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Author
Selkowitz, S.E.

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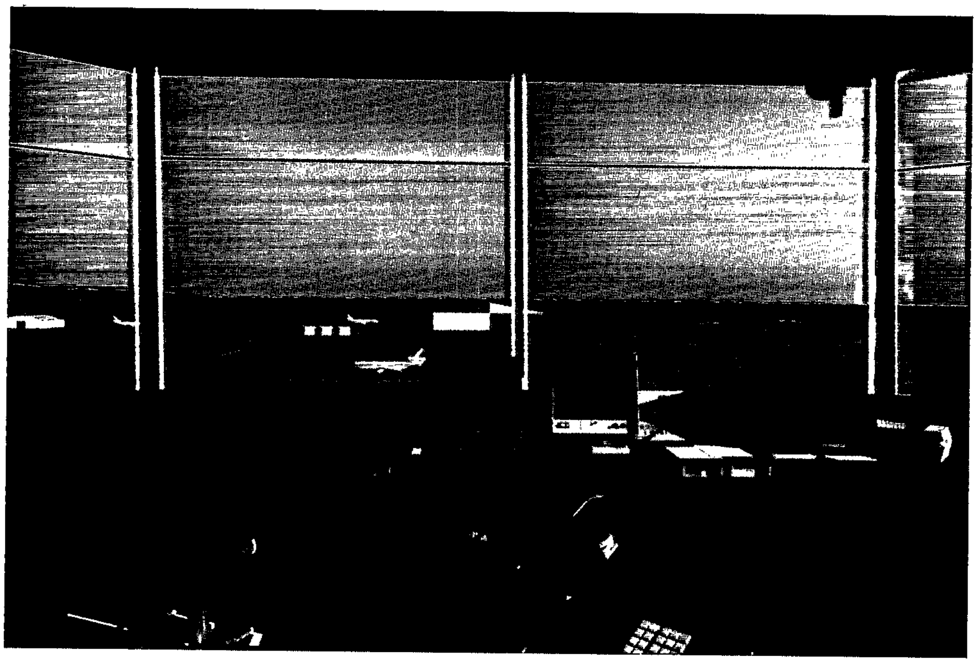
Energy & Environment Division

Building Technologies Program

1995 Annual Report



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Cover illustration: Eastward-facing scene from FAA's San Francisco control tower, generated using the RADIANCE ray-tracing program. Various glazings and shades have been evaluated to determine how to minimize unwanted reflections in the computer screens without compromising the visibility of airplanes outside. *DOE-2* simulations were used to optimize the building's overall energy performance.

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Building Technologies Program 1995 Annual Report

Stephen E. Selkowitz, Program Head

MASTER

Energy & Environment Division
Ernest Orlando Lawrence Berkeley National Laboratory
University of California
Berkeley, California 94720
phone (510) 486-5605
fax (510) 486-4089
world wide web http://eande.lbl.gov/BTP/BTP.html

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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 allow professionals to fully evaluate and 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 are 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.

cont.

Program Staff

Stephen E. Selkowitz*, *Program Head*

Dariush Arasteh
Vladimir Bazjanac
Frederic Beck
Liliana Beltran
Charles Benton
Samuel Berman
Bruce Birdsall
Donald Bromley
Fred Buhl
William Carroll
James Chan†
Robert Clear
Hannah Chauvet
Deirdre Collins
Douglas Crawford
Dennis DiBartolomeo
Paul Donahoe
Michael Donn†
Rosinda Duarte†
Charles Ehrlich
Kathleen Ellington
Peter English
Ahmet Erdem
Wayne Feller
Elizabeth Finlayson
Karl Frost
Tracy Fu†
Daniel Fuller
Ellen Gailing
Kristen Giang
Jean-Cristophe Giron†
Chad Goudey
Carl Gould
Brent Griffith
Ruth Haynes
Robert Hitchcock
Radim Jasek†
Clay Johnson
Evan Jones
Guy Kelley
William King
Joseph Klems‡
Carl Lampert
Paul LaBerge
John LaPorta
Eleanor Lee
Rene Meldem
Martin Moeck†
Oliver Morse§
Jean-Michel Nataf
Werner Osterhaus
Nilgun Ozer†
Erik Page
Eric Pankonin
Konstantinos Papamichael
Alex Pascual
Susan Petersen
Chad Praul
Patricia Ross
Michael Rubin‡
Francis Rubinstein*
Jessica Sadlier
John Sadlier
Amritpal Sidhu
Mark Silva
Michael Siminovitch
Dean Simmons
Jonathan Slack
Greg Smestad
Michael Streczyn
Robert Sullivan
Ian Sundly
Jack Thorpe
Tom Trzcinski
Daniel Turler
Gregory Ward
Jeffrey Warner
Michael Wilde
Frederick Winkelmann*
Mehrangiz Yazdanian

*Group Leader
†Participating Guest
‡Deputy Group Leader
§Department of Plant Engineering, LBNL

The **Windows and Daylighting Group** focuses on the technical aspects of understanding and improving the energy-related performance of windows and then deploys 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 two major project areas are (1) advanced materials and concepts and (2) fenestration performance and applications.

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. We also study innovative concepts for large-area envelope enclosures. 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 their heating bills alone. Our current efforts focus on a cost-shared initiative with industry to develop electrochromic "smart windows," whose optical properties can be dynamically controlled in response to climate or occupant needs.

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 comprise 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. LBNL 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.

Results of fenestration performance studies in various building applications help us to understand complex design tradeoffs as a function of building type, orientation, and climate. For example, 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 on visual productivity and lighting quality, and building applications.

Our interest in advanced light sources is with the exploration of new technical concepts for efficiently converting electrical energy into visible light. We have conducted research on long-lived electrodeless lamps that use very-high-frequency (VHF) power to produce broadband white light, potentially without the use of mercury. We have demonstrated a low-power, radio-frequency-driven sulfur lamp that operates at efficacies of more than 100 lumens per RF watt. We are developing novel fixture designs that can exploit the technical properties of the new sulfur lamp and other high-output sources, and we are exploring concepts for improving the efficacy of filament-based lamps.

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 conducted research 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 research to produce light that is more visually effective per unit of power consumed.

The building applications research currently focuses on advanced lighting controls, residential lighting, and the application of advanced simulation and visualization tools for solving complex lighting problems. We have explored advances in fixture efficiency via improved optical design and better thermal management of fluorescent sources. Several major fixture manufacturers have recently adopted our innovative, cost-effective approaches for improving fixture efficiency by as much as 20%.

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 version of DOE-2 that is user-friendly and more cost-effective.

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 HVAC system of interest. SPARK will allow researchers to explore the dynamic behavior of complex systems with an ease and accuracy unachievable with conventional software. We are also working with BLAST developers at the Civil Engineering Research Lab to develop a next generation simulation engine that combines the best elements of DOE-2 and BLAST, and we are working with NREL to incorporate new daylighting algorithms into Energy 10.

The **Advanced Building Systems** activity has grown from a realization that changes in the building sector often require an R&D focus that transcends a particular technology, such as windows, a single performance parameter, such as energy savings, or a single point in the life cycle of a building, such as design. We have increasingly turned our attention to optimizing individual technology elements within the context of an integrated building system.

One of our major commercial building projects is to develop a series of integrated envelope/lighting systems where the building facade has been developed in conjunction with the lighting/daylighting systems to minimize cooling and lighting energy use and to maximize comfort, productivity, and occupant satisfaction. Although these latter issues are more difficult to assess, they can be critical factors in the adoption of new design strategies. Using a similar philosophy, we are developing integrated window systems for residential applications and advanced insulations that could improve the efficiency of appliances and manufactured housing.

In examining the obstacles to widespread implementation of energy efficiency strategies, we identified the lack of cost-effective tools designed to meet the needs of users from different professions throughout the building life cycle. We are engaged in three interrelated activities to address this need.

The first activity is the Building Design Advisor, a new design tool concept that is focused on meeting the needs of designers early in the design process. This new tool is built around a new integrated building data model and a versatile user interface with multimedia capabilities that allows the user access to many different information resources and multiple simulation engines. We are also exploring the feasibility of using BDA as a platform to integrate life-cycle environmental impact information into design decisions.

The second activity is the Building Performance Assurance project, whose goal is the development of an expanded set of tools that assist in assuring energy efficiency, comfort, and productivity over the life cycle of the building. This activity was initiated as an internal exploratory development effort using staff from all three Energy and Environment Division programs in the Center for Building Science and colleagues in the Information and Computing Sciences Division. We are developing prototypes of commissioning tools and performance tracking tools that will inherit and update building information from a life-cycle database created during design.

These tool development efforts complement our third activity, participation in the Industry Alliance for Interoperability (IAI), an industry group whose goal is to bring software interoperability to architecture, engineering, construction, and facilities management. IAI is developing Industry Foundation Classes, a software library of commonly defined "objects" that can be shared by diverse applications throughout the building life cycle. These should facilitate the sharing of information between energy tools and other software tools used by the building community.

Windows & Daylighting

Investigators

S. Selkowitz
D. Arasteh
F.A. Beck
D. Curcija*
D. DiBartolomeo
E. Finlayson
C. Goudey
B. Griffith
R. Hitchcock
J. Huang
C. Huizenga†
G. Kelley
J. Klems
E. Lee
M. Rubin
J. Sadlier
R. Sullivan
M. Yazdanian

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 deployment programs that will accelerate market penetration of promising technologies in the marketplace. To carry out this effort, we have organized our research into two major areas:

- **Innovative Technology and Systems**
  Advanced optical and thermal materials
  Advanced glazing systems and integrated fenestration concepts
  Electrochromics Initiative
  New materials processing technologies

- **Fenestration Performance, Building Applications, and Design Tools**
  Window rating systems
  Thermal analysis
  Daylighting analysis
  Field measurement of performance
  Residential and nonresidential building simulations
  Design tools and decision-support tools
  Deployment programs
  Market assessment

*University of Massachusetts
†University of California, Berkeley

Innovative Technology and Systems

New high-performance glazing materials are a critical requirement for buildings that will consume significantly less energy than current practice. Identifying, characterizing, and developing promising new optical materials for these applications has always been a priority for our program. By working closely with industry, we hope to accelerate the introduction of advanced fenestration systems to the market. In addition to our internal R&D efforts, 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, well-targeted, and consistent effort over time. Despite the difficulties, our program has made significant gains in bringing new technology, such as low-emittance (low-E) coatings, to the market. They were introduced commercially in 1982 after six years of DOE-funded research. By incorporating low-E coatings into conventional double-glazed windows, the resultant unit is lighter and more compact, with better thermal performance than a triple-glazed window. Today, low-E coatings are used in more than 35% of all residential windows.

We next turned our attention to the development of highly insulating "superwindows," which 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 have promoted development of improved spectrally selective coatings—modified low-E coatings that transmit daylight but reject near-infrared radiation. We helped industry establish the value of these products, helped specifiers use them more effectively, and are working to develop improved coatings of this type.

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.

Advanced Coating Development

Thin-film coatings are versatile technologies that can be used to insulate and control solar heat gain as well as to redistribute light. Durability of spectrally selective coatings can be improved to allow their use in retrofit configurations. Angle-selective coatings that block summer sun and redirect daylight are under development. Dynamic coatings have an even greater potential to save energy. They are discussed separately in the section on Electrochromics below.

