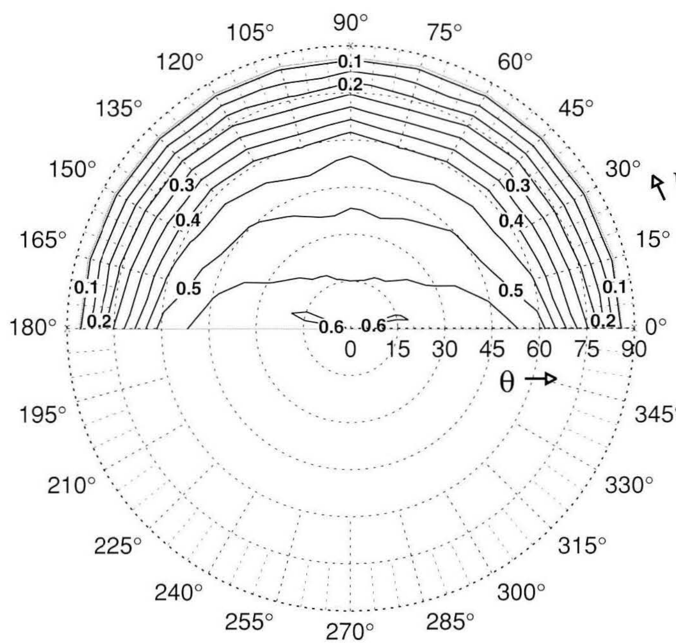

Figure 8. *Calculated Solar Heat Gain Coefficient. Utilizing the layer method, the measured bidirectional photometric properties and inward-flowing fractions were utilized to calculate the directional solar heat gain coeficient (for downward-sloping incident directions), which is displayed here as contours of constant SHGC in a polar plot where the radius is the incident angle, θ, and the azimuth is the incident azimuthal direction, ψ.*

able to predict the quantity and quality of light in the environment. Over the years, we have developed a range of tools for making such predictions. We continue to expand our modeling and measurement capabilities and improve the accuracy of our calculations.

SUPERLITE Development

Our daylighting software, SUPER–LITE 1.01, is an analysis tool that operates on personal computers. Users enter data about the geometry of a space, the surrounding windows, and the sky conditions and obtain information about the illumination level of the space. We continue to upgrade the modeling capabilities of SUPERLITE 1.01. SUPERLITE 2.0, which added electric-lighting analysis to the capabilities of Version 1.01, was widely distributed in 1994. Version 3.0 will be available in 1995, adding complex fenestration systems and shading devices to the current daylighting-analysis capabilities.

SUPERLITE Integration with ADELINE

In FY94, SUPERLITE 1.01 was integrated with ADELINE 1.0, the product of a multinational daylighting research effort sponsored by the International Energy Agency (IEA) as part of its Solar Heating and Cooling Task 12 efforts. ADELINE 1.0 links a three-dimensional computer-aided design (CAD) program with SUPERLITE and RADIANCE, an LBL program that generates graphic images of lighted spaces. (See the Lighting Systems section of this report for more information on RADIANCE.) Integration of these programs offers a DOS-based graphical interface that lets users create a design through the CAD program, analyze the design with SUPERLITE, and then display the results through RADIANCE. During FY94, ADELINE 1.0 reached the limited-distribution phase. Development of ADELINE 2.0 will continue in FY95 with integration of SUPERLITE 2.0 and improvement of the user interface.

Field Measurements of Fenestration System Performance

In conducting field measurements of fenestration system performance, we measure the energy flows through window systems under realistic weather and application conditions. For most of this work, we use the LBL Mobile Window Thermal Test (MoWiTT) Facility, a unique, highly-instrumented double calorimeter currently situated in Reno, Nevada. We conduct studies ranging from how new or improved window technologies perform to whether computer models effectively calculate window performance in a building.

Exterior Heat Transfer Coefficients

A study of exterior heat transfer coefficients completed in FY94 illustrates the practical importance of this work. The exterior heat transfer coefficient is a part of the overall thermal transmittance, or U-factor, of a window or a wall and encapsulates much of the information about exterior weather conditions (for example, wind speed). Published window U-factors are based on laboratory measurements under worst-case conditions. For improvements in window energy efficiency, however, calculating the cost savings by comparing worst-case conditions produces a biased result: savings are overestimated, sometimes by as much as a factor of two. Our new research on exterior heat transfer coefficients, when included in the standard calculations, produces for the first time a reliable calculation of average savings. It has also improved the accuracy of cooling-load calculations in building simulation programs such as DOE-2.

Selective-Glazing Systems

Our work in FY94 included a study to determine how effective commercial selective-glazing systems are at reducing summer solar heat gain (Fig. 9). These glazings, which appear to be identical to clear double glazing or to be lightly tinted, were shown to admit 40–45% less solar energy. This result confirms our expectations based on calculations and makes the glazings an attractive option for reducing air-conditioning loads.

DOE-2 Building Simulation Tool

We also began detailed tests of DOE-2 calculations for glazings and perimeter spaces. These tests will be important to the use of this simulation tool by the NFRC as a basis for voluntary energy ratings. Our other work includes studying systems with actively controlled interior venetian blinds (see Envelope and Lighting Technologies to Reduce Electric Demand in Commercial Buildings) and both fixed and active between-pane blinds. During FY95, we plan to continue the testing of DOE-2 and the study of active smart window systems and highly insulating superwindows.

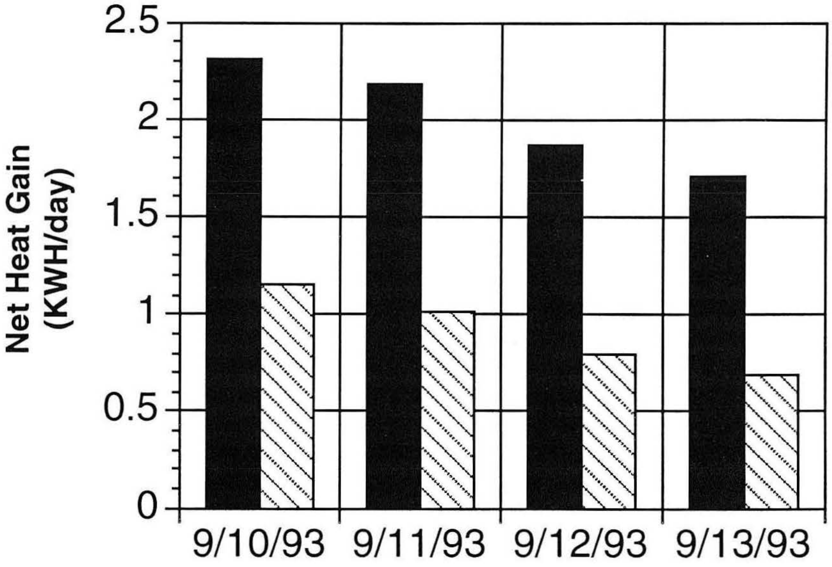

Figure 9. *Summer Performance of Selective Glazing Compared with Clear Double. MoWiTT measurements of the net heat flow through a glazing system consisting of a spectrally selective tinted glazing combined with a low-emissivity glazing (striped bars) are added up over 24-hour periods and compared with simultaneous measurements of clear double glazing (solid bars). Both glazing systems were measured without frames.*

Building Applications and Design Tools

We incorporate the knowledge gained in our basic research studies into tools that help building designers select appropriate window design solutions. In this way, new knowledge about glazing materials and fenestration system performance is consolidated into the window selection criteria of architects, engineers, and builders. These efforts are furthering the development of better tools for window selection in both residential and nonresidential buildings. We work with other national and regional groups to understand market trends and to encourage use of efficient window products in new buildings as well as in existing ones. We also develop tools that will allow us to track market trends and to predict the impacts of new programs on national energy consumption.

Market Analysis

To better understand the energy implications of the existing window stock and the forces that will affect this market in the future, we recently began an in-depth market analysis. An important goal of this program is to assess the demand for windows and to what degree energy efficiency is part of that demand. Another factor studied is the supply of windows to the market and how that is changing and can change over time with regard to energy efficiency. With such information, policy makers will be able to know what the changes in supply will do to regional and national energy demand. It should also help to focus research efforts on developing products with maximum potential energy savings.

In FY93 and FY94, we pulled together data about the existing residential building stock with a focus on window parameters. From this data, we created a Window Assessment Model (WAMO), which allowed us to compute the energy impact of residential windows nationally. This tool also allows us to estimate the national energy impacts of advanced technologies, implemented at various penetration rates, in any future year. It showed for example that the use of technologies now available in all existing buildings and all new construction could lower the national energy impact of windows from about 2.2 quads to about .8 quads.

In the coming year, we will develop a similar model for the commercial sector. We will also revise our residential model to reflect new market and performance data.

Nonresidential Building Simulation Studies

Task 18 Advanced Glazing Materials

We continued our participation in Task 18 of the International Energy Agency's Solar Heating and Cooling program (IEA/SHC). This five-year task focuses on advanced glazing materials. Seeking to realize significant energy and environmental benefits, participants from 13 countries are developing the scientific, engineering, and architectural basis for the use of these materials in buildings.

Task 18 comprises two subtasks, A and B. Those engaged in Subtask A analyze potential glazing materials to identify their building applications and their energy and environmental benefits. Subtask B participants characterize glazings and daylighting-component materials in the laboratory.

The United States leads the Modeling and Control Strategies Activity associated with Subtask A. The objectives of this activity are:

- To evaluate the potential performance of advanced glazing systems and dynamic control strategies. Systems and strategies to be evaluated include high-performance and wavelength-selective glazings, chromogenic optical-switching devices, and light-transport mechanisms.
- To evaluate the ability of simulation tools to properly characterize the performance of glazing systems and improve these tools as necessary to create common technical approaches for simulation.
- To develop models that can meet the simulation needs of groups, such as the International Standards Organization (ISO), CEN, and NFRC, that are developing national and international window-rating systems.

Electrochromic Simulation Studies

We completed a simulation study on the use of various controls for electrochromic "smart windows" in a prototypical commercial office building (see earlier section on electrochromic coatings). Electrochromic windows are made of materials that switch their molecular state when changes in a predetermined control parameter occur (for example, an increase in incident solar radiation).

We analyzed strategies for controlling these windows based on the following parameters: daylight illuminance, incident total solar radiation, and space-cooling load. Our results showed that when a daylighting strategy was used to reduce electric-lighting requirements, control algorithms based on workplace daylight illuminance resulted in the best overall annual energy performance. If daylighting was not a design option, controls based on space-cooling load yielded the best performance through reductions in solar heat gain. The performance of control strategies based on incident total solar radiation varied as a function of the switching setpoints. For small to moderate window sizes, which result in small to moderate solar heat gains, a large setpoint range was best, because it provided increased illuminance for daylighting without much cooling penalty. For larger window sizes that admit adequate daylight, a smaller setpoint range was best to reduce unwanted solar heat gains and the associated cooling requirement.