In FY94 we developed a new type of plasma source to deposit improved coatings for spectrally selective and angularly selective applications as well as electrochromics. In FY95, we constructed sealed, flange-mounted versions of the source suitable for production coating. Several variants of the source were tested for different industrial coating applications and inquiries for several more were received. The characteristics of the source make it extremely attractive for industrial applications, especially in conjunction with the DC magnetron sputtering technology used throughout the window industry. The sources work over a wide range of pressures including those found in both sputtering and evaporation processes. Stable operation has been achieved with a variety of gases including oxygen, nitrogen, and water vapor. No filaments, grids or other consumable parts are used, and the source will operate indefinitely on DC power. Figure 1 shows a new version of the source with multiple apertures and magnetic confinement.

In FY96 more sources will be constructed and evaluated by various manufacturers. LBNL will assist with installation, testing, and materials development. The source will also be used for internal development of angularly selective microstructures using the beam to induce preferential grain growth at oblique angles.

A preliminary analysis was performed on angle-selective glazings being developed by the University of Technology in Sydney, Australia as part of an International Energy Agency collaborative project. Using LBNL's Radiance computer program, the angle-selective coating was predicted to introduce 20% less daylight than a standard spectrally selective low-E at the front of a prototypi-

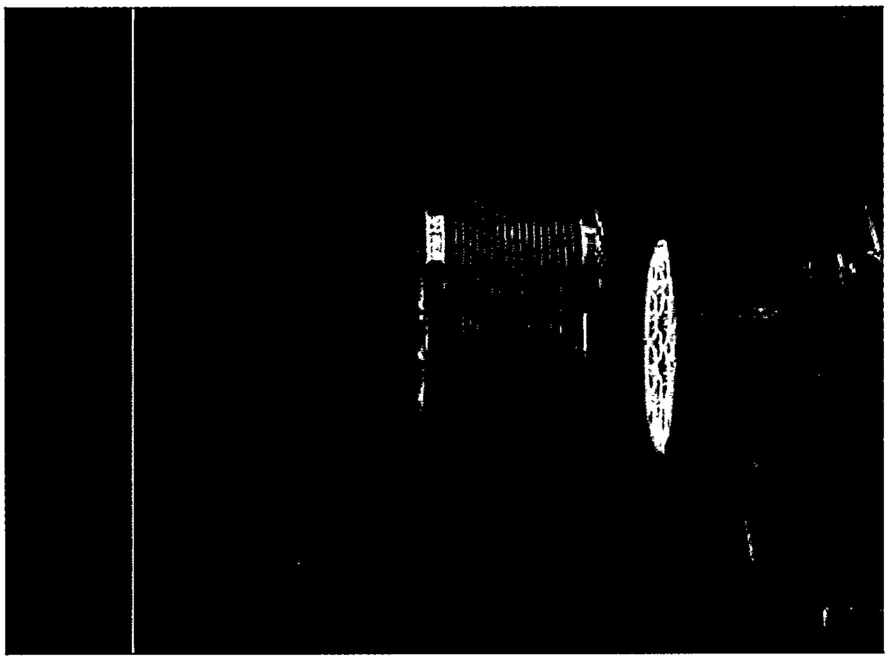

Figure 1. *Broad-beam oxygen plasma source for growth and modification of oxide films.*

cal commercial office building space and 6-26% more light at the back of the space, thus improving overall light distribution. Modifications were made to the DOE-2 simulation program that will facilitate annual and hourly thermal/solar/optical analysis of angle-selective glazings. This will allow us to more completely analyze heating, cooling, and lighting tradeoffs as a function of coating design parameters. The coating developers are working to modify the optics of their coating based on feedback from this simulation study.

Electrochromic Smart Windows

Electrochromic switchable glazings, or "smart windows," can dynamically control the flow of light and heat through a glazing in response to changing requirements for energy management and occupant comfort. In many glazing applications, the smart window will have a considerable energy advantage over conventional windows. The goals of our project are to develop advanced materials and devices, to characterize their performance, and to work with industry to develop large-area prototype products.

Over the last decade, DOE-supported basic materials research at LBNL and elsewhere has helped establish the technical viability of electrochromic coatings. In FY95, DOE launched an Electrochromic Initiative to accelerate R&D that would lead to marketable products. As a result of a competitive solicitation, two industry teams were selected for the multiphase project: one led by Optical Coating Laboratories, Inc. of Santa Rosa, CA; the other led by Donnelly Corporation of Tuscon, AZ. Each team consists of a coating development company and at least one firm with glass or window production and marketing experience. LBNL staff served a variety of technical and management roles for DOE in launching this project. Now that it is underway, our materials scientists are working with OCLI and Donnelly, and other staff are sharing results of performance assessment studies. A National Renewable Energy Laboratory team will support durability assessment. At the conclusion of Phase I, in mid-1996, one-square-foot samples will be submitted for optical and durability testing to determine which team will proceed to Phase 2.

During FY95 we continued development of LBNL devices using Li_xNiO_2 and other complementary counter-electrodes together with the more commonly used electrode WO_3. A thorough comparative study of these counter-electrodes is underway to help determine the best components for use in electrochromic devices. Rapid prototyping is achieved by using laser ablation or cathodic arc deposition; both of these techniques use very small targets which can be fabricated in the ceramic shop at LBNL so that deposition can begin the same day. Since both electrode and counterelectrode color simultaneously, these devices tend to have a very high range of coloration. Also, the Li_xNiO_2 has a neutral color, which moderates the strong blue color of the WO_3. The WO_3 layer in these devices is provided by industrial partners OCLI and Donnelly and also made by sol-gel techniques at LBNL. Advancements were made in the polymer electrolyte by capping the end groups of the polymer chain to reduce secondary chemical reactions in the device. Our cyclic testing of these materials and devices involves the use of adaptive control techniques. One of the most successful of these techniques is optical feedback control. Overdriven devices sometimes begin to lose dynamic switching range over thousands of cycles, as show in Figure 2 with a sample that had been switched 9000 times. However, when the switching protocol was changed to utilize optical feedback control to adjust the driving voltage, after only 30 cycles under this switching protocol, the dynamic range improved dramatically from 11% (50% bleached to 39% colored) to 52% (70% bleached to 18% colored).

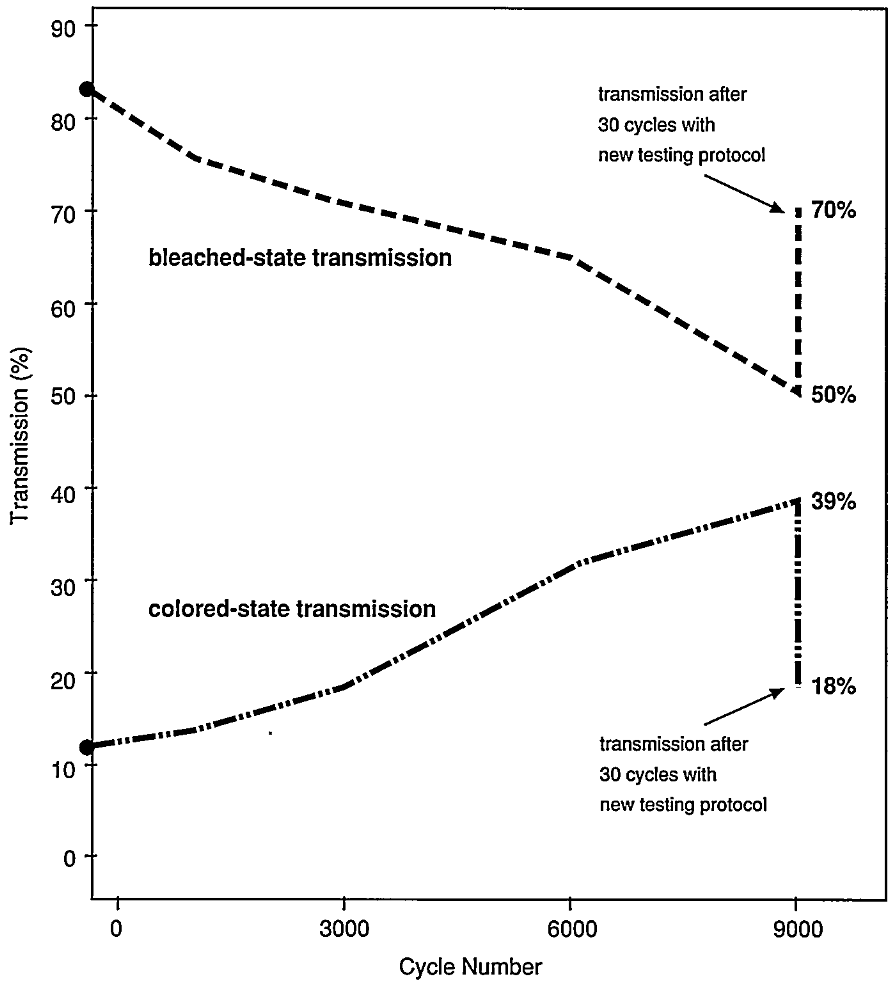

Figure 2. *Device recovery following the onset of optical feedback control.*

Chromogenics include many different types of materials technologies in addition to electrochromics. In our international work under the IEA/SHC, Task 18, we are evaluating a range of chromogenic prototype glazings, including thermochromic materials and polymer dispersed liquid crystal devices. This work provides us with a better understanding of their properties and helps to determine their relative strengths and weaknesses.

In FY96, we will continue our study and construction of devices using various complimentary counterelectrodes. Long-term testing will continue to determine the lifetime of our devices and to develop more advanced control strategies. Several materials exchanges have been arranged to test our special electrode materials in industry devices that are in advanced stages of development. Also, some of their electrolytes will be tested in our devices. We will continue our partnerships with the companies involved in the DOE Electrochromics Initiative with the goal of assisting them in meeting project objectives.

Performance Analysis of Electrochromic Glazings

Glazing manufacturers who are developing new electrochromic glazings do not have enough information on the relationship between coating properties and the resultant energy performance of the glazing. In FY95, we expanded our studies to include a more comprehensive analysis of energy performance, materials development guidelines, market potential, and visual comfort to support the practical concerns of industry partners participating in the DOE-Electrochromics Initiative. Some of this work was done under the Modeling and Control Strategies Activity led by the U.S. for IEA Task 18.

In FY95 annual and detailed hourly energy analysis in a prototypical residence was performed using the DOE-2.1E energy simulation program in order to better understand the relationship of control strategies to building performance. Of the three control strategies studied, switching strategies based on space-cooling load control provide the best performance for all electrochromic devices that were modeled. For commercial buildings, prior studies have explored the relationship between daylight modulation and solar gain control. We extended our studies to include commercial buildings in heating-dominated climates. Results showed that best performance is achieved if the electrochromic is left in its clear or bleached state during the heating season, but controlled to avoid glare and controlled during the cooling season using daylight illuminance control. Prior studies have demonstrated the performance advantage of a reflective electrochromic over an absorptive device. However, most devices now under development operate in an absorptive mode. We examined a variety of near-term solutions for improving absorptive electrochromic device performance by combining the electrochromic with static spectrally selective low-E coatings and glazing layers to achieve higher solar heat gain rejection without unduly impacting daylight transmission.