Reductions in peak electric demand were found to be independent of the type of control strategy used for electrochromic switching. This is true because the electrochromics are generally in their most colored state under peak conditions, and the mechanism for achieving this state is not important.

Envelope and Lighting Technologies to Reduce Electric Demand in Commercial Buildings

In commercial buildings, the full benefit of energy-saving lighting and fenestration technologies depends upon their being designed and packaged as integrated systems. The design work must be supported by appropriate tools. Since 1991, we have been developing and promoting advanced building systems that integrate high-performance envelope and lighting technologies. This multiyear project is supported by the California Institute for Energy Efficiency (CIEE), major California utilities, and the DOE. Because lighting and cooling account for the largest share of the peak electrical demand in commercial buildings, promoting such integrated systems can be a cost-effective, demand-side management option for utilities.

During the first and second phases of this research, the major focus of the project was on designing, developing, implementing, and evaluating two advanced envelope and lighting systems. We accomplished this through a series of computer simulations, field tests, industry consultations, and building demonstrations. With a series of energy simulations, we explored the performance of intelligent control systems designed to efficiently and comfortably link an advanced lighting system with a dynamic envelope system (i.e., automated venetian blinds or electrochromic glazings). In parallel, the control system for an automated venetian blind was breadboarded and tested in real time in a 1:3-scale outdoor test facility to evaluate its logic and to test its robustness in implementation. The testing helped us resolve pragmatic issues such as sensor design and placement, control stability under variable sun and sky conditions, etc. This was accomplished in cooperation with manufacturer representatives from the controls, shading, and lighting industries. Using the MoWiTT facility, we measured a 50% reduction in the heat gains caused by solar radiation and electric lighting for a smart automated venetian blind system over a typical static bronze glazing system (Fig. 10). Separate designs for deep perimeter daylighting systems, a light shelf, and a light pipe were developed iteratively through advanced ray-tracing simulations, outdoor physical models, and a comprehensive daylighting analysis tool that combines experimental measurements from the LBL scanning radiometer with analytical computer routines. These advanced designs increased the depth of daylight penetration to 10 m throughout the year, increasing the daylight uniformity in an open-plan office space while comfortably increasing daylight illuminance levels at the workplane.

The focus of the third phase of research, in 1994, was deployment. We conducted showcase demonstration projects in partnership with California utility sponsors and expanded the reduced-scale field tests to full-scale development and evaluation in an occupied testbed office building. The primary goal of this strategy was to demonstrate current conceptual designs in order to accelerate their adoption by building professionals. In addition, the process provided valuable feedback to the R&D efforts and enriched our understanding of how the designs could be improved to address pragmatic issues such as construction, design engineering, cost, user acceptance, and occupant comfort.

Partnering with Southern California Edison, we demonstrated the concept of integration in a renovation of the Palm Springs Chamber of Commerce building. In addition to employing advanced energy efficiency measures that are available commercially (e.g., thermally broken storefront frames, state-of-the-art spectrally selective glazing, direct/indirect lighting with daylighting controls and occupancy sensors, and two-stage indirect evaporative cooling), we built a skylight prototype based on design concepts developed for the light shelf. The skylight was designed to split and redirect incoming daylight to the ceiling plane in two separate windowless offices throughout the year (Fig. 11). Considerable first-hand experience was gained by working with the manufacturer of special optical films, the building contractor, the architect, and the utility. Occupants reported that the skylight provides lively bright daylight throughout the space. During some periods, though, it was too bright for VDT tasks). Work is in progress to ameliorate the outstanding issues of visual comfort and to measure the system's performance under occupied conditions.

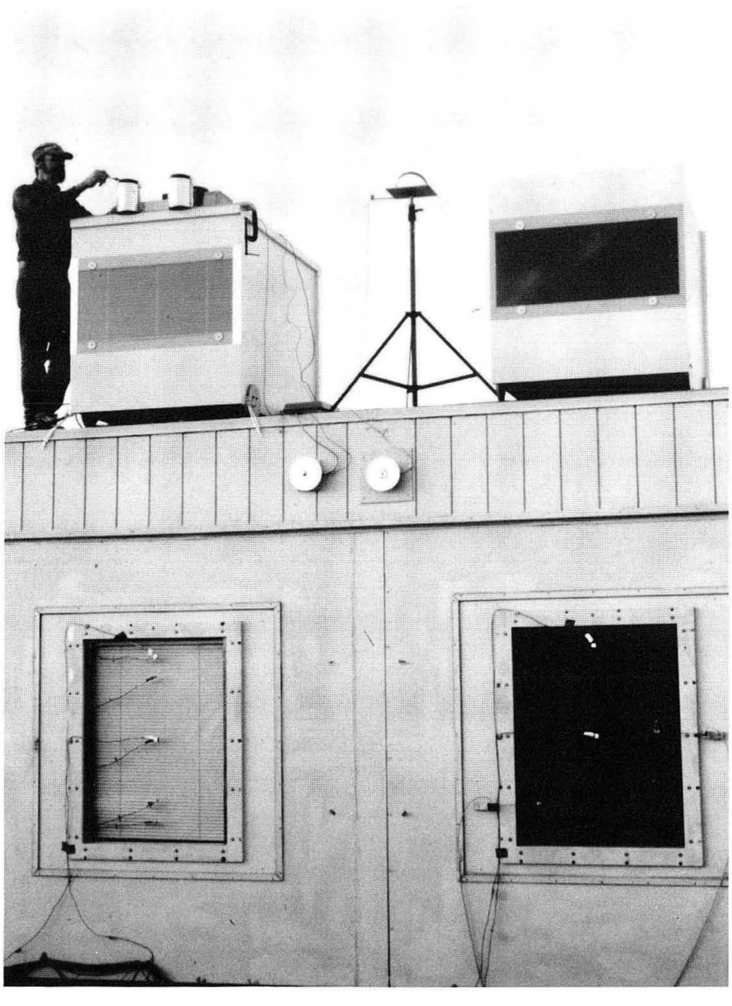

Figure 10. *Closeup of MoWiTT facility with sample A, static bronze tinted glazing, in the right-hand chamber and sample B, motorized venetian blinds, in the left-hand chamber. The two daylighting models have been set on top of the MoWiTT facility above each corresponding chamber. Note that the two sun angle sensors (being checked by Guy Kelley) have been set on top of the venetian blind daylighting model to detect solar position.*

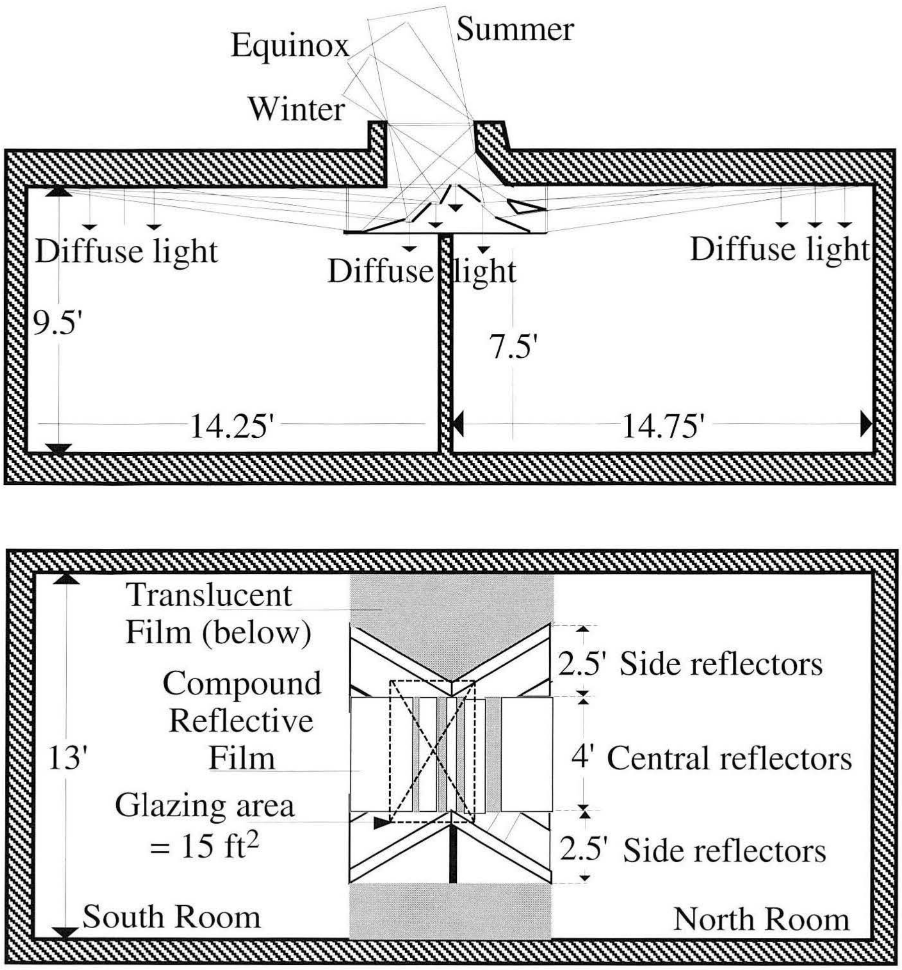

Figure 11. *Design of the reflector system used in the prototype skylight for the Palm Springs Chamber of Commerce. This reflector system was designed to split the incoming daylight flux and redirect it to the ceiling plane of two separate rooms. The central reflector (center) optimizes daylight redirection for the noon hour throughout the year. The side reflectors (left and right "wings") optimize daylight redirection for late afternoon and early morning hours. The system uses a combination of several different 3M reflective films to maximize daylight reflection and redirection.*

As part of our testbed demonstration effort, negotiations are continuing to form a collaborative partnership with Pacific Gas and Electric and a large U.S. commercial developer with a high-rise office building in downtown Oakland. This collaboration has the additional objective of showcasing advanced daylighting and lighting concepts to commercial building clients.

In 1995, we will continue to focus on deployment through demonstration efforts and further R&D on the two prototypes, tempered by feedback from industry and the demonstrations. Additional work on tools for integrated design, commenced in 1994, will continue to progress in the direction of quick, accessible reference materials for designers.

Residential Buildings

Window Rating Methodologies

With NFRC members in the private and public sectors, we are working to create an annual energy rating system for residential windows. Our goal is a simple, easy-to-understand system that yields accurate information about the heating and cooling energy performances of windows and their cost. We are trying two approaches, each suited to decision makers at different levels of technical sophistication.

The first approach, a simplified methodology, rates windows on relative seasonal energy performance using two numbers, a fenestration heating rating (FHR) and fenestration cooling rating (FCR). These nondimensional numbers establish how well a window performs relative to other windows. A higher FHR or FCR means more energy savings can be expected. The number which is intended to be used throughout the United States represents a percentage of the total house energy savings a particular window provides compared to a baseline window under the same conditions. We are substantiating the FHR/FCR approach through a study of the sensitivity of windows to parameters such as geographic location, wall insulation level, foundation type, floor area, window type, distribution, and size.

The second approach is a more detailed procedure that will calculate the energy performance of windows in a specific home. This methodology is a follow-up to our RESFEN program, which has now been in use for three years (Fig. 12). Users can enter any combination of window orientation, size, U-factor, shading coefficient, air leakage, and exterior or interior shading and obtain the amount of energy used annually for heating and cooling and its cost. In addition, RESFEN calculates the peak heating and cooling increments due to the windows. A new version of RESFEN incorporating the most recent NFRC default parameters and a window-based interface will be released in FY95.

RESFEN Kiosk

We also developed a user-friendly version of RESFEN that could be used by homeowners at a building supply store as they purchase windows. Built into an interactive kiosk, the program calculates the heating and cooling energy use of windows, helping homeowners in their evaluation of alternative window products.

The kiosk was evaluated for three months in a retail window store located in the San Francisco area. When a customer approached the kiosk, the store manager would discuss its purpose and

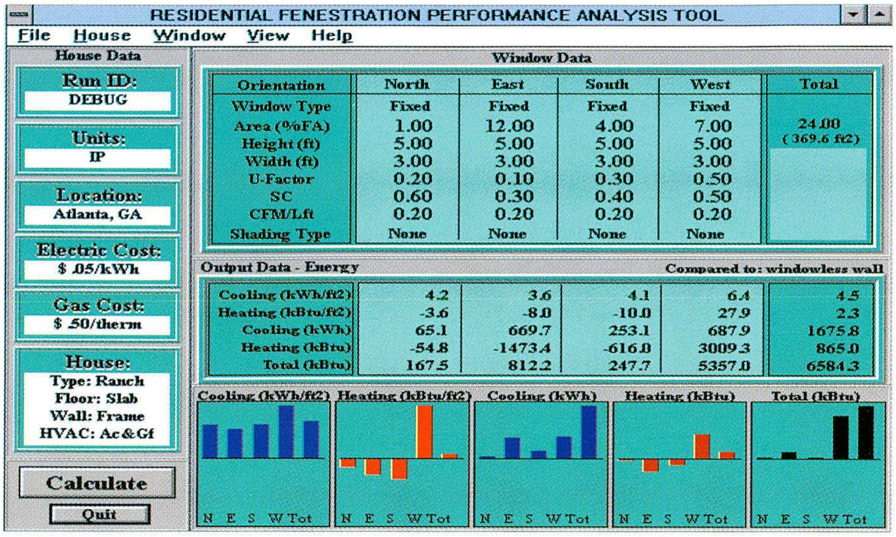

Figure 12. *Screen image showing the input/output user interface of a residential fenestration performance analysis tool. Input consist of House Data and Window Data. The output shows numerical and graphical heating and cooling energy usage values.*

guide them through a complete run. A series of runs might be made, using different parameters to answer specific questions by the customer. The evaluation showed that such a kiosk is a very good point-of-sale tool but probably requires staff assistance to help explain results and place the energy performance in a broader context.

This type of kiosk could also be used for comparing the performance of generic window products in locations where users are not subject to sales pressure, for example, in museums, lobbies of public buildings, or conference booths sponsored by nonprofit organizations. We plan to improve future versions of the kiosk by adding other factors of interest to purchasers, for example a method for evaluating thermal and visual comfort. In locations with a mild climate, these issues can be more important window-selection criteria than energy concerns.

Window Design Guidelines

We have been working with writers at the University of Minnesota to revise and finalize the draft Window Design Guidelines developed in previous years. The Guidelines will provide fenestration design information to architects, engineers, builders, and homeowners, including

- An overview and historical discussion of residential windows.
- Specific design recommendations regarding view, lighting, ventilation, insulation, solar heat gain, condensation, and acoustics.
- Information on material selection and installation, including glazing products and framing.
- Regional climate guidelines on energy performance.

We began prototyping an electronic multimedia version of the Guidelines that will include graphics, animation, and video as well as text. We also plan to integrate the Guidelines with the most recent version of RESFEN to facilitate calculation of the heating and cooling use associated with windows.

Advanced Design Tools: Building Design Advisor

FY94 marked the start of a project to develop a new computer-based building design tool, Building Design Advisor (BDA). With funding from Pacific Gas & Electric and Southern California Edison through the CIEE, as well as from DOE, BDA will initially focus on schematic phases of building design. It grew out of earlier efforts to develop a comprehensive tool for optimizing the design of building envelopes.

BDA allows building designers to evaluate and compare various design solutions with respect to multiple design considerations. It lets designers look beyond energy efficiency to comfort, cost, aesthetics, and any other quality that can be enhanced through the use of analytical computational models. BDA is designed to link to analytical modeling programs such as PowerDOE. Through a simple interface that incorporates two sophisticated graphical user interface (GUI) elements, BDA hides the complicated building representation of analytical models while allowing designers to take advantage of their prediction power through a single, object-based representation of the building and its components (Fig. 13). In addition to PowerDOE, BDA links to a multimedia case studies database, manufacturers' product catalogs, a daylighting-analysis module, and a schematic graphic editor. The initial version of BDA is scheduled for release in late 1995.

Electronic Media for Technology Transfer

The Windows and Daylighting Group has often been recognized for its long-term, effective collaboration with industry. Effective communication about our activities is essential. We strive to reach a diverse audience of researchers, professional and industrial societies, manufacturers, consumers, and educational institutions through a variety of media, including trade journals, network and utility-based television, electronic publications, and exhibits. We also sponsor workshops to exchange ideas with manufacturers, design firms, educators, and utilities.

In addition to working with traditional media, much of our exploratory communications effort has centered on electronic media—particularly CD-ROM publishing and point-of-purchase information systems. These media can potentially reach larger decision-making audiences than paper-based media, with a lower cost-per-person investment. FY94 brought a new opportunity for electronic communications via the "information superhighway." We developed a World Wide Web home page on the Internet. Users of the Internet may view this report, abstracts of current papers, and user-facility information (including graphics) through Mosaic or other Web browsers.

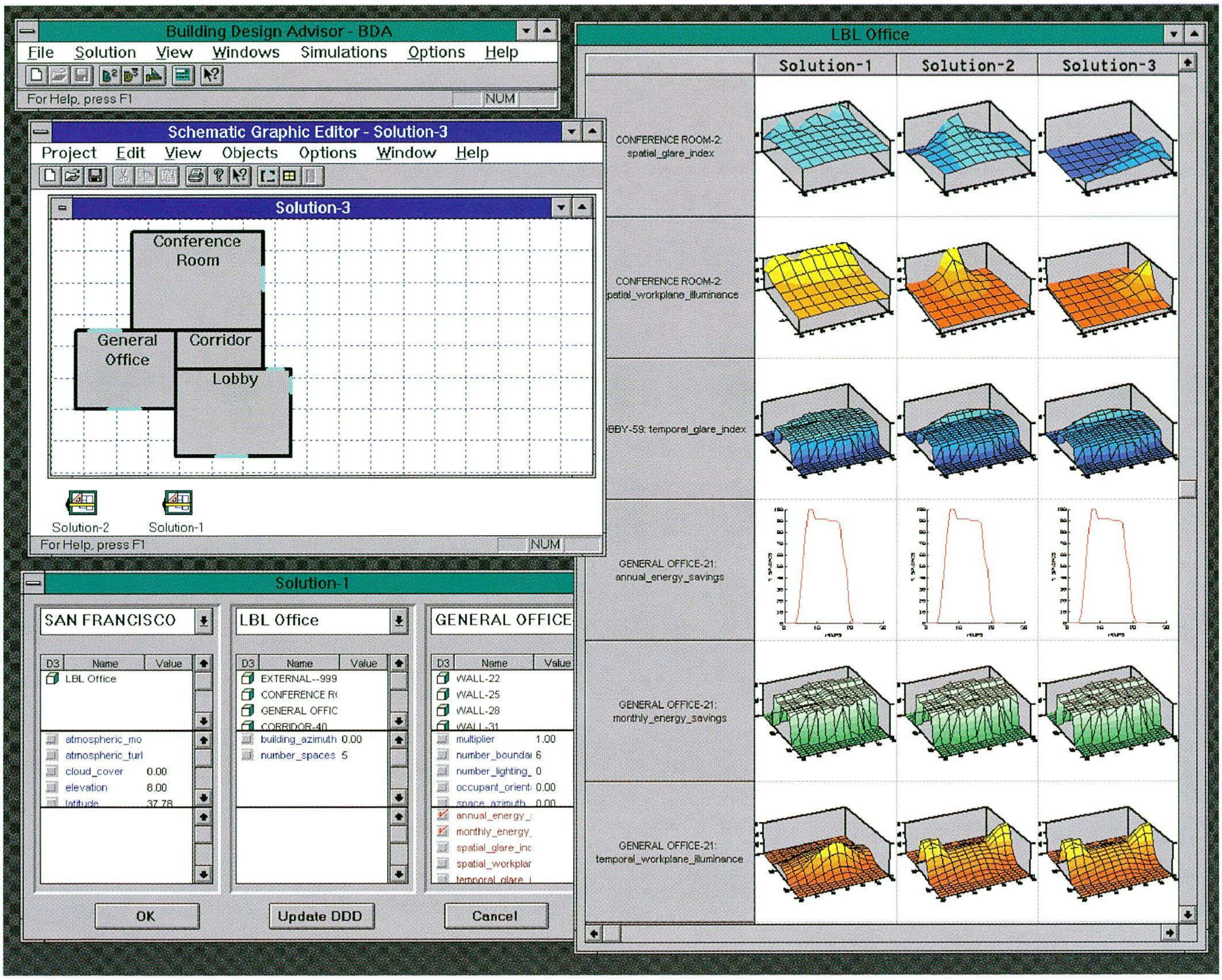

Figure 13. *A screen snapshot from a design session with the Building Design Advisor where the user compares three alternative design solutions.*

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Lighting Systems

Investigators

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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 50% savings equal to 20 billion dollars 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 effective technology transfer program, assuring that the technology base and concepts developed at the laboratory are transferred to the lighting community in a useful and timely manner. This program, which represents a unique partnership between a national laboratory-university complex and industry, facilitates technical advances, strengthens industrial capability and competitiveness, and provides designers, specifiers, and the end-user with much-needed information on the performance of energy-efficient lighting systems and concepts.