Using these performance data, a U.S. market performance assessment study was initiated to ascertain the potential energy and economic impacts of electrochromic devices in non-residential buildings. Savings accrue from a combination of cooling load reductions and electric lighting savings. Actual market impact will depend on cost and other performance parameters. We will attempt to determine the impact of these parameters in the coming year.

Electrochromic glazings should provide increased visual comfort for critical visual tasks because of their ability to respond to changing exterior daylight levels and to limit interior daylight levels to an acceptable range. Using the powerful capability of the RADIANCE visualization program (Fig. 3), we examined illuminance levels, luminance, and patterns in office spaces with different types of coatings and operating strategies throughout the year. We found that one might want a minimum transmission level as low as Tv =0.01 to achieve privacy, a near glare-free environment for computer use, and relatively constant interior daylight levels. However, at such low transmittance levels the exterior view quality may be diminished to unacceptable levels. Further studies of the effects of device parameters on thermal and visual comfort are planned.

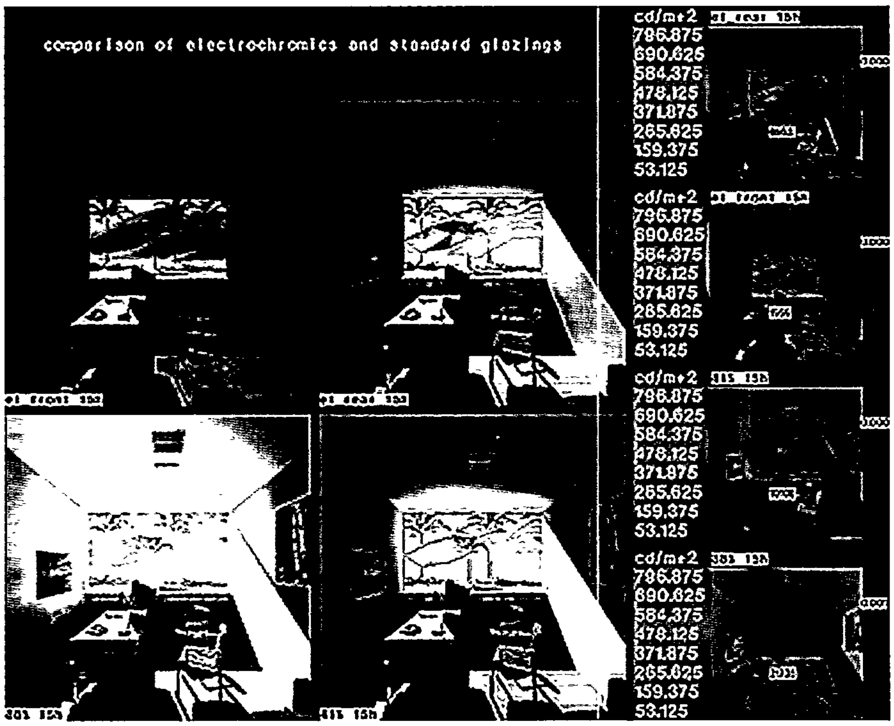

Figure 3. *Photo-realistic and false color luminance map showing a 120 degree view of the interior looking towards the west-facing window. Clear sky, August 21, 15:00 in Phoenix, Arizona.*

Superwindows

Highly insulating windows have long been considered important in virtually all residential and some commercial buildings that have a sizable heating load. 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, LBNL 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" would therefore require less heating energy per square foot over a full heating season than would an insulated wall.

This knowledge, combined with an understanding of heat transfer through multiple glazings, low-emissivity coatings, and gas-fills, led us to develop a prototype superwindow (three layers, two low-E coatings, Krypton gas-filling) in the late 1980s. 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. The LBNL superwindow design concept was quickly commercialized, and participation in utility-supported field tests validated window performance claims. Our participation in the National Fenestration Rating Council's energy rating programs (see page 6) have ensured that superwindows are properly credited in the marketplace. An infrared (IR) thermography laboratory, established at LBNL, aids us in our superwindow research by allowing us to better quantify two-dimensional heat transfer through insulated window frames and edges (see page 7). Activities in FY95 on the development of superwindow prototypes using commercially available technologies have focused on more efficiently incorporating superwindow designs into wall sections (see page 32, Integrated Window Systems).

Also in FY95, we continued our collaboration with Australian (University of Sydney) researchers working on the development of an evacuated glazing prototype. Evacuated glazings, two sheets of glass with a vacuum space between them, have the potential to be effective superwindows due to the extremely low-conductance of evacuated gaps and the high solar transmittance resulting from the use of only two glazing layers. However, thermal short circuits and structural stresses result from the glazing spacers (which must be used to keep the glass layers from collapsing) and from the solder glass edges (necessary to maintain the vacuum). We used our IR thermography facility to perform detailed temperature maps of a prototype vacuum glazing (Fig. 4) in order to better understand these effects and to validate computational models. With validated models, the University of Sydney team can now continue their efforts to better quantify the thermal and structural issues surrounding the long-term use of evacuated glazings in cold climates. We also introduced these researchers and their technology to several U.S. manufacturers interested in learning more about the technology.

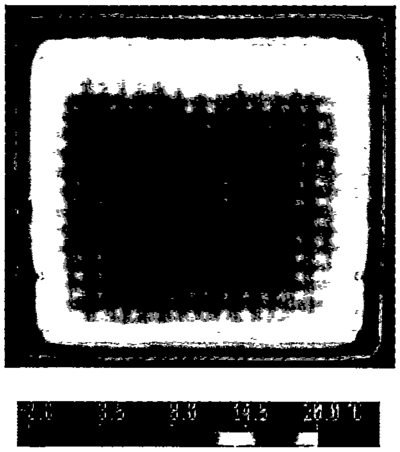

Figure 4.
LBNL's Infrared Thermography Laboratory helps industry, university, and other laboratory researchers develop effective new building insulating materials. Shown is the warm-side temperature image of a prototype super-insulating vacuum window developed at the University of Sydney. As part of an international collaboration, LBNL researchers evaluated the effectiveness of this prototype, suggested design changes, and introduced it to U.S. window manufacturers.

The annual energy savings of prototypical evacuated glazings were evaluated using DOE-2 and the results were compared to savings from highly insulated superwindows as well as more conventional insulating glass with a low-E coating and gas fill. Depending on climate and orientation, there is an energy performance trade-off between the superior U-value of the superwindow and the higher solar heat gain coefficient of the evacuated glazing.

In FY96, we will continue to use the IR facility to aid U.S. industry and international researchers working to develop advanced and more cost-effective energy-efficient window products. A collaborative project with UC Berkeley's Department of Chemical Engineering on alternative krypton and xenon distillation technologies has begun in order to identify the potential for producing lower-cost, gas-filled superwindows.

Fenestration Performance, Building Applications, and Design Tools

Achieving greater energy efficiency in buildings through improvements in window technology involves more than developing new components and systems. Obtaining accurate and consistent energy performance and cost information about commercially available products as well as products under development is critical to window specifiers and researchers. With such data, a designer can match fenestration systems to architectural needs and a researcher can understand the energy savings potentials of products during the development process.

Our work in this area aims to assess fenestration components and whole systems at standard test conditions as well as over the entire range of operating conditions that may exist in any climate or building type. We are developing and refining component and total-window test procedures and analytical models for determining the heat transfer and solar optical properties of window systems. These test procedures and models are compared with field tests and experiments in order to validate them and better understand their limitations, thereby guiding future research efforts.

The algorithms and test procedures developed at LBNL have found many uses. Our algorithms are packaged in several software packages used by the window industry and by building energy simulation programs. In turn, these software packages as well as the basic algorithms and test procedures are utilized by standards-writing organizations such as the National Fenestration Rating Council (NFRC), the Primary Glass Manufacturer's Council (PGMC), the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), the American Society for Testing and Materials (ASTM), and the International Standards Organization (ISO). Finally, knowledge about fenestration system performance is incorporated into specification guidelines and tools used by architects, engineers, builders, and consumers.

National Fenestration Rating Council

Incorporated

CERTIFIED

AAA Window Company.

Manufacturer stipulates that these ratings were determined in accrodance with approved NFRC procedures.

Energy Rating Factors	Ratings Residential	Ratings Commercial	Product Description
U Factor Determined in Accordance with NFRC 100	0.40	0.38	Model 1000 Casement Low-e=0.2 0.5" gap Argon Filled
Solar Heat Gain Coefficient Determined in Accordance with NFRC 200	0.65	0.66	
Visible Light Transmittance Determined in Accordance with NFRC 300 & 301	0.71	0.71	
Air Leakage Determined in Accordance with NFRC 400	0.20	0.21	

NFRC ratings are determined for a fixed set of environmental conditions and sizes and may not be appropriate for directly determining seasonal energy performance. For additional information contact:

Figure 5. *LBNL researchers have worked with NFRC members to develop the software and procedures necessary to rate and label windows with thermal performance indices.*

Window Rating and Labeling Systems

As highly efficient window systems have evolved over the past decade, the need for a fair, accurate, and uniform system to assess the thermal performance of these systems has grown. The National Fenestration Rating Council (NFRC) was founded in 1989 to answer this need.

By bringing together manufacturers, architects, engineers, builders, state regulators, utility incentive programs, and consumers, NFRC has been able to design a rating system which answers the diverse needs of all its members. Consumers, architects, and engineers have access to reliable information, and utilities can be assured of real energy savings. State energy offices are spared the need to develop their own rating systems, and manufacturers only have to meet a single standard.

Researchers at LBNL are leading the NFRC efforts in the development and implementation of technical procedures to rate the thermal and optical properties of both simple and complex fenestration products and in the development of procedures to evaluate the annual energy effects (costs) of products based on these properties. LBNL staff members either chair or are actively involved in all the NFRC'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 and DOE-2 computer programs to study issues relating to the annual energy effects of windows.

LBNL activities during FY95 focused on helping NFRC meet the requirements of the Energy Policy Act (EPACT) of 1992, which required the development of a basic window rating and labeling system. Technical procedures to determine the U-values, Solar Heat Gain Coefficients (SHGCs), and Air Infiltration (AI) rates for most common window products have been developed. Window U-values from many U.S. manufacturers now appear on NFRC labels and in NFRC's Certified Products Directory; the addition of SHGCs and AI are in progress (Fig. 5). Much of our efforts during 1995 were aimed at ensuring that the SHGC rating process under development was technically accurate yet cost-effective for manufacturers. We also worked with other NFRC members to complete a draft of the first annual energy rating methodology for residential windows.

In FY96, we expect to work with NFRC members and staff to finish the implementation of the solar heat gain and infiltration procedures. We will also work with the U-value subcommittee as they revise their standard to address more complex fenestration systems. We will improve the accuracy of procedures which apply to complex products (i.e., skylights and other projecting windows, non-homogeneous glazings, and shading systems) and curtainwalls.

While the focus of our window rating and labeling efforts has been to support NFRC activities, we have also worked with other complimentary organizations on the development of window thermal and optical standards. Such activities include chairing an ASHRAE Standards Projects Committee, participation in ISO Technical Committees, and contributing to the development of ASTM and PGMC standards.

WINDOW and THERM Computer Programs

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 nationally and internationally 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).