A major thrust of the lighting program has been the development of more energy-efficient light sources that operate at very high frequencies (VHF) without electrodes. Electrodeless, VHF-operated light sources offer the promise of significantly higher efficiency, longer equipment life, and improved environmental quality. In addition, the program is developing comprehensive strategies to capitalize on the performance attributes 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. In its study of the relation between lighting variables and visual function, the lighting program is identifying visual responses to lighting conditions—research results that are leading 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 Program has produced over 180 reports and publications documenting research on solid-state ballasts, operation of gas-discharge lamps at high frequency, scotopically enhanced lighting, energy-efficient fixtures, advanced lighting simulation and visualization, 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.

Lighting, or illuminating engineering, is a surprisingly complex field with a bewildering assortment of different applications each requiring different solutions. Consequently, we believe that there is no one "magic bullet" for lighting—a single lighting technology that could improve lighting energy efficiency in all applications. To be effective, our program must be multi-disciplinary and have breadth. To realize this broad-based agenda, our strategy is threefold: (1) to assist industry in the development of the next generation of energy-efficient light sources and luminaires; (2) to develop techniques for manipulating lighting spectral content and spatial distribution that improve visual performance and comfort while reducing energy requirements; and (3) 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 seeks to develop the basic engineering science that would form the basis for new, highly efficient light sources that contain no toxic materials. To put this project in context, note that the most efficient white light source in general use today—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), significantly 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 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 perceived toxicity.) The advanced lamp technology program is developing the engineering science that will help achieve a target lamp system efficacy of 150 lumens per watt within the present decade.

Our lamp technology research has concentrated 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 produce a desirable light spectrum 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 that lighting designers need, but would contain minimal toxic materials.

Besides the lamp itself, the other important component of a gaseous discharge lighting system is the electronic power supply (ballast), which must convert incoming wall plug power to the high-frequency power required by the electrodeless lamp. Because of the absence of commercially available, efficient power supplies operating at power levels and frequencies needed for efficient light source operation, we had intended to issue a request for proposal in FY94 for manufacturers to produce these power conditioners. However, that effort was postponed in order to redirect resources to the new sulfur lamp.

Sulfur Lamp

In October 1994, the Department of Energy (DOE) officially announced the new sulfur lamp and unveiled two installations of sulfur lighting systems at DOE's Forrestal Building in Washington D.C. and the large Space Hall of the Smithsonian's National Air and Space Museum (NASM). These sulfur lamps use microwave energy to excite sulfur gas, producing an efficient, bright white light. In these two installations, light pipes are used to distribute the light from the 3.5 kW sulfur lamps to the area below. LBL played an important role in these demonstrations by (1) helping fund the design, purchase, and installation of the systems, (2) providing technical assistance in the design of the light pipe reflector assemblies, and (3) measuring and analyzing the energy and luminous performance of the systems relative to the old, in-place lighting systems.

The sulfur lamp represents an entirely new method of producing light. The sulfur bulb itself consists simply of a spherical quartz envelope filled with a few milligrams of sulfur and a small amount of an inert noble gas, such as argon. Using waveguides that direct microwave energy from magnetrons onto the bulb, the argon in the bulb is weakly ionized. The argon in turn heats the sulfur into a gaseous state where it tends to form dimers— diatomic sulfur molecules. When the sulfur dimers are excited by the hot argon and the microwave energy, they emit a broad continuum of energy as they drop back to lower energy states—a process called molecular emission. Conveniently, molecular emission from gaseous sulfur occurs almost entirely over the visible portion of the electromagnetic spectrum; very little undesirable infrared or ultraviolet radiation is produced. Conventional mercury lamps and most other high-intensity discharge (HID) sources use atomic emission to produce light. The spectral content (spectral power distribution) of an atomic emitter is often very non-uniform, which may cause the emitter to render certain colors unsatisfactorily (low color rendition index). Molecular emission from sulfur, though, produces a broadband light that covers the visible spectrum uniformly, somewhat similar to sunlight, making sulfur an extremely efficient emitter of balanced white light (Fig. 1).

In addition to its high efficacy, sulfur lighting has several other advantages over existing light sources. Sulfur lamps contain no mercury—a toxic substance used in all other conventional efficient sources. Thus sulfur lighting has the potential to be not only the most efficient light source but also the most environmentally benign. Sulfur lamps are also expected to maintain their efficiency and light output over their entire lifetimes, unlike conventional sources whose outputs typically diminish by 75% by the end of their lives. By eliminating the need to compensate for lamp lumen depreciation, fewer sulfur lamps can be used to provide a required light level, providing potential first cost advantages. Finally, if research can eliminate the need to rotate the lamp, extremely long-lived products (over 50,000 hours) could result.

The high-power, microwave-driven, sulfur lamps on demonstration at the Forrestal Building and at the Smithsonian's NASM were originally developed five years ago by scientists now working at Fusion Lighting in Rockville, Maryland. Fusion found that sulfur excited by microwave energy could be used in place of mercury in their ultra-violet industrial lamps to produce a very bright, high-quality white light. These lamps operated at high power and light output levels (3.5 kW input and 450,000 lumens)—too high for most commercial applications. Furthermore, because of the high wattage, the lamps had to be both spun and air-cooled in order to operate.

In 1992, having identified the energy savings potential of sulfur lighting, DOE enlisted Lawrence Berkeley Laboratory to explore the physical processes underlying the sulfur lamp and to begin developing a practical source for general energy-efficient illumination. To apply LBL expertise on RF operation of HID lamps to the sulfur lamp for which Fusion Lighting held proprietary rights, an

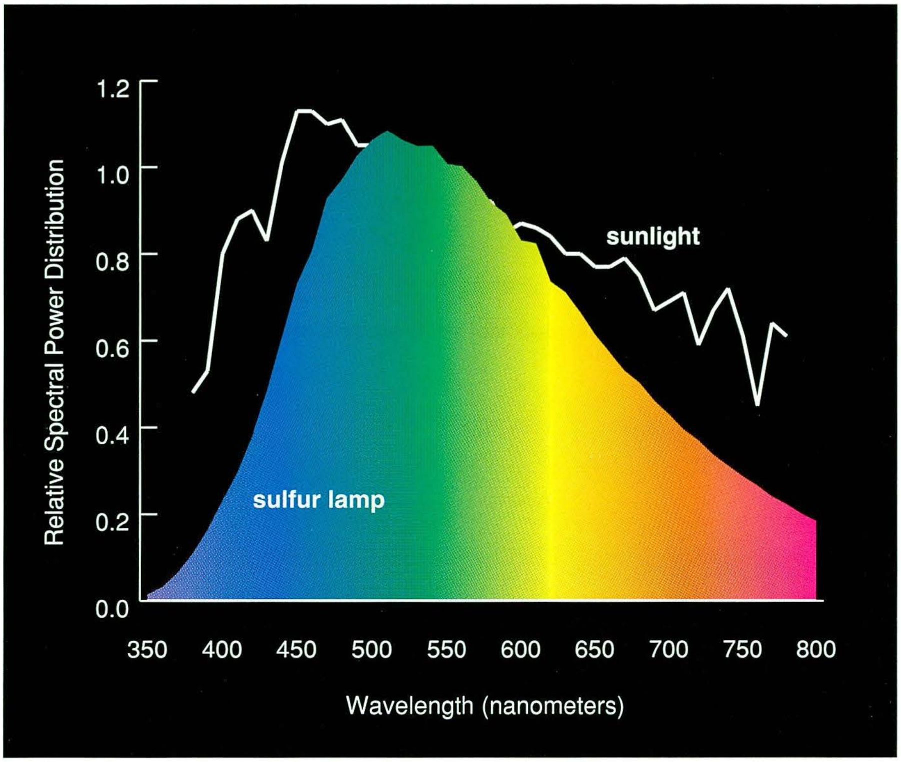

Figure 1. *The spectral power distribution (SPD) of an RF-driven, low-power sulfur lamp compared to the SPD for a phase of daylight — CIE illuminant D65. These spectral power distribution curves are normalized to be equal at 555 nanometers — the wavelength at which the daylight-adapted eye is most sensitive.*

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.

In FY93 and FY94, we demonstrated a sulfur lamp operating at low power (approximately 100 watts), using VHF (very high frequency) radio-frequency power instead of microwaves. By reducing the power loading and capacitively coupling the RF supply to the lamp using specially conformed external electrodes, we operated a sulfur lamp at up to 15,000 lumens with an RF input of only 100 watts (Fig. 2). At these lower power loadings and pressures, the lamp no longer needed to be air cooled, thus eliminating the noisy air compressor that had been required for Fusion's high power, microwave-driven lamp. We were further able to demonstrate that the spectral output of a low-power sulfur lamp could be altered and tuned by varying the concentration of sulfur. This should be particularly advantageous from a commercial standpoint, since it means that a variety of sulfur lamps could be produced with different spectral distributions depending on the application.

Allowing for unavoidable overhead in producing the RF power (an RF power supply with 85% efficiency is easily achievable), we project that a low power sulfur lamp of 120 lumens per plug watt is achievable before the end of the decade. This is at least 30% more efficient than a metal halide lamp, the most efficient white light source currently available.

LBL's technical advances in sulfur lighting operation were the subject of a major patent filed by LBL in 1994. We anticipate that our industrial partner, Fusion Lighting, will exercise its option to license our technology as the basis for further commercial development of low-power sources. This should push forward the date that future end-users can take advantage of this exciting new light source.

Despite the potential advantages of the RF frequency operation, initial commercial sulfur lighting systems will be microwave rather than RF-driven because the popular microwave oven has already stimulated the market to produce microwave magnetrons of roughly the right power ratings for lighting applications.

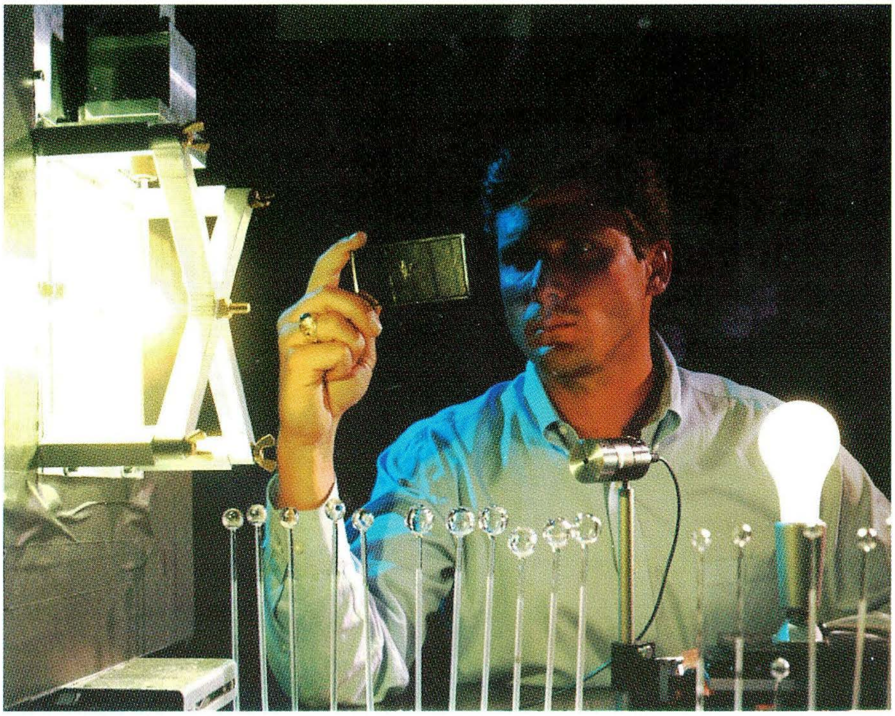

Figure 2. *Researcher observes a low power sulfur lamp through a low-transmittance filter. In the foreground are a series of unlit sulfur lamps of varying size. The incandescent light bulb shown at rightuses the same amount of power as the sulfur lamp but is much dimmer.*

In order to accelerate the commercialization of the sulfur lamp technology, DOE charged LBL with the technical oversight of a subcontract to Fusion Lighting to develop a microwave-operated, high-power sulfur lamp of approximately 1000 watts. It is anticipated that these first commercial lamps will produce approximately 120,000 lumens—a luminous efficacy of 120 lumens per watt. Because of their high output, these lamps are initially expected to find use in sports stadiums, convention centers, aircraft hangars, large maintenance facilities, and in roadway lighting. Other applications include shopping mall and industrial lighting. In addition to the development of a high-power lamp, DOE is also funding a three-year contract to Fusion Lighting to complete the basic engineering science required to produce a commercially viable RF-driven sulfur lamp at low power (50-200 watts) before the end of the century. If economical, low-power sulfur lamps could eventually challenge fluorescent lighting in commercial buildings and even find use in homes during the next century.

If sulfur lighting is to bring about significant reductions in energy usage, many challenges still remain. Sulfur lamps will initially be available only at lumen ratings of more than 100,000 lumens per lamp. Conventional HID lamps with this high output currently constitute a minor fraction of the HID lamp market. With some retooling costs, fixture manufacturers can adapt existing large HID fixtures to accommodate high-power sulfur lamps, but these applications account for perhaps 10% of the national lighting energy budget. For sulfur lighting to significantly displace the majority of HID sources, new lighting systems that can effectively distribute the light from the very bright sulfur lamp must be developed.

If low-power sulfur lamps (under 10,000 lumens) can be demonstrated to be both efficient and inexpensive, the energy-saving potential of sulfur lighting will increase dramatically. Packaged at 10,000 lumens, sulfur lamps could displace fluorescent lighting in commercial structures—the largest fraction of U.S. lighting energy use.

Advanced Lighting Distribution System Demonstrations

If highly efficient, high-output sources such as the sulfur lamp 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 where the light is needed. This supposition is confirmed by other developments within the lamp industry, such as the electrodeless HID, which indicate that other new light sources will, at least initially, be extraordinarily efficient only at high output ratings. Consequently, the light source development project has expanded its scope to include the development and measurement of advanced lighting distribution systems (ALDS)—specially designed lighting fixtures that use hollow light guides, fiber optics, and other optical transport techniques to efficiently distribute light from high-lumen sources. Last year, we collaborated with TIR , 3M Corporation, and the University of British Columbia to produce a prototype four-way light pipe system that could effectively meet the lighting needs of four adjacent workstations using one 20,000 lumen source. In 1994, we focused our research in ALDS on measuring the *in situ* performance of light pipe systems coupled to high-power sulfur lamps.

The sulfur lamps demonstrated at DOE's Forrestal Building and at the Smithsonian's National Air and Space Museum represent first generation high-output sulfur lights. They produce approximately 450,000 lumens at 3.5 kilowatts of microwave energy (5.9 kW plug watts). Because of the lamps very high lumen output, light pipes are required at both sites to distribute light from the high-radiance lamps to the areas below.

In 1994, to provide supporting technical information for DOE in their announcement of the sulfur lamp, we conducted detailed photometric surveys of the Forestall and NASM sites to verify the energy savings from the systems and to better understand the currently achievable performance of these novel lightingdistribution systems.

At the Forrestal Building, a 280-foot light pipe and two 5.9-kW sulfur lamps replaced approximately 280 175-watt mercury vapor fixtures, resulting in an energy savings of over 65% (Fig. 3). This early sulfur lamp system today saves DOE approximately $8,000 annually in energy costs. Because the sulfur lamp system replaced an old mercury system at the end of its maintenance cycle, LBL found that the post-relighting light levels were roughly four times those of the old system. (Had the old system been recently maintained, pre- and post-relighting light levels would have been approximately equal.)

Figure 3. *A photograph of DOE's Forrestal Building showing the 240-ft.-long light pipe running over the plaza. The enclosure that houses one of the two high-power sulfur lamps is just visible at the left end of the light pipe. The old lighting system, consisting of 280 mercury vapor fixtures, was also switched on for this photograph but is ordinarily off.*

Our photometric measurements showed that the coefficient of utilization (CU) for this advanced lighting distribution system was 0.42—a surprisingly high value considering that the light pipe system is still in its relative infancy. Thus, 42% of the 450,000 lumens produced by each sulfur lamp arrive at the walkway and roadway surface below, providing useful illumination for walking and driving. While the high-power sulfur lamps demonstrated at the Forrestal Building and the Smithsonian do not represent final products, the installations are nonetheless energy efficient. As this was a demonstration system, the $100,000 in equipment costs were higher than they would be in a more mature market. Nonetheless, DOE will obtain a payback for this installation in energy savings alone in about 10 years.

In 1995, we will complete the analysis of the data collected from these sites and present the findings in technical papers at the 1995 National Conference of the Illuminating Engineering Society of North America (IESNA). We will also partner with lighting fixture manufacturers and interested end-users in setting up demonstrations of early, but realistic, applications of advanced lighting distribution systems using prototype 1000-watt sulfur lamps that Fusion Lighting will produce in early 1996.

Low-Lumen Sources

Although the successful deployment of the sulfur lamp is expected to have major impacts on commercial and industrial lighting, the search continues for an efficient, low-lumen source that might compete effectively with the ubiquitous incandescent light bulb in the residential sector. To this end, we undertook a study in 1994 to determine the technical feasibility and market acceptability of a moderately efficient "incandescent-like" lamp. Our goal was to determine the current as well as expected future level of performance of such a lamp from a technical standpoint as well as to explore the surrounding policy issues.

Using an advanced, commercially available PAR lamp as a point of departure, we constructed prototypes of a general service lamp that used a tungsten halogen burner coated with a multilayer selective reflecting film. These prototypes exhibited luminous efficacies of 26 lumens per watt with a 3000-hour lamp life. This SR lamp (selective reflector) is 63% more efficient and lasts three times as long as a standard 60-watt light bulb, yet it will fit in virtually any incandescent socket (Fig. 4)

Our economic analysis showed that there is a sizable niche in the residential lighting market where an SR lamp would be more economical than either a standard incandescent or a more expensive compact fluorescent lamp. However, to be economical as well as attractive from a marketing standpoint, we determined that the general service SR lamp should have an end-user price of not significantly above $3/lamp. To achieve this low price would require sufficient volume such as might be possible with a government-sponsored buyers' group. To this end, we developed a proposal to use funds earmarked for DOE's Climate Change Action Plan (CCAP) Initiative to assemble a critical mass of buyers within the government procurement community in order to "jump-start" an early market for more efficient incandescent lamps.

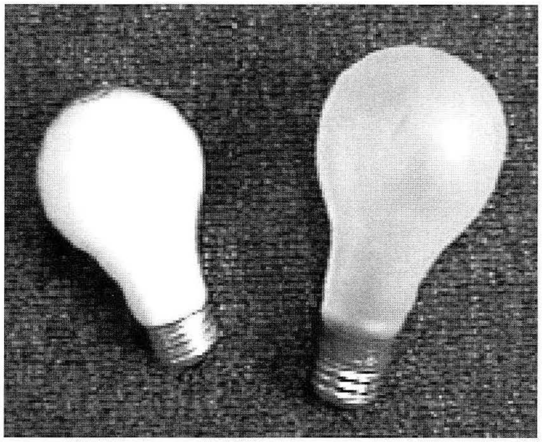

Figure 4. *A standard 100-watt incandescent lamp (left) produces 1750 lumens and has a 750-hr life. The prototype selective reflector (SR) lamp built at LBL shown at the right also uses 100 watts but produces 2600 lumens and has a 3000-hr life.*

Impacts on Visual Performance

We can achieve major benefits to lighting energy efficiency by studying how the human visual system responds to light of different spectral content and spatial distribution. Determination of visual effectiveness in terms of human subject responses requires an understanding of how lighting affects performance. A fundamental understanding of how the human visual system perceives the world around it is essential to energy-efficient lighting technology development. With this in mind, our impacts work has focused on exploring (1) how altered lamp spectral distribution can be exploited to reduce lighting energy requirements while maintaining visual performance and (2) development of a rigorous, defensible model of visual performance that takes into account recent research results as well as economic considerations.

Effect of Lamp Spectral Content on Visual Performance and Perceived Brightness

Through the study of human response to the lighting spectrum, research undertaken by LBL and its subcontractor, Abratech Corporation, seeks to determine a more valid lighting photometry, leading to increased lighting energy efficiency. Lighting photometry, as it is currently defined, is based solely on the photopic content of lighting; it does not account for the effects of scotopic content, which have been proven to be significant. These studies identify the key lighting factors involved in visual performance and, as such, provide the underlying basis for obtaining optimal visual effectiveness per watt of input electric power.

This project is now poised to have immediate impacts on U.S. energy consumption and lighting product development. The critical path to these positive impacts is likely to involve an expansion of classical photometry to include measurements more appropriate for lighting practice. The international bodies that define lighting quantity and quality standards are now holding technical discussions on the subject in response to DOE/LBL research. Modifications of traditional definitions and recommendations will promote the acceptance and penetration of the LBL findings to general lighting applications. The accomplishments briefly reviewed here add further to the evidence of the beneficial impacts of scotopic sensitivity on lighting energy efficiency. They also add to the scientific basis for the adoption of a new, more comprehensive, photometry, with the ensuing benefits of energy efficiency and new product development.