One of our primary program goals is to ensure that the WINDOW software meets the needs of the fenestration industry and market in determining product thermal and optical performance parameters. WINDOW is unique in that it both serves manufacturers' design development needs and meets product rating requirements. Manufacturers can be assured of a specific NFRC rating before a prototype new product is ever built, thereby saving the cost of developing and testing a prototype to see if it meets thermal/optical performance expectations. We continually strive to improve upon program capabilities so that advanced products can be designed and rated accurately. We will also improve the program's ease of use so that it can be used effectively by a wider audience.

In FY95, our efforts focused on the completion and release of a beta-version of THERM, a two-dimensional, finite-element-analysis (FEA) heat transfer program which will first function as a stand-alone program and then as the cornerstone for future versions of the WINDOW program. The currently available version of WINDOW relies on onedimensional analysis or on input from outside two-dimensional heat transfer programs. THERM allows the user to directly import CAD drawings or scanned images of window frame/sash profiles and to easily model their true geometry. The calculation engine of THERM is being developed in collaboration with colleagues at the University of Massachusetts and is based on code previously developed at Lawrence Livermore National Laboratory. Much of our efforts during 1995 focused on implementing an automated (no user input required) meshing code (Fig. 6) and on creating a robust but simple interface compatible with window industry practices.

During FY96 we will integrate THERM and WINDOW 4.1 algorithms into one piece of software, WINDOW+5. WINDOW+5 will also include technical improvements to the center-of-glass modeling as adopted by ASHRAE SPC142. Other technical improvements to increase the modeling accuracy for complex products will be implemented into developmental versions of WINDOW. The graphical user interface developed for THERM will be invaluable in meeting manufacturers needs to describe geometrically complex products in a graphical format.

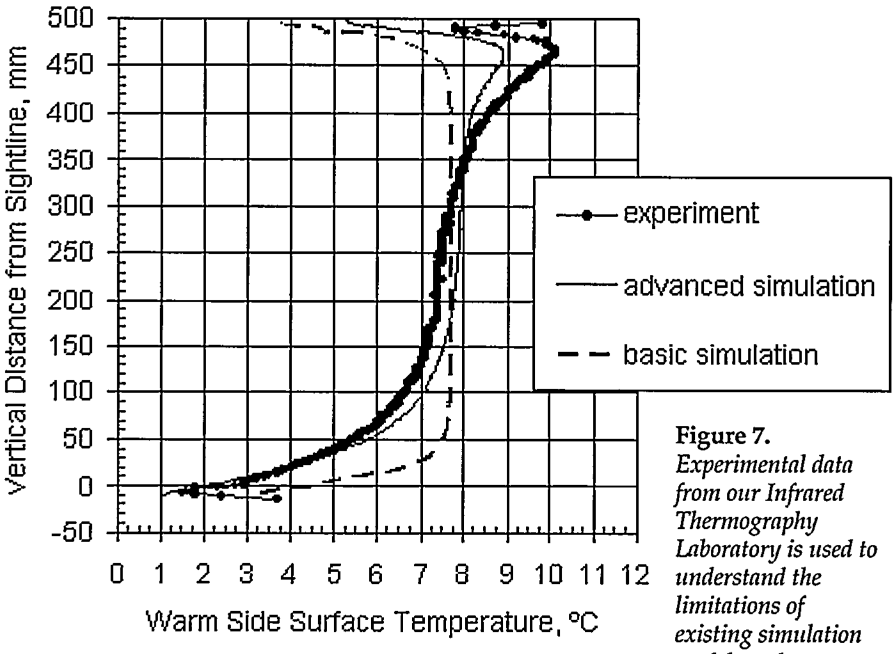

Figure 7. *Experimental data from our Infrared Thermography Laboratory is used to understand the limitations of existing simulation models and to validate advanced algorithms.*

Thermal Analysis

Research efforts over the past few years have shown that the procedures we have developed to quantify the thermal performance of commercially available "simple" fenestration products are accurate. However, these same validation studies have show that our information base for complex or 3-D products (greenhouse windows, skylights, etc.) and high-performance products is lacking. In order to improve upon this knowledge base, we have developed new experimental techniques and are using advanced heat-transfer simulation codes.

Over the past several years we have been continuously upgrading the measurement capabilities of our Infrared Thermography Laboratory. In this facility, 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. Warm-side surface temperatures are recorded with a sophisticated IR detector and presented as color images or thermographs. These surface temperatures can be compared to simulation results of the same product to better understand the limitations of the simulation model (see Fig. 7).

Significant improvements to our ability to quantify the accuracy of our Infrared Thermography Laboratory were completed during FY95. We demonstrated an absolute accuracy of 0.5°C in temperature resolution and 4 mm in spatial resolution. We rebuilt the warm and cold chambers of the facility so that we can maintain and quantify standard heat transfer film coefficients and to keep humidity levels low enough so that condensation does not form on the glazings. We added a remote-controlled background temperature mirror, isolated the reference emitter from the warm-side air flow, and added a second (glass surface) reference emitter. We have also taken part in conferences and symposia on the topic of IR thermography in order to help develop a standard test procedure using this measurement technology.

In FY96 we will use the IR facility to document the warm-side surface temperatures for a variety of fenestration products. The resulting database will be used to guide the development and validate future versions of the WINDOW/THERM software. It will also be made available to other window heat transfer researchers for their algorithm validation efforts. We will begin with a series of

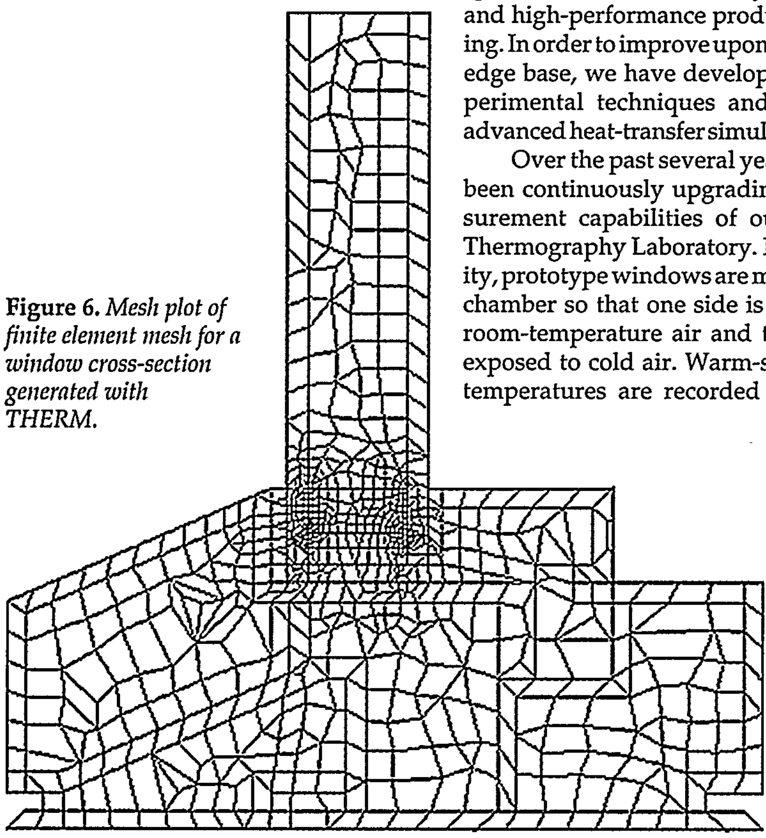

Figure 6. *Mesh plot of finite element mesh for a window cross-section generated with THERM.*

tests of seven insulated glazing units, which are part of a US-Canada simulation and testing round-robin exchange aimed at developing a Condensation Resistance Index. Following that, we will work on frame film coefficients and on quantifying the convective and radiative effects of projecting products. The resulting data will be compared to data from an advanced heat-transfer simulation model (FIDAP) as part of a collaboration with University of Massachusetts researchers.

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 and data for determining energy performance properties (U-values, Solar Heat Gain and Shading Coefficients, and overall product Visible Transmittances).

For the past decade we have actively served as an unbiased source working to improve the measurement and corresponding calculation procedures used by industry to quantify the optical performance properties of glazings. We continue to lead and participate in round-robin experiments and national and international standards-writing organization task groups, and to develop new hardware to better characterize the optical properties of commercial and research-level products.

In FY95 we led the NFRC development and implementation of a basic rating system for the optical properties of conventional glazings. Two procedures for determining solar and infrared optical properties were developed by LBNL for the NFRC. These procedures are used by glazing manufacturers to measure the optical properties of their products. A data validation procedure was developed by LBNL and approved by the NFRC. This validation procedure was used to check each data file submitted for both format and technical errors. The final result was the compilation of over 700 product files representing virtually the entire glazing industry. The files are in WINDOW 4.1 format and can be used directly for simulating solar heat gain and visible transmittance for rating and labeling purposes. We also completed a supplementary optical model to allow the properties of applied films on glass to be calculated from the measured properties of the components. This model has been embodied in a computer program that produces new files readable by WINDOW 4.1. A thorough validation of the model was performed and published in cooperation with the major applied film manufacturers. This accomplishment now forms the basis for rating the first attachment products. Harmonization of these procedures with international standards activities from Europe, Japan, and ISO is well underway and expected to result in consistent procedures by FY97.

Analogous procedures for complex glazings and shading systems are currently under development. We are researching two approaches for determining the optical properties of complex layers. Our scanning radiometer allows us to measure the average optical properties of complete, complex layers. This data can then be used with a calculation method we developed for determining the optical properties of complete systems. The second approach utilizes a custom instrument for measuring the bi-directional properties of materials. Completion of this instrument is expected in FY96. Ray tracing programs can then take these measured materials properties and compute total system optical properties (Fig. 8). Each approach is appropriate for a specific class of products: the first approach is best suited to unique and extremely inhomogeneous materials difficult to characterize geometrically; the second approach offers the potential for significant cost-savings for products which take one form but use many different base materials (i.e., venetian blinds of different colors). Validations on both approaches will proceed in FY96 as part of a collaboration with the IEA. A draft procedure will be written for NFRC in FY96 with the goal of an initial NFRC implementation in FY97.

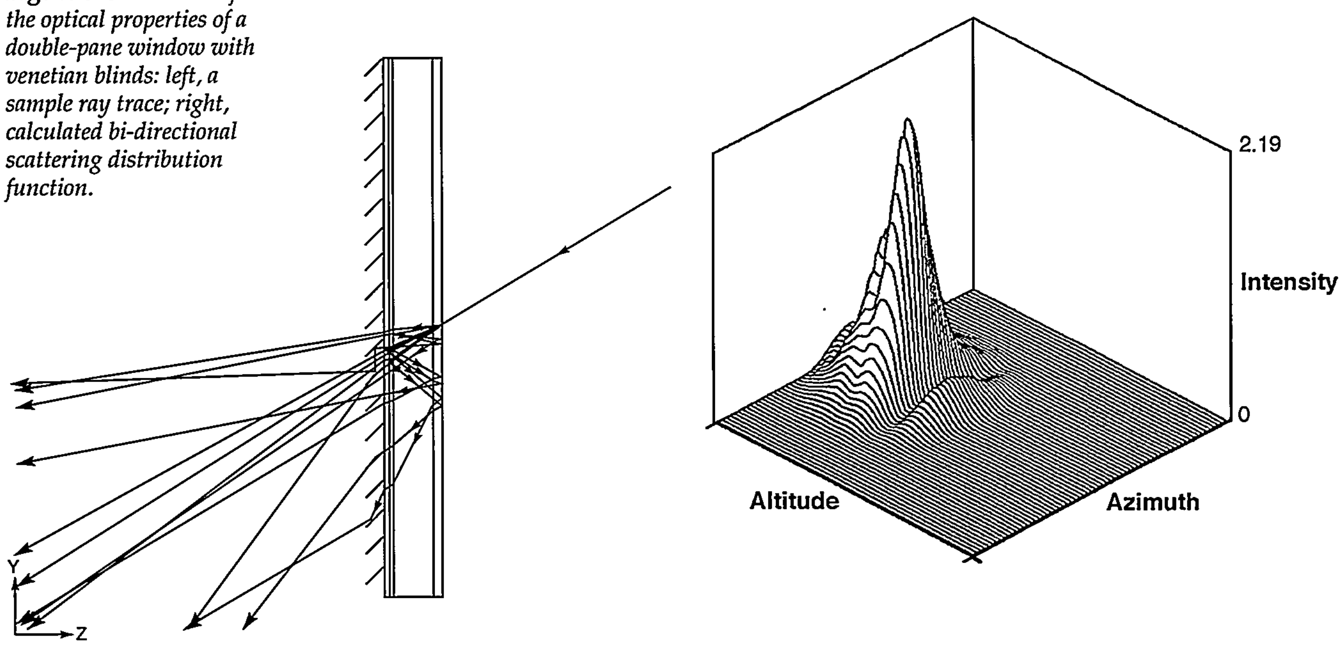

Figure 8. *Simulation of the optical properties of a double-pane window with venetian blinds: left, a sample ray trace; right, calculated bi-directional scattering distribution function.*

Solar Heat Gain

The fraction of the incident solar energy let into a building by a window (called the solar-heat-gain coefficient, SHGC) 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.

The SHGCs of simple windows at normal incidence, consisting of specular glazings without inhomogeneous shading systems, can be calculated with a high degree of accuracy based on the component optical properties and on existing heat-transfer correlations (see sections on WINDOW/THERM and on Optical properties above). While the SHGCs of uncoated simple windows at off-normal angles of incidence can also be easily computed, we are still working to improve the procedure used to calculate the SHGCs of coated simple windows at off-normal angles of incidence. In FY95 we measured the SHGCs at off-normal angles of incidence for several coated glazings using our Mobile Window Thermal Test (MoWiTT) Facility (Fig. 9). These tests indicated that the approximate model used in WINDOW adequately predicts the performance of spectrally selective glazings. In FY96 and FY97 we plan to measure the angular SHGCs for a wider variety of coated products.

Determining the SHGCs of complex products (i.e., those with shading systems or other inhomogeneous layers) is a more involved procedure. Determining the optical properties for such components and systems is an ongoing element of our research program (see Optical Properties section above). In addition, the heat transfer effects between layers must be quantified. Our research has led to the development of a method for measuring this effect; specifically a procedure to measure the Inward Flowing Fraction (IFF) of absorbed energy within a layer. During FY95 we published a database of such IFF values and an overall test of the method, in which we showed good agreement between the SHGC calculated from our layer measurement library and measured in our MoWiTT (see section on Field Measurement) calorimetric facility. During FY96 and FY97 we plan to make this calculation and database available to the NFRC and other interested users, first as a stand-alone computational tool and later as a component of the WINDOW system. Completing this research task will make predicting the performance of fenestrations with complex shading devices as reliable and cost-effective as procedures used by the NFRC today for simple windows, thereby making the substantial energy savings from these systems more accessible and marketable.

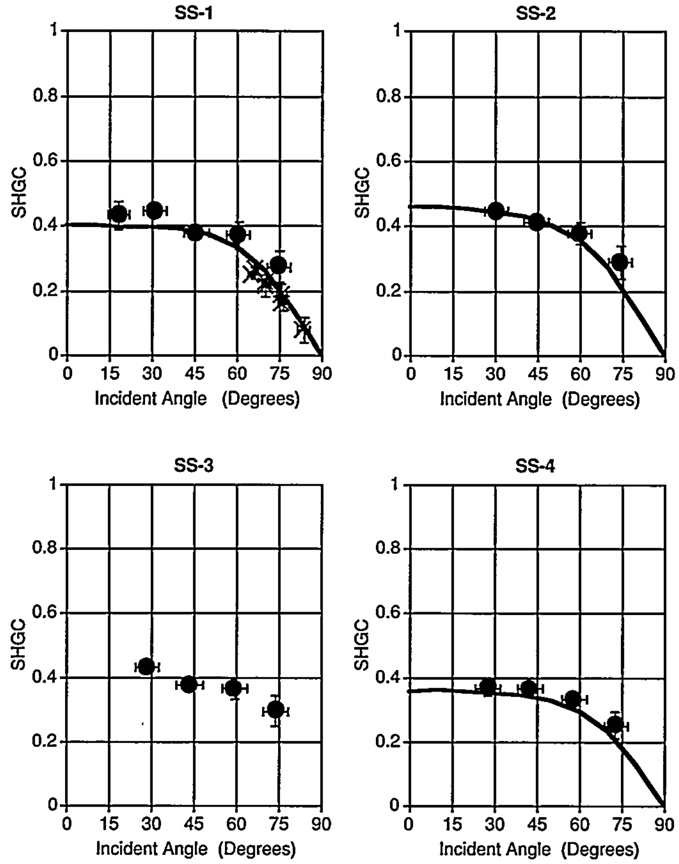

Figure 9. *Measurements on four selective glazing systems compared with WINDOW4 model for three of the systems. SS-1 was a system with a modified low-E coating that had a shorter wavelength infrared cutoff. There is more large-angle data because this system was measured in a south-facing orientation as well as a west-facing. SS-2, SS-3 and SS-4 were systems utilizing a combination of normal low-E coating and selective (tinted) glass.*

Daylighting

Lighting is one of the largest electrical loads in commercial buildings. An efficient daylighting design can displace 70% of the lighting energy requirements in a typical office building. Predicting the quality and quantity of the luminous environment is essential for energy-efficient daylighting design. Over the years, we have developed a range of daylighting analysis and design tools, continuously expanding modeling capabilities and improving calculation accuracy.

In FY95, in collaboration with an International Energy Agency (IEA) effort on daylighting research, we completed the integration of our daylighting software program, SUPERLITE 1.01, into ADELINE 1.0. ADELINE 1.0 (Fig. 10) links a 3-D CAD program with both SUPERLITE and RADIANCE (see the Lighting Systems section of this report), thus improving user capabilities by providing a DOS-based graphical user interface for both CAD input of a design and for graphical display of analysis results. We have established an effective method to distribute ADELINE 1.0 to users in the U.S. and are providing informal user support through an electronic mail list server and a World Wide Web (WWW) site specific to ADELINE. The list server allows users to communicate with each other via e-mail messages. The WWW site (http://radsite.lbl.gov/adeline/HOME.html) provides widely distributed access to ADELINE information via this increasingly popular Internet technology.

The modeling capabilities of SUPERLITE continued to be enhanced in FY95. Development of SUPERLITE 3.0, which includes the capabilities to analyze complex fenestration systems and shading devices, resulted in a beta version which is now undergoing testing and validation. FY96 efforts will focus on developing a release version of SUPERLITE 3.0. Until then, we will continue to distribute the 1994 release of SUPERLITE 2.0, which added electric lighting analysis to the capabilities of the previous version.

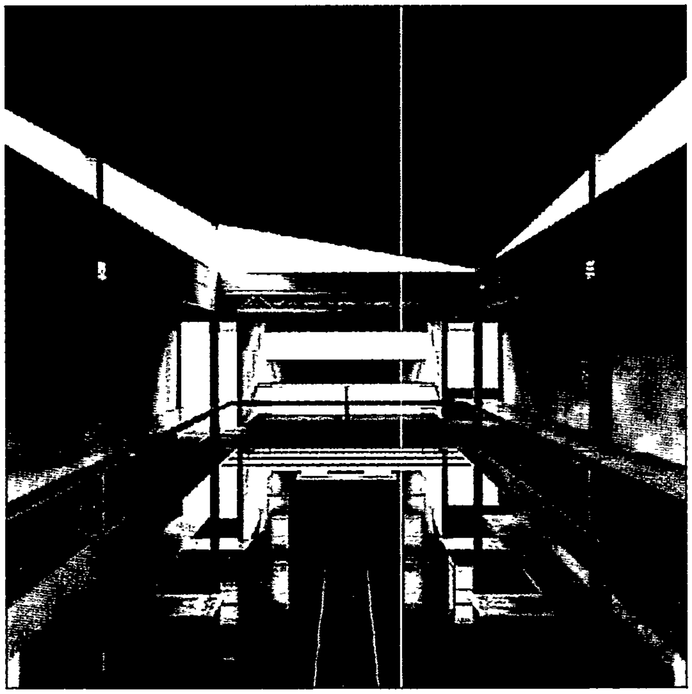

Figure 10. *Rendering of an architect's office using ADELINE in conjunction with AutoCAD.*

The underlying algorithms for analyzing complex fenestration systems that have been implemented in SUPERLITE 3.0 will also provide the basis for ongoing development of the daylighting analysis engine incorporated into Energy-10 (see the Simulation section of this report). This daylighting analysis engine, which is currently based on the DOE-2 daylighting algorithms, is written in C/C++, can be compiled under a variety of environments, and is modularized for ease of integration into other design tools that wish to address daylighting issues. This engine will provide a vehicle for continuing our enhancement of daylighting modeling and analysis algorithms and tools in FY96.

Field Measurements of Fenestration System Performance

In order to realistically present information on fenestration performance to specifiers and consumers, fenestration products must be evaluated at a limited set of standard conditions and through the use of computational procedures and laboratory tests. Field measurements are essential to ensure that the energy effects predicted by these standard tests and calculations adequately reflect what happens in the dynamic and complex environment within which fenestration products actually operate. Field measurements are also instrumental in telling us how new window technologies (e.g., electrochromics) for which there are not yet standard evaluation procedures actually perform. In conducting field measurements, we measure the energy flows through window systems under realistic weather and application conditions. For most of this work, we use the Mobile Window Thermal Test (MoWiTT) Facility, a unique, highly instrumented, double calorimeter currently situated in Reno, Nevada.

In FY95 we undertook efforts to test several products which are at the computational frontier—products for which computational procedures exist, but which need improvements. Field measurements on these products will help simulation tool developers better understand how much and where their tools need to be upgraded. Our tests focused on determining U-factors and Solar-Heat-Gain Coefficients for a garden window (Fig. 11) and on determining the off-normal SHGCs for windows with coated glazings (see Solar Heat Gain section). In FY96 and FY97 we plan to complete this work and extend it to skylights.

As window energy ratings become established, the question, "Is window A's U-factor lower than window B's ?" increasingly changes to "How many energy dollars will window A save as compared to window B?" This represents a shift from rating relative performance under extreme or test conditions to quantitative comparisons under average or representative conditions. To answer the latter question confidently, one must validate building energy simulation models and confirm that the quantitative conclusion will be applicable to the intended situation. To further this goal in FY95, we used the MoWiTT for detailed tests of DOE-2 calculations for glazings and perimeter spaces. These continuing tests will aid in validating the use of this simulation tool by the NFRC as a basis for voluntary annual energy ratings (see Window Rating and Labeling Systems).

Annual Energy Effects in Residential Buildings

While much of our research efforts focus on quantifying window thermal and optical properties, we are also working to better understand the annual energy implications of fenestration products, with given properties, in residential buildings throughout the United States. Our efforts on this topic cover a range of inter-connected activities: we develop and validate software to quantify annual energy use and costs, we work with the National Fenestration Rating Council (NFRC) to incorporate this software into rating systems so that consumers can quickly comprehend the annual energy effects of fenestration products, and we are developing written and electronic media to explain window energy effects to those responsible for window purchasing decisions.

RESFEN Software

Developing and validating software to analyze the impacts of different window technologies in typical residential buildings throughout the United States is the first step towards ensuring that the optimum products are used in a specific application. Historically, we have worked with LBNL's Building Energy Simulation Group (see page 25) to ensure that the DOE-2 building energy analysis program accurately models window energy effects. RESFEN is a regression-based, condensed version of the DOE-2 program, which focuses specifically on window effects. With RESFEN, now in its fourth year of use, users can determine the annual energy (or peak demand) effects of window products given their U-values, Solar Heat Gain Effects, and Air Infiltration rates.

In FY95 we upgraded RESFEN so that its calculated values of heating and cooling energy reflect changes made to the latest version (E) of the DOE 2.1 simulation program. We also formally released a version that uses the MSWindows operating system, which complements the DOS-based version that has been available for several years.

During the coming year we plan to increase the number of geographic locations to 45 from the current set of ten. We will also revise the program to calculate the FHR/FCR ratings (NFRC's Standard annual energy ratings) for a particular window in addition to determining whole-house window heating and cooling energy usage quantities. RESFEN's capabilities will also be incorporated into the WINDOW 5.0 development effort.

Support for NFRC Rating Efforts

Since NFRC's inception in 1989 we have been providing technical support to the Annual Energy Performance Subcommittee as they work towards their goal of developing a state-of-the-art simplified rating system to quantify annual energy effects. The goal is to provide window purchasers with a simple system to assess the heating and cooling energy impacts and costs of windows. NFRC is developing 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 non-dimensional numbers valid throughout the entire United States: a fenestration heating rating (FHR) and fenestration cooling rating (FCR). The second approach, which builds on the RESFEN program, is a more detailed procedure that will calculate the energy performance of windows in a specific home.

In FY95, we continued our efforts to substantiate 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. We worked with NFRC members on the development of Standard 900, which documents the use of the FHR/FCR approach. We also began efforts to document the proper use of the RESFEN program in order to help NFRC write Standard 901 which covers the detailed procedure to assess specific annual energy effects.

During FY96, our efforts will focus on developing an updated version of RESFEN (see above) and on the documentation necessary in order to make this program part of Standard 901. We will also aid in the development of a User's Guide to Standard 900 to ensure that FHR/FCR numbers are used appropriately.

Window Selection Guidelines

The previous two sub-sections discussed our efforts to develop quantitative measures of window energy performance. We have continuously provided the window manufacturing and design community with articles and presentations relating to designing or selecting the optimum fenestration products for energy efficiency. In recent years we have developed audio/visual material on this topic and incorporated it into interactive kiosks and multimedia packages.

Over the past year, we worked with University of Minnesota researchers to develop a Window Design Guidelines document, which provides window design guidance for architects, engineers, builders, and homeowners. The document was reviewed by other experts in the field and has been substantially revised this year. Its publication is being postponed until FY96 so that it can be rewritten to be consistent with recent decisions made about rating the annual energy effects of windows by the NFRC (see above).

We also recently completed prototyping an electronic multimedia version of the Guidelines that includes graphics, animation, and video as well as text. Once the Guidelines themselves are completed, this version will be revised accordingly and distribution accomplished via CD-ROM. A version shown at the Pacific Coast Builders show was received very favorably and generated considerable interest.

Annual Energy Effects in Commercial Buildings

While conductive losses through windows are not as significant in commercial buildings as they are in residential buildings, solar gains through commercial building windows are typically a large percentage of cooling loads. Furthermore, if lighting systems are controlled to take advantage of available daylight, lighting energy requirements in commercial buildings could be reduced substantially. Since the early 1980s we have been involved in DOE-2 simulation model improvements and studies aimed at quantifying this effect.

Figure 11. *A garden window set up for testing in the MoWiTT. Unusual projecting shapes such as this raise a number of window performance questions that can be answered through tests under realistic conditions.*

Our activities in this field in recent years have been curtailed due to our commitment to aid NFRC in the development of a residential annual energy rating system. As this residential system comes on-line, our and NFRC's efforts will turn towards the development of a standard methodology for assessing the effects of fenestration systems in commercial buildings. Our initial efforts will identify the potential advantages and problems associated with simple indices, which may not be appropriate for this problem. Other work will center on adapting existing whole building simulation software for this rating purpose.

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Lighting Systems

Investigators

F. Rubinstein
S. Berman
R. Clear
D. Crawford
C. Ehrlich
C. Gould
J. Jennings
O. Morse
E. Page
M. Siminovitch
D. Simmons
G.J. Ward

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 annual lighting energy use from 515 BkWh to 260 BkWh—a 50% savings equal to 20 billion dollars—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 up $100 billion of capital to be used for other purposes.

To help achieve this more energy-efficient economy, the LBNL 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. The program is now 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 and improved optics, 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 LBNL Lighting Program has produced over 200 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 applications, each requiring a different solution. 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 broad and multi-disciplinary. To achieve this breadth of 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 of lighting on visual performance and lighting quality, and building applications.

Advanced Light Sources

The goal of the advanced lamp technology project is to develop the scientific and engineering 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 (lpw). 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 allow 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 objective of the advanced lamp technology program is to achieve a target lamp system efficacy of 150 lumens per watt.

Prior to 1992, our lamp technology research concentrated on very-high-frequency operation of 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.

Sulfur Lamp

In 1993, we redirected our lamp technology research to focus on the sulfur lamp, which produces light by means of molecular, rather than atomic, emission. Scientists at Fusion Lighting in Rockville, Maryland had found that elemental sulfur, excited by microwave energy, could be used in place of mercury in their ultraviolet industrial lamps to produce a very bright, high-quality, white light. Fusion's initial lamps operated at 3.5 kW input power and 450,000 lumens of light output—levels too high for most commercial lighting applications. Furthermore, because of the high power involved, the lamps need to be both spun and air-cooled. Having identified the energy savings potential of sulfur lighting, DOE enlisted LBNL to explore the physical processes underlying the sulfur lamp and to begin developing a practical source for general energy-efficient illumination.

We concluded a technology licensing agreement with Fusion Lighting and commenced work on demonstrating a low-power sulfur lamp that would be driven by radio-frequency energy rather than microwaves, which was Fusion's preferred mode of operation. By concentrating on low-power, RF-driven lamps, we hoped to demonstrate a low-power sulfur lamp operating at approximately 100 watts and producing 10,000 -15,000 lumens. At these lumen levels (roughly 3-4 times the output of a standard fluorescent lamp) sulfur lighting could have major energy savings implications in commercial and residential buildings.

The sulfur lamp, whether driven by microwave or RF energy, 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, or diatomic sulfur molecules. As the sulfur dimers are excited by the hot argon and microwaves, 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 it 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.

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 drop 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.

In FY93 and FY94, we demonstrated a sulfur lamp operating at low power (approximately 100 watts), using VHF radio-frequency power at 3-35 Mhz instead of microwaves (at 2.45 Ghz). By reducing the power loading and capacitively coupling the RF supply to the lamp using specially conformed external electrodes, we operated differently configured sulfur lamps at up to 15,000 lumens with an RF input of approximately 100 watts. Operating the lamp at these lower power loadings and pressures eliminates the need for air cooling with a noisy air compressor. 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.

LBNL's technical advances in sulfur lighting operation were the subject of a major patent filed by LBNL in 1994. In FY95, we filed a modification of the previously mentioned patent application. Our industrial partner, Fusion Lighting, also exercised its option to license our technology as the basis for further development of low-power sulfur lamps .

During FY94 and FY95, DOE charged LBNL with providing technical oversight of a major subcontract with Fusion Light-

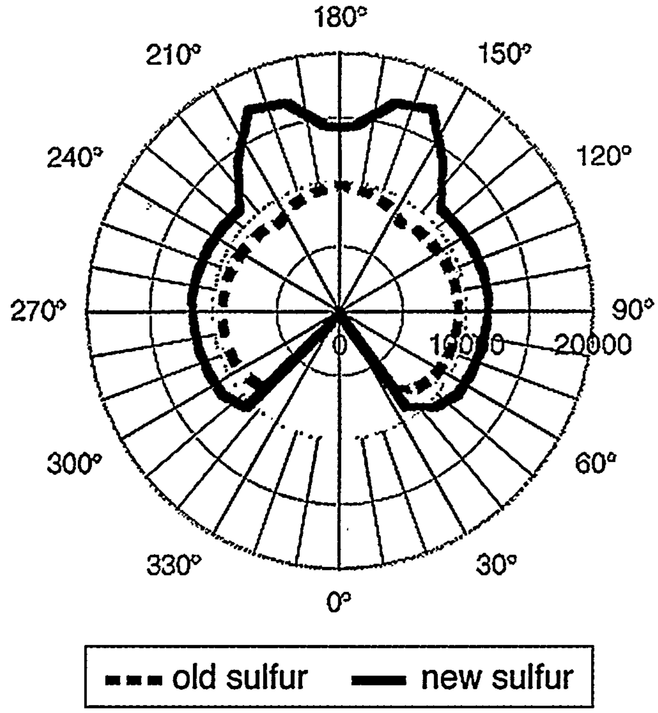

Figure 1. *Candlepower distributions for two 1000-watt sulfur lamp prototypes submitted to LBNL by Fusion Lighting for testing in the Lighting Group's goniophotometer. The new lamp's candlepower distribution in the upper hemisphere is augmented due to the presence of a reflector element added near the lamp base (at 0°).*

ing to: (1) 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, and (2) to accelerate the commercialization of a microwave-operated, high-power sulfur lamp of approximately 1000 watts. These first commercial sulfur lamps will produce approximately 120,000 lumens at a luminous efficacy of 90-100 lumens per watt. Because of their high output, these lamps are initially expected to find use in sports stadiums, convention centers, aircraft hangers, large maintenance facilities, and in roadway lighting. Other applications include shopping mall and industrial lighting.

In fulfillment of the subcontract, Fusion Lighting submitted early prototypes of the 1000-watt, microwave-driven lamp to LBNL for testing and analysis. This provided us with the opportunity to use our new goniophotometer (described in the 1994 Annual Report) to perform detailed measurements of the candlepower distribution of this new sulfur lamp. To perform these measurements, the sulfur lamp is mounted at the photometric center of the goniophotometer. The fully computer-automated device then measures, in precisely controlled increments, the polar distribution of lamp flux over a complete range of angles. This angular characterization is repeated for multiple vertical planes through the lamp to give a full spherical distribution of flux. The data is then used to determine the total flux of the lamp, calculate lamp efficacy, and prepare polar graphs of the distribution. With this information, reflector designers can then develop appropriate reflector profiles for a given application. These distribution studies are required in order to develop accurate, high-performance reflector systems. This information is being made available to fixture manufacturers and to the lighting industry in order to accelerate the efficient applications of sulfur and other high-lumen sources.

Figure 1 shows a plot of the candle power distribution of an old prototype sulfur lamp vs. that of the new model. The polar plot obtained from a goniometric test illustrates the distribution differences and increased light output of the new system.

In FY95, Fusion Lighting, LBNL, and the Department of Energy were awarded the prestigious R&D100 Award for helping to develop the Solar 1000 Sulfur Lamp: the first commercial sulfur light source.

Low-Lumen Sources

Although the successful deployment of the sulfur lamp can be expected to have a major impact on the commercial and industrial lighting of the future, we continue our search for an efficient, low-lumen source that might compete effectively in the near term with the ubiquitous incandescent light bulb in the residential sector. In 1994, we reported that we had constructed a prototype of a more efficient general service lamp by blowing a heavy glass envelope around a selectively coated tungsten-halogen burner that we had extracted from a commercially available PAR HIR™ lamp. These prototypes exhibited luminous efficacies of 26 lumens per watt with an expected lamp life of 3,000 hours. These selective reflector (SR) lamps, which we could produce at only 60 and 100 watts due to the current availability of PAR HIR lamps, are 60-65% more efficient and last three times as long as standard 60-watt light bulbs, yet fit in virtually any incandescent socket.

Emboldened by our success at transforming commercially available 60- and 100-watt PAR HIR lamps into improved-efficiency general service lamps, we began an analysis to determine the efficacies of general service SR lamps at other wattages and lifetimes. Because lamp manufacturers can produce incandescent lamps over a wide range of efficacies depending on the lamp life, comparisons between the various incandescent technologies are complicated. We produced a general model that can predict the efficacy and lifetime for all incandescent and halogen lamp technologies, as well as the selective reflector technology. Our analysis showed that the efficacy and lifetime of all incandescent lamps could be estimated using a simple mathematical expression and five fitted parameters. With this empirical expression, we were able to compare the performance of different lamps on an equal footing and were able to estimate the performance of SR lamps with different wattages that did not yet exist.

Building on this analysis, we applied conventional life-cycle cost and return-on-investment techniques to SR lamps with the same light output as a 60-watt incandescent lamp to demonstrate that a SR lamp priced at $3-4 would have the lowest life-cycle cost (LCC) compared to either standard incandescent lamps or compact fluorescent (CFL) lamps for lamps that are operated 1-2 hours per day. At lower hours of operation, the standard incandescent lamp had the lowest LCC, while for high hours of operation (over 3 hours/day) the CFL proved most cost-effective. Thus our 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 less than $4/lamp. To get to this low price would require sufficient volume such as might be possible with a government-sponsored buyers' group. Several government agencies are now studying the feasibility of such an approach.

Advanced Lighting Distribution Systems

As described previously, the advent of highly efficient, high-output lamps, such as Fusion Lighting's Solar 1000 sulfur lamp or electrodeless metal-halide lamps under development by the lamp industry, heralds a new era of advanced lighting distribution systems (ALDS) that can efficiently distribute light from very intense sources to where the illumination is needed. The significant barriers impeding the deployment of these systems are (1) unavailability of existing fixture designs that can exploit high-lumen sources, (2) a lack of working knowledge and good exemplars as to how to cost-effectively design an ALDS, and (3) lack of performance data showing clearly the application efficiency and operational advantages of these new systems. The primary challenge for the effective market penetration of these systems is the development of cost-effective, high-efficiency, light delivery systems. These systems must handle large lumen packages and deliver the light flux uniformly over a wide area while limiting the potential glare associated with highly intense sources.

Our objective in this work is the development of high-efficiency light delivery systems for high-lumen-output sources that can compete with conventional, lower-wattage, metal-halide systems. We will accomplish this objective by creating a coordinated industry development and demonstration plan that will showcase the efficiency and operational benefits of light distribution systems to the lighting industry.

In 1995, we completed the analysis of the data collected from early sulfur lamp/light pipe demonstration sites at DOE's Forrestal Building and at the Smithsonian's Air and Space Museum and presented these findings in technical papers at the 1995 National Conference of the Illuminating Engineering Society of North America. While these demonstrations showed that reasonable efficiencies could be achieved by coupling very-high-output lamps to custom-designed light pipes for flux delivery, the light pipe efficiency was not as high as could be obtained with more conventional fixture designs.

Development and Demonstration of High-Efficiency Indirect Lighting System

To raise the efficiency of lighting fixtures that can exploit high-output sources, we developed a new, high-efficiency, low-glare, indirect lighting system for light industrial, commercial, and office applications. The system will consist of a basic fixture module that can be installed with different reflectors to provide three distinct flux distribution patterns depending on the ceiling height and desired uniformity. The basic fixture module can be mounted in various ways—kiosk-, wall-, and ceiling-mounted—to provide a high degree of flexibility and suitability across a broad range of lighting applications.

In the preferred kiosk embodiment, the module will be mounted onto a cylindrical, free-standing structure (Fig. 2) that will be tall enough to eliminate direct view of the source or reflector when viewed from floor level. The structure as a whole will be both sturdy and aesthetically appealing, while providing a high degree of mobility and ease of maintenance. For appropriate applications, this system will achieve superior visual quality by means of indirect lighting, while taking advantage of the high efficiency and high color rendering index (CRI) of the new 1000-watt sulfur lamp system. By incorporating modular reflector elements, a wide variety of flux distribution patterns can be obtained, making the system effective at a variety of ceiling heights.

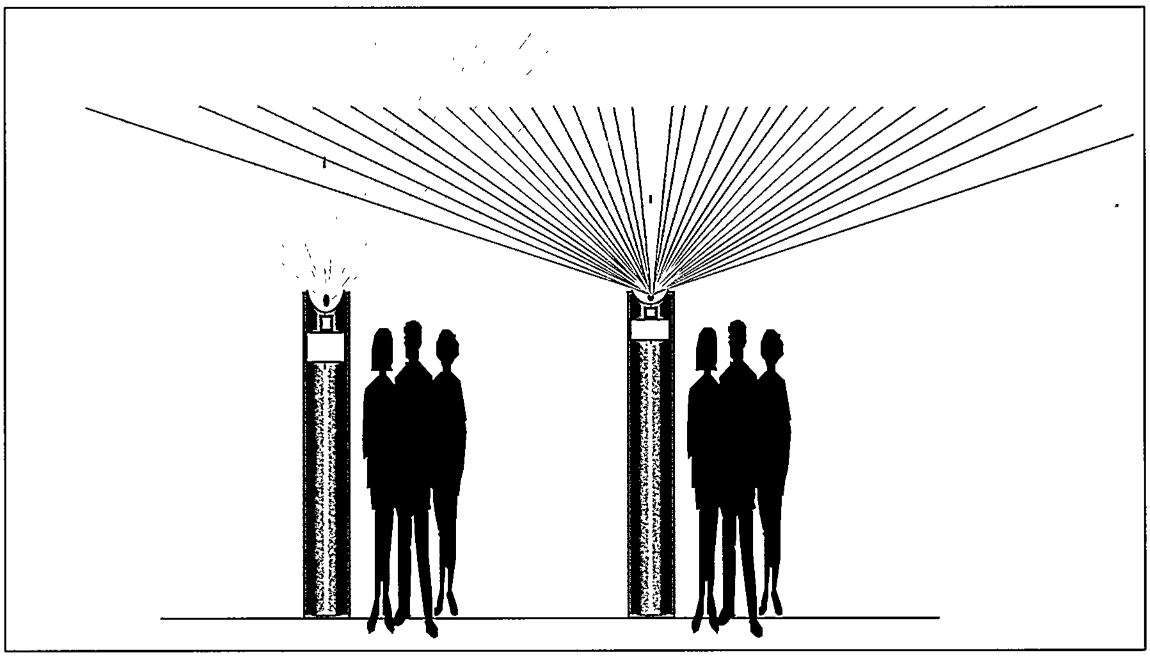

Figure 2. *Schematic drawing showing the indirect kiosk fixture designed at LBNL for the Solar 1000 sulfur lamp. Note the different distribution patterns from the two kiosks.*

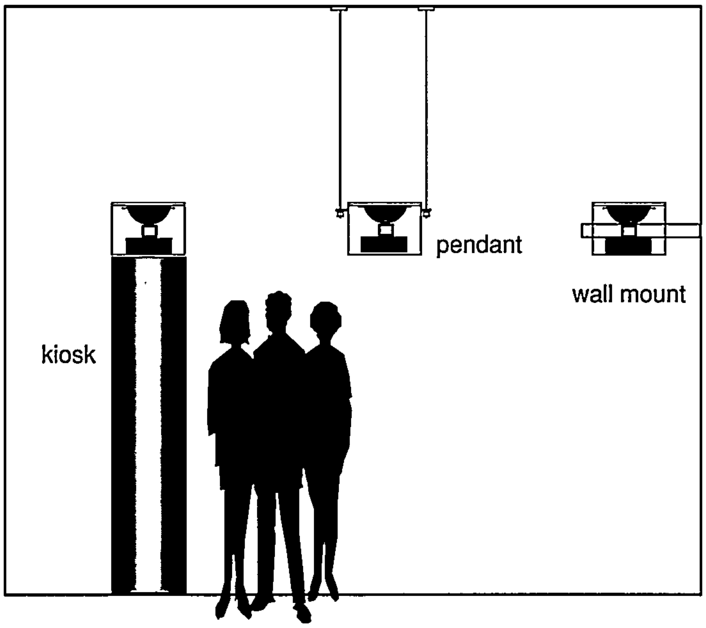

Figure 3. *Different mounting configurations for the high-efficiency uplighter.*

In addition to the kiosk configuration, the basic fixture module could be mounted to a wall with a rotatable yolk or pendant-mounted from the ceiling (Fig. 3). By providing several mounting options, this one basic fixture design can accommodate many lighting applications, including lighting for gymnasia, shopping malls, high- and medium-bay industrial spaces, and assembly areas.

We established an industrial partnership with a large U.S. fixture manufacturer to design a wide-distribution prototype of the indirect lighting system and produce it in sufficient quantities to allow a monitored field test at a highly visible site in California. We have selected the Sacramento Municipal Utility District's (SMUD) corporate headquarters lobby for the initial demonstration. The lobby is approximately 2000 square feet and is highly visible to the industry and business in the area. SMUD has been one of the country's leading utilities in conservation and energy efficiency.

Development of Novel High-Efficiency Reflector Systems for Sulfur Lamps

One of the major challenges in designing fixtures for high-lumen sources is the wide-distribution reflector assembly. The reflector must be capable of distributing light uniformly over a large ceiling area with maximum efficiency and no glare. Wide-angle reflector systems for conventional discharge lamps would be sub-optimal for the new sulfur lamp because of the requisite microwave screen that surrounds the lamp and affects its optical properties. In FY95, we used our newly acquired optical measuring and design capabilities (specifically the ASAP optical design program, in-house code, and the newly modified goniophotometer) to design a reflector that minimizes internal optical losses that occur with the microwave screen and provides a very wide distribution for efficient spacing of the high-power lamp.

Axially symmetric reflector designs can be characterized by whether reflected light rays spread out from (diverging) or cross over (converging) the symmetry axis of the reflector. For reflector-to-target distances and power density requirements mandated by an indirect application of the Solar 1000 sulfur lamp, diverging reflector designs yield reflectors that are far too large to be practical. Conversely, traditional converging reflector designs allow reflected flux to repeatedly traverse the extensive microwave screen surrounding the sulfur bulb and suffer subsequent optical and efficiency losses.