The importance of the scotopic content of lighting was established by two major findings in our research: (1) that pupil size, which strongly affects visual function, is predominantly governed by the scotopic content of the ambient lighting, and (2) that brightness perception itself, in full field of view, depends on both the photopic and scotopic content of the ambient illumination. The relevance of pupil size to lighting application was established in our studies carried out during FY93 and FY94 showing that, for a given task luminance, visual performance as measured by contrast sensitivity, acuity, and depth of focus are all better with smaller pupils. Thus, at light levels typical of interior requirements, the rod photoreceptors of the retina are active in affecting at least two major processes that are important to lighting practice (Fig. 5).

These findings have substantial implications for energy-efficient lighting because illumination with higher scotopic content per unit of photopic content is perceived as brighter and produces small pupils. Thus when photopic output is reduced to save energy, visual function and brightness can be maintained by scotopic content. Finally, if photopic lamp output is decreased to save energy (while increasing scotopic output to maintain visual function), then disability glare may also be reduced, providing an additional benefit from the scotopically enhanced lamps.

Two studies were completed during FY94. These investigated (1) the effect of surround luminance on word-reading accuracy, and (2) how color induction and refractive state in spectrally controlled pupil size affects Landolt C recognition.

The first study extends our prior visual performance studies to word reading tasks presented at fixed high contrast (black print on white background), but with varying character size. Word reading is a complex resolution task, but one that is representative of tasks encountered in the workplace. It has been used extensively in vision research as a measure of visual performance and has been shown to correlate well with face recognition and other complex recognition tasks. Our goal was to examine the effect of pupil size on the letter size/acuity function. In this study, the task was shielded from the surround lighting, allowing surround and task luminance to be controlled independently. Two pupil-size conditions were compared, where pupil size was controlled by high or low luminance levels of a single surround illuminant. We chose to use a single illuminant to control pupil size to avoid changes in induced color which occur when pupil size is changed by varying the surround spectrum (see study 2, below).

The results for nine subjects ages 23 to 59 years replicate and extend our Landolt C studies and show again that smaller pupils improve visual performance, even though task retinal illuminance is markedly reduced. The improvement in visual performance obtained here with smaller pupils also more than compensates for increased disability glare present in the high luminance surround condition.

The second study focused on eliminating an alternative explanation of our performance results that is not based on pupil-size changes. When pupil size is changed by varying the surround spectrum, there is a perceived color change of the task towards the complimentary color of the surround, even though none of the surround light falls on the task. This color effect is neural and is most likely caused by the chromatic adaptation effect of the surround light scattered in the eye. To investigate whether such a mechanism is an alternative explanation of our results on visual performance for spectrally controlled pupil size, we performed a study with and without mydriasis; i.e., with dilated and with fixed pupils. If the induced color hypothesis is valid, then it should occur for both fixed and light-sensitive pupils. In addition, we examined whether the pupil-size effect on visual performance is present in correctly refracted subjects.

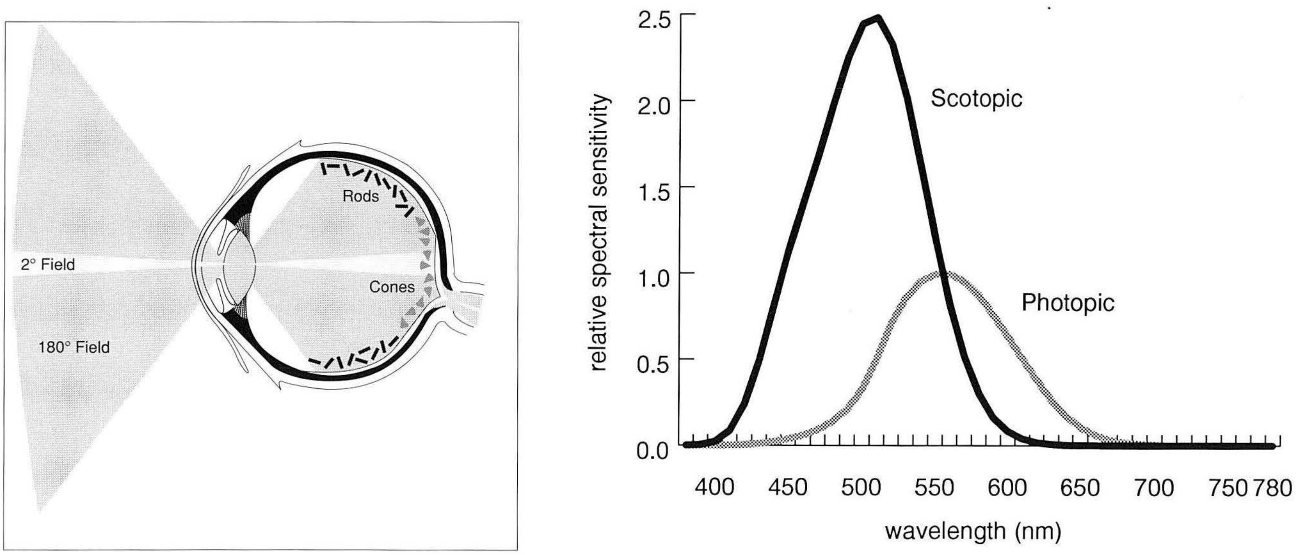

Figure 5. *At left is shown a section of the human eye depicting the cones, which are confined to the foveal (central) area of the retina, and the rods, which cover most of the rest of the retina. The cones, which are responsible for daytime vision, exhibit the photopic sensitivity function while the rods, which are responsible for night vision, exhibit the scotopic sensitivity function (at right). LBL research has shown that the rods are the major determinant of pupil size at typical office light levels.*

We studied twelve subjects 21 to 35 years of age, correctly refracted for both normal pupils and under mydriasis. We compared Landolt C recognition at a fixed task luminance for two different surround spectra, both producing 50 photopic cd/m^2. For normal pupils performance was better when pupils were smaller, while under conditions of mydriasis changing the surround spectrum had no effect on performance. We can thus rule out the induced color hypothesis and demonstrate the benefits of smaller pupils on contrast sensitivity, even when subjects are correctly refracted. These studies are expected to be presented at the summer 1995 national meeting of the IES.

To ensure that the findings of this laboratory research are readily applicable to general lighting applications, the efforts of this program are now directed towards their confirmation in realistic environments. The pupil lumen—which has been established in a room with essentially uniform luminance conditions—needs to be quantified under conditions where surface luminance variations are typical of normal workplace environments. Similarly, the visual performance effects measured in the white chamber need to be established in more realistic conditions. To this end we are constructing two separate rooms: one for the determination of the pupil lumen and a second—a simulated office—with several different color schemes for verifying the visual performance benefits of scotopically enhanced lighting.

Visual Performance

The objective of this work is to develop a rigorous, defensible model of human visual performance that takes into account economics as well as recent research such as that on spectrally controlled pupil size and the polarization of reflected light.

One of the major activities of the Illumination Engineering Society of North America (IESNA) is the development of light level recommendations. The present recommendations are based on consensus opinion of a body of expert practitioners and have no clearly defined analytic basis. Yet these light level recommendations have major implications for lighting energy consumption in the United States. Last year we developed a method for finding optimum light levels based on identifying the point at which the economic value of performance benefits to workers (i.e., due to increased lighting) was incrementally less than the cost of the added energy and equipment. Our work is the first to explicitly combine both the benefits and costs of lighting in deriving a light level recommendation.

In FY94, in response to a request from DOE to update NEMA's 1988 Human Performance Report, we reviewed the recent literature on visual performance and related issues. Undertaken in collaboration with Rensselaer Polytechnic Institute's Lighting Research Center, this review will assist DOE in establishing an agenda for future visual performance research. We produced a draft report summarizing research gleaned from recent issues of the *Journal of the Illuminating Engineering Society* and *Lighting Research & Technology*, grouped into the performance categories listed in the 1988 NEMA report.

As an outgrowth of the review work, we performed a comparison of two of the leading visual performance models developed in the last five years and showed some surprising similarities that have not been previously described. This indicates progress toward developing a robust general visual performance model.

In the upcoming year, we will complete our review of the vision research literature and produce the draft agenda for future visual performance research. In addition, we will publish a paper comparing the Rea reaction time model with the Clear/Berman VL model.

We have also been undertaking research to evaluate whether polarized lighting can be used to save energy and, if so, under what circumstances. This information has been requested by regulatory bodies such as the California Energy Commission as well as the design community. If polarized lighting is found to save energy, this will be directly beneficial to the lighting consumer.

The subject of polarized lighting is a complex one that has both bemused and beleaguered the lighting community for decades. In 1994, the IES (Illuminating Engineering Society) charged a task force to prepare a draft technical memorandum on polarized lighting and LBL is assisting in this effort. In addition, LBL, in collaboration Pennsylvania State University, is submitting a technical paper on the applicability of polarized panels for saving energy in buildings for presentation at the 1995 Annual IES Conference.

The California Energy Commission (CEC) is also investigating whether polarized lighting is an energy-saving strategy and they have commissioned a study (by Lighting Technologies of Boulder, Colorado) to examine this issue. We have assisted the CEC in this task by reviewing the subcontractor's draft report. Our review found what appear to be inconsistencies in the reflectance data used for the analysis in this work. We continue to work with the CEC and Lighting Technologies to resolve these discrepancies.

Building Applications

To achieve real energy savings with new energy-efficient lighting technologies, we are assisting 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 lighting fixtures. 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. 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.

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 compact fluorescent lamps (CFLs) operating at elevated temperatures. Convective venting of CFL fixtures—an idea pioneered by LBL three years ago—has been adopted by several major fixture manufacturers in 1993 and 1994.

Energy-Efficient Fixtures

Due to its nearly exclusive use of inefficient incandescent sources, the residential lighting sector represents a significant opportunity for energy conservation. Compact fluorescent lamps (CFLs) have the potential to transform this market by using one fourth as much power as incandescents to provide the same amount of light. However, CFLs still face significant market barriers, particularly their "perceived brightness" level in traditional fixture applications. Due to differences in their light distributions, CFLs can appear dimmer than traditional A-lamps even though their lumen ratings are equivalent.

In order to analyze the light distributions of different CFL luminaires, LBL constructed a gonio-photometer with automated control and data acquisition systems (Fig. 6). The control system enables measurements to be taken in zones as small as 1°, with positioning accuracy of ±0.05°. Computer-controlled tests generate standard photometric reports with candela plots and total lumen output. The results are then compiled into a comprehensive database of goniometric reports on commercial and residential CFL fixtures.

With the help of the gonio-photometer, LBL conducted a series of studies comparing table lamp fixtures equipped with incandescent A-lamps to those containing compact fluorescents. The objective was to match the light distribution of the consumer-accepted A-lamp with CFLs. Our photometric studies indicate that circular CFLs may produce more desirable distributions than either A-lamps or vertically oriented CFLs by minimizing shade losses and thus maximizing the useful light leaving the fixture. Optimizing fixture geometry and lamp position can significantly increase the efficiency of these CFL fixtures. Ongoing research with the fixture industry seeks to identify and develop more efficient source/fixture configurations.

Goniometric studies were performed on a variety of different sources installed in a standard screw-base table lamp fixture. We found that circular fluorescent lamps distribute the majority of their flux vertically, due to the geometry of the lamp relative to the shade. And since the lamp extends out beyond the base, light is seen at nadir (toward the lamp base). The A-lamp yields a fairly symmetric distribution, except for where the base blocks the flux at near-nadir angles.

These studies show that different sources yield significantly different light distributions when installed in table lamp fixtures. Lamp position and geometry can have a significant effect on the light output, light distribution, shade losses, and thus fixture efficiencies. The data suggest that a predominately horizontally oriented (in this case a circular) source outperforms both a symmetric (A-lamp) and a vertically oriented (T-lamp) source in table lamp fixtures. Thus, the circular lamp proves to be more efficient than the A-lamp not only because of the inherent advantage in fluorescent vs. incandescent lighting, but also because of its distributional advantage. The circular lamp is particularly well-suited to table lamp applications, with the geometric differences from the A-lamp providing an additional benefit. While typical household fixtures can limit circular retrofits due to the significant size/shape differences between circular fluorescents and A-lamps, most table lamp fixtures can readily accept circular lamps.

Ongoing studies with the fixture manufacturing industry continue to develop different fixture designs that optimize vertical CFLs. By tilting the lamps or changing the shade geometry, it may be possible to fully utilize the unique candela distribution of vertical CFLs as well.

A second project, undertaken in cooperation with Lumatech Corporation, was the development of a new fixture design that maximizes the output of retrofit compact fluorescent fixtures. This technology is now patented and we are pursuing a technology transfer agreement and license of the invention. With this product, the efficiency of compact fluorescent fixture systems can be improved by 20%, greatly expanding the market for energy-efficient compact fluorescent fixtures by allowing higher-wattage incandescent lamps to be replaced with CFLs (Fig. 7).

The invention applies specifically to the operation of retrofit compact fluorescent fixtures that employ lenses and

Figure 6. *Researcher checks the alignment of LBL's recently completed mirror-based goniophotometer. A goniophotometer is used to measure the angular distribution of light (candlepower) emanating from a lighting fixture.*

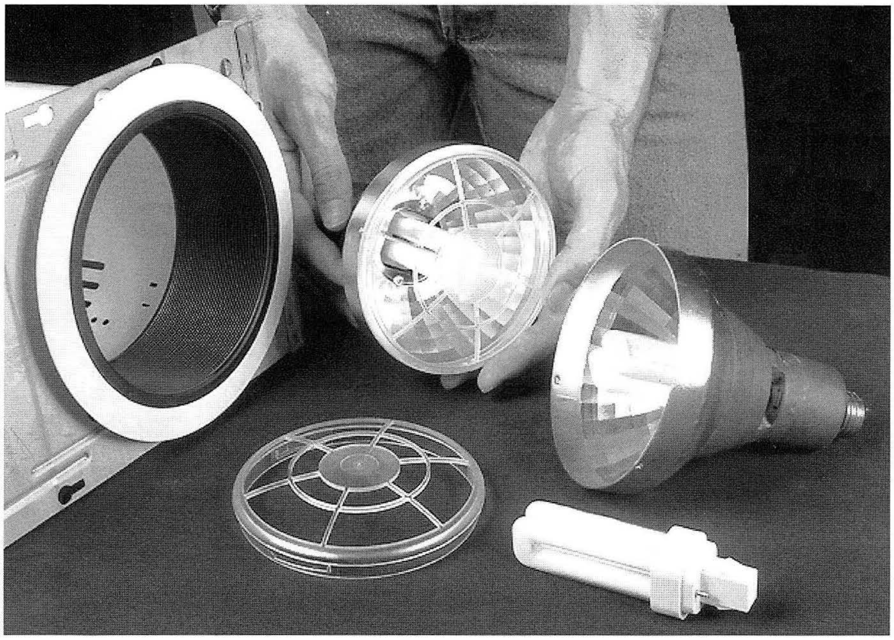

Figure 7. *An improved compact fluorescent lamp fixture recently patented by LBL and licensed to the Lumatech Corporation. The fixture contains vents in the reflector that prevent hot air from being trapped in the fixture and a specially designed lens that allows airflow while reducing glare.*

reflectors. The geometry of these reflectors traps hot air within the lamp compartment, reducing convective cooling. This results in elevated lamp wall temperatures and thus reduced lamp efficacy. Outlet apertures positioned around the upper area of the reflector allow the trapped air in the compartment to convect out of the fixture, reducing the temperature at the ends of the lamps. This reduction in minimum lamp-wall temperature reduces the mercury vapor pressure in the lamp, resulting in increased lumen output and system efficacy.

This system allows a fixture to operate at nearly 100% of its maximum lumen output, as compared with the 80% attained by most existing fixtures. The increase in lumen output will enable the retrofit fixture to replace higher-wattage incandescent sources. The venting system can be easily integrated into the manufacturing process and will have immediate and widespread application among lighting retrofit manufacturers.

A third project was to assess the feasibility of developing new computational techniques and procedures for designing energy-efficient light fixtures. Optimizing fixture design could reduce energy requirements by permitting lower installed power densities for the same lighting quality level in interior spaces. Such technology would provide luminaire manufacturers with more economical design techniques and better (i.e., more marketable) products. A computer-aided fixture design program would also reduce the cost of prototype testing and could streamline the manufacturing process by providing electronic cutting specifications, etc. Building operators would benefit indirectly through reduced energy costs, employees from improved lighting, and the nation as a whole from the resulting energy conservation.

In 1994 we studied the feasibility of luminaire design optimization programs and partially implemented Monte Carlo sampling techniques for fixture and lamp geometries. These activities were summarized in a report on luminaire design optimization. In 1995, we will initiate development of a program for designing energy-efficient light distribution systems for high-output sources such as the sulfur lamp.

Computer Imaging

The goal of our computer imaging program for FY94 was to transfer RADIANCE lighting simulation software technology to the design community. This technology enables users to optimize their lighting designs prior to construction or retrofit, thereby minimizing the final, installed energy requirements. The primary beneficiaries of this project are lighting designers and architects, who can use RADIANCE to test innovative design concepts and to demonstrate efficient lighting to clients prior to installation. Lighting clients will benefit from improved visual environments, lower operating (energy) costs, and enhanced worker performance. The country as a whole will see energy savings resulting from better, more energy-efficient lighting installations.

In FY94 we created a universal licensing agreement for the RADIANCE simulation engine so that third parties could incorporate and market the software in their own design tools. One company, GENLYTE Corporation, has already written the program into their GENESYS lighting design tool for IBM PC-compatibles. GENESYS is used by a sizable population of lighting designers in the United States and Canada and has one of the best user interfaces in today's market.

We developed a Graphical User Interface (GUI) to RADIANCE using the freeware package Tcl/Tk from the University of California at Berkeley. This user-friendly front end offers a point-and-click interface to RADIANCE rendering and display on UNIX workstations and serves as a model for developing user interfaces on other platforms. We expect this to vastly improve the acceptance of RADIANCE in the design community, where command-line software is unmarketable.

We also designed a new language standard for describing physical materials and geometry, called the Materials and Geometry Format (MGF). This standard was developed in cooperation with NIST and members of the IES Computer Lighting Committee and may be included in a future IES standard for luminaire data. MGF provides a much needed basis for describing light fixture geometry and has potential for describing other manufactured items as well, such as furniture and building fixtures. In the future, we hope that this or some similar standard will be adopted by the manufacturing industry for the creation of electronic catalogs which can be applied in lighting and energy analysis software.

RADIANCE was applied in the energy-efficient lighting retrofit of the Office of Environmental Policy in the Old Executive Office Building of the White House. This work was underwritten by the Greening of the White House initiative. An original retrofit design had been studied and rejected on the basis of inadequate lighting and excessive initial and operating costs. Subsequent designs reduced the absorption of daylight by partitions and improved the quality of electric lighting while reducing initial cost and energy consumption. Using RADIANCE , each of these design scenarios was realized entirely in simulation and evaluated on the basis of lighting quantity and visual quality. A sample rendering of the final design is shown in Fig. 8. This image was used as a starting point in an interactive CD-ROM presentation of the OEP retrofit. As a demonstration of what RADIANCE can do for energy-efficient lighting design, this project will be appreciated by public and private building organizations throughout the country.

To provide technical information and access to RADIANCE and its associated software, a World-Wide Web (WWW) site was established. The Uniform Resource Locator (URL) for the site is: "http://radsite.lbl.gov/radiance/HOME.html".

We produced two Siggraph papers, which appeared in the 1994 issue of ACM Computer Graphics. One of these is a systems paper that will act as a general reference for RADIANCE and its algorithms. We developed a prototype wide-angle stereoscopic viewer that uses an intense quartz-halogen back light to reproduce the full visual field with a dynamic range of about 5000:1. In 1995 we will use this device to conduct visual experiments using simulated environments, including light sources and daylight, in order to test new CRT display brightness mappings and visual performance metrics.

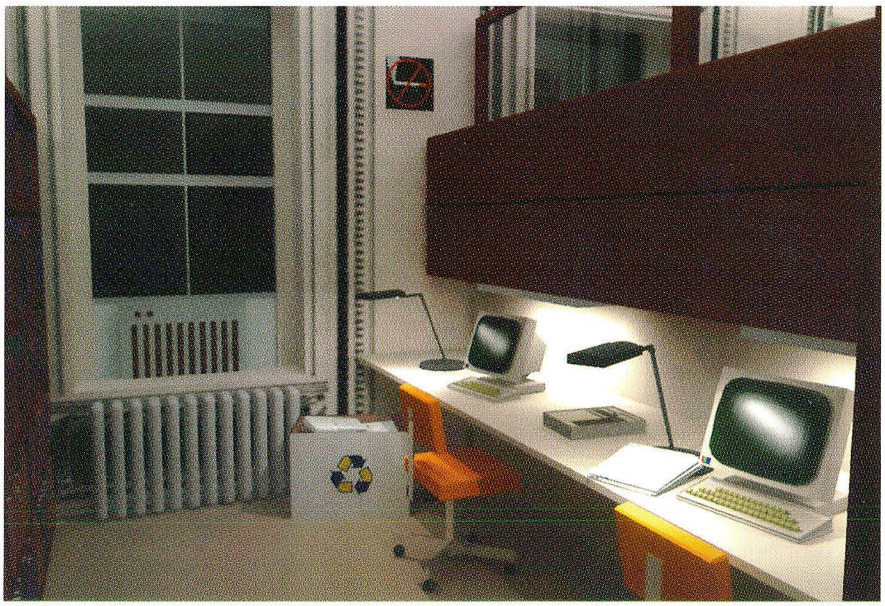

Figure 8. *A rendering from the RADIANCE computer simulation program showing a simulation of how a cubicle in the Office of Environmental Policy (OEP) suite would look under one of the design scenarios considered.*

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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, e.g., DOE-2, 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.