As a hybrid solution to these problems, we designed a 'bi-phase' reflector (Fig. 4) that allows reflected flux from the first stage of the reflector to diverge from the optic axis—thus directing it away from the screen enclosure—and produce a wide-angle ring of illumination on the ceiling. A secondary converging profile is used to keep the overall system to a practical physical size. This second-stage reflector, which is elevated with respect to the microwave mesh and prevents reflected light from re-entering the screen (Fig. 5), provides illumination in the central portion of the area on the ceiling.

These reflector profiles were designed with the ASAP optical design program, in-house developed code, and light source models derived from our goniophotometric facilities. We have developed reflector profiles that produce a widespread, even distribution while minimizing re-entrant flux on the microwave screen and associated efficiency losses. A volume-source, ray-trace model is subsequently run to assess fixture efficiency and illuminance distribution and to indicate any modification requirements (Fig. 6).

In the coming year we will fabricate the bi-phase reflector, install it in the prototype uplighting fixture under development by our industrial partner, and test it to assure that it meets performance specifications.

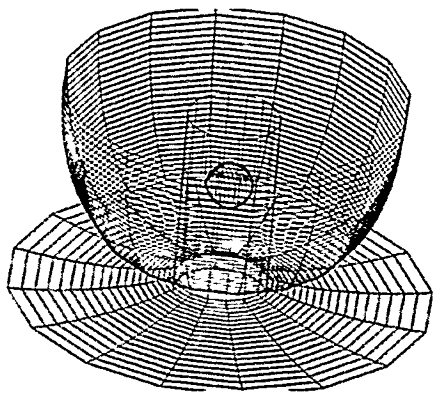

Figure 4. *Three-dimensional wireframe drawing of the bi-phase reflector designed for the high-output sulfur lamp.*

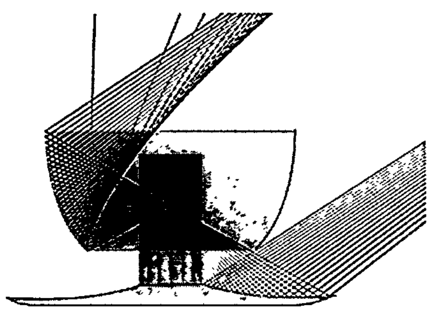

Figure 5. *Two-dimensional profile through the bi-phase reflector. The reflected ray directions, computed using the ASAP program, are directed to avoid traversing the cylindrical microwave screen around the lamp.*

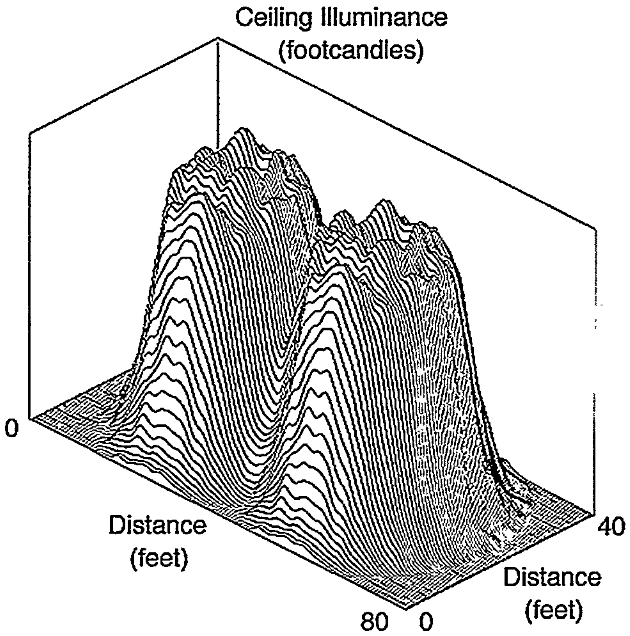

Figure 6.
Computed ceiling illuminance for two kiosk uplighters using the bi-phase reflector design. The two stages of the reflector combine to produce a wide distribution pattern on the ceiling.

Impacts of Lighting on Visual Performance and Lighting Quality

To ensure that energy-efficient lighting technologies and concepts will not negatively affect occupant productivity and comfort, the Lighting Group conducts research examining the relationship between physically measurable lighting characteristics and visual performance, comfort, and satisfaction. Current research activities are focused on (1) demonstrating the energy savings and acceptability of scotopically enhanced (i.e., blue-rich) lighting under realistic conditions and (2) developing improved models of visual performance.

Scotopic Lighting

The human visual system has evolved to include two types of photoreceptors: the cones, which are responsible for daylight-adapted color vision, and the rods, which allow for monochromatic vision at much lower adaptation levels. Because it accounts only for the response of the eye's cone photoreceptors, and not for that of the rods, conventional photometry provides an incomplete measure of lighting levels. Photometry has traditionally been based on the psychophysical response of subjects with field-of-view confined to two degrees. The region of the retina utilized in such experiments contains only cones; it does not contain rods. However, the majority of the retina is dominated by rods. Perhaps because the measurement of rod spectral response requires extremely low light levels in order to remain below cone threshold, it has been erroneously assumed that rods are inactive at normal interior light levels. Thus, any effects of rod receptors have not been included in the measurement of light quantity that is applied to lighting practice.

Our research supports the proposition that a satisfactory assessment of interior lighting must include the effects of rod activity. Specifically, we have shown that, in conditions of full field of view, pupil size is predominately controlled by the scotopic spectrum—the portion of the visual spectrum to which rods are sensitive—and that scotopic light plays an important role in brightness perception as well. Smaller pupils reduce the effects of optical aberrations (imperfections that are found in the eyes of all humans) and thus improve visual performance. Smaller pupils yield better depth of field and visual acuity for both high and low contrast tasks, while providing the additional benefits of reduced disability glare and accommodation demand.

Having demonstrated the basic effects of scotopic sensitivity at interior light levels, our efforts are now aimed at showing the applicability of scotopic lighting to general lighting practice. To improve the likelihood of bringing these new findings into lighting practice, we have outlined five goals that can be accomplished over the next three years:

1) Demonstrate the benefits of scotopically enhanced lighting in a simulated office environment (as compared with the "white" chamber used in our previous studies).

2) Design a meter, based upon the appropriate studies, that will correct the inadequacies of present photometers when used to design or evaluate interior lighting.

3) Conduct studies that demonstrate the inadequacy of present photometers for full-field viewing conditions.

4) Conduct studies that quantitatively show the spectral determinants of full-field brightness.

5) Conduct field studies that demonstrate energy savings and acceptability of scotopically enhanced lighting in real office environments.

Our efforts in FY95 were focused on completing the expansion of our test facilities. These four new facilities—a simulated office, spatial chamber, brightness test room, and refraction chamber—are described below. Each of these four rooms is designed to operate independently, allowing a full range of experimentation and evaluation to proceed concurrently. Results of the various studies will be the principal expectations for FY96.

Simulated Office. The simulated office is an 8'x12' modular room with an overall height of 10'. The wall surfaces can be automatically changed to provide four different visual patterns/colors. Lighting is provided by 24 fluorescent lamps, controlled in pairs by 12 dimmable ballasts. The lamps are mounted at a 45 degree angle from the back wall, above and behind the subject position, such that illumination falls directly on the viewed surfaces. The lamp control system offers a wide range of light levels from each lamp pair and allows for mixing of different lamp spectra. The control system allows for rapid comparisons to be made between lamps of differing spectra. Pupil size is determined by a non-invasive remote pupilometer. All pupil size and point of gaze information is electronically stored in real time, which allows off-line processing with our specialized software. A pilot study testing depth of field demonstrated the successful functioning of the equipment and allowed debugging in preparation for the major study to be undertaken in FY96.

Figure 7. *Photograph of the spatial chamber designed for determining pupil size as a function of luminance variation. Note the subject is wearing a head-mounted pupilometer, which permits researchers to determine precisely where the subject is gazing when pupil size measurements are taken.*

Spatial Chamber. Determination of pupil size as a function of luminance variation is essential in order to understand the angular averaging that sets pupil size in realistic environments. To study these effects we constructed a spatial chamber with an array of 12 individually controlled light boxes distributed through the visual field(140 degrees of azimuth angle and 80 degrees of elevation). Each lightbox subtends 10 degrees of visual angle, and provide a variable luminance ranging from 100 to 3,500 cd/m2. Ambient lighting for the spatial chamber is provided by fluorescent cove fixtures. Wall illumination can be varied from 10 to 1500 lux as measured in the vertical plane at the subject's eye. Electronic controls with a computer interface and dedicated software operate the chamber and box lighting, while pupil area is measured by a head-mounted pupilometer. A pilot study has confirmed satisfactory functioning of the chamber; the major study will take place in FY96.

Brightness Test Room. The brightness test room has been designed to demonstrate directly that rod photoreceptors contribute to brightness perception at typical interior light levels. In previous studies subjects compared the room brightness levels produced by two illuminants, perceived to be of equal color, presented sequentially. Subjects generally perceived the scotopically enhanced illumination to be brighter, even though it was 25% dimmer photopically than the scotopically deficient illumination. Although this study demonstrated a significant scotopic sensitivity to brightness perception at typical interior light levels, it did not determine the ratios of scotopic and photopic luminances that correlate with given levels of brightness perception.

To obtain a quantitative estimate we undertook the challenging task of mimicking traditional flicker photometry methods, but with full-field viewing. Our plan was to modulate two illuminants of quite different S/P ratios in counter phase at a frequency below the rod fusion frequency (6 Hz) and have subjects adjust the relative amounts of scotopic and photopic content to eliminate perceived flicker.

The challenge was to produce an electronic system for producing a controlled and high level of amplitude modulation in a variety of different fluorescent lamps with different phosphors. The control system was constructed using dimmable electronic ballasts with special DC power supplies. An eight-lamp feedback control system allows compensation for the different lamp phosphor decay rates and handles both manual and computer inputs. The test room and fixture arrangement were modified to assure the absence of shadows and uneven luminance distributions in the room corners.

The viability of the overall experimental design may be compromised by limits on the lower level of dimmability inherent in fluorescent lamps. 100% modulation depth in light output is, of course, the ideal. However, the need to maintain a fixed color with lamp combinations as they travel through their modulation cycles and the onset of striations at low light levels limit the scotopic modulation to less than 30%. This value may not be sufficiently above threshold to achieve a clear rod temporal response. Pilot subject testing will commence in early FY96 to examine the system's capability to elicit a satisfactory psychophysical response.

Refraction Chamber. The purpose of the refraction chamber is to measure individual subjects' refractive states and the presence of any opacities in their optical media. The chamber—which is six by eight feet, with an eight-foot ceiling—is outfitted with a calibrated and fully operable auto-refractometer. Subjects have been examined successfully with accuracies of 1/4 diopter for both spherical and cylindrical conditions and within 15 degrees for cylinder axis.

Discomfort Glare Research

In FY95, we also completed a study begun previously that examined how lamp spectrum affects discomfort glare for large surfaces, such as a window or a fluorescent luminaire. We were particularly interested in increases in discomfort glare that might be due to increased brightness sensitivity to scotopically enhanced lighting. The study, conducted with 12 subjects, utilized both objective and subjective assessments of discomfort glare caused by scotopically enhanced