We are also collaborating with the National Renewable Energy Laboratory (NREL) and the Passive Solar Industries Council in the development of Energy 10, a computerized tool that will provide design guidance for the optimal utilization of passive solar technologies in small commercial buildings.

DOE-2

We completed testing and documentation of DOE-2.1E, an enhanced version of DOE-2, and submitted the program to the Energy Science and Technology Software Center for distribution. Major new features in DOE-2.1E include switchable glazing, evaporative cooling, ice storage, add-on desiccant cooling, heat pump water heaters, packaged variable-volume variable-temperature system, residential multizone variable-volume variable-temperature system, variable-speed electric heat pump, gas heat pump, evaporatively-cooled condenser, and end-use metering. In addition DOE-2.1E contains a new window library with 200 glazings, including the latest high-technology windows—such as those with low-emissivity coatings—and experimental electrochromic glazings.

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 1994, work continued on the SPARK graphical editor with which users connect building components into networks that represent building systems. Ayres-Sowell Associates began developing a library of HVAC component models that can be assembled with the graphical editor. These components include mixing boxes, fans, heating coils, cooling coils, heat exchangers, direct evaporative coolers, indirect evaporative coolers, humidifiers, pumps, controllers, boilers, compression chillers, and cooling towers. Our collaborators at École des Ponts et Chaussées in France began writing an improved translator from Neutral Model Format (a new, standard way of expressing component models) to SPARK. As an in-house test of SPARK, the program was successfully used to create a detailed model for radiant cooling (see "Radiant Cooling," below).

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. Using DOE-2 as its core calculation engine, PowerDOE features a graphical user interface running under Microsoft Windows that will make DOE-2 much easier to use. PowerDOE 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.

Key features of PowerDOE aimed at flexibility and ease of use include:

- on-line documentation
- automatic generation of a complete building description from user-input values of building vintage, number of floors, floor area, window-to-wall ratio and HVAC system type
- customizable libraries of building inputs, including walls, windows, lighting fixtures, rooms, operation schedules, HVAC systems, plant components (boilers, chillers, etc.), utility rate schedules, weather data, and whole buildings
- graphical display of building description—including building geometry, shadow casting, floor plans, HVAC system schematics, and operation schedules
- graphical display of calculation results—including line graphs and scatter plots of hourly variables, bar charts for monthly variables, 3-D plots of illuminance distributions, and comparative plots for sensitivity analysis.

In 1994 Regional Economic Research continued work on the PowerDOE user interface. Southern Company Services began development of the PowerDOE results display module, which allows graphical display of the PowerDOE calculations and creation of customized tabular reports. LBL and Hirsch & Associates began work on modifications to the DOE-2 engine to allow it to work interactively with the new user interface. Figure 1 shows a sample PowerDOE screen for inputting HVAC system data. PowerDOE will be the primary analysis tool used by the Building Design Advisor (BDA), a new development begun in FY94 to assist designers in making energy decisions in the schematic phase of design (see Windows and Daylighting section for more details).

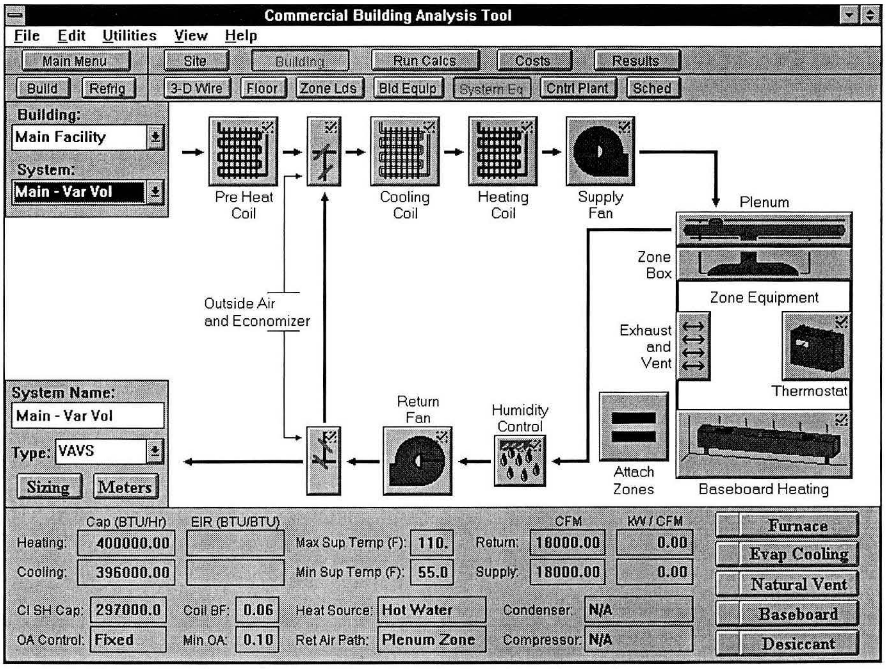

Figure 1. *PowerDOE input screen for entering HVAC system data.*

Alternative Cooling Strategies

Radiant Cooling

In a California Institute for Energy Efficiency exploratory project, the Simulation Research Group and Energy Performance of Buildings Group completed development of 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. RADCOOL was developed using a test version of SPARK. After validation against measurements (Figure 2), RADCOOL was used to analyze the thermal performance of a radiatively-cooled, prototypical office module in different California climates.

Alternatives to Compressor Cooling

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

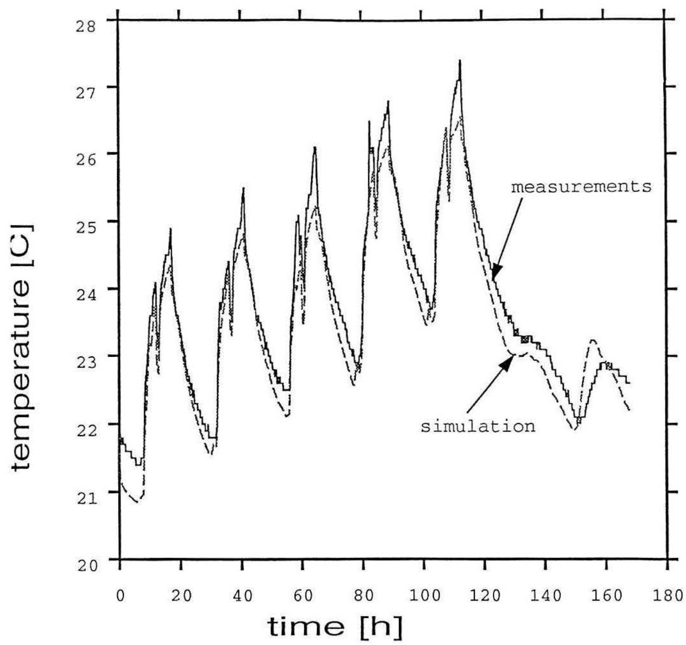

Figure 2. *RADCOOL simulation results compared to measurements of a radiatively cooled office room in Horgen, Switzerland (data provided by Robert Meierhans & Associates, Zürich). The room has a concrete ceiling with embedded tubes through which chilled water is circulated. Shown is the predicted and measured inside air temperature for a 7-day period beginning on a Monday. The office has automatic exterior blinds that close when the incident solar radiation exceeds 120 W/m*^{2}*. On the last two days (Saturday and Sunday) the blinds were forced to be closed all day.*

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.

This PC-based tool will have several innovative features including 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.

Current LBL support efforts, which will continue on into 1995, relate to the building design issues of daylighting and electric lighting. We have provided algorithms for evaluating simple daylighting energy-efficient strategies that can be applied to building designs (vertical glazing and skylights).

We also designed and implemented the user interface dialogs for describing the daylighting aspects of a building (see Figure 3) and developed an approach for automatically specifying building description modifications that add daylighting features to a reference building. During FY 1994, we developed algorithms for evaluating more complex fenestration system (CFS) types for daylighting, including specular light shelves and geometrically complex roof monitors.

During FY 1995, we will enhance the capabilities of the tool by incorporating these CFS algorithms into the daylighting analysis engine. We will also develop algorithms for the description and evalu-

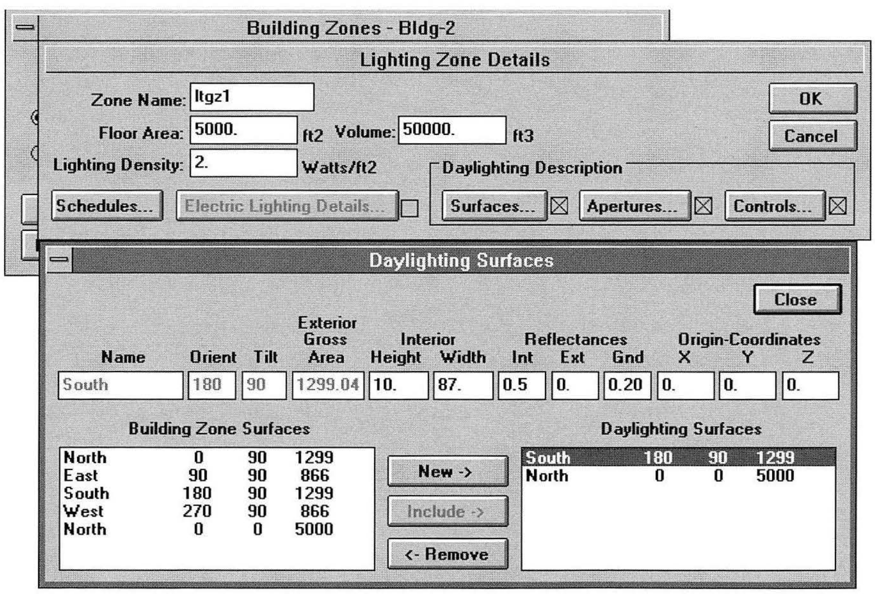

Figure 3. *Prototype user interface for describing a daylighting system.*

ation of electric lighting systems in a manner that is consistent with our daylighting system description and evaluation approach. We will also explore methods for automating the specification of an appropriately integrated daylight and electric lighting system strategy for the building under design.

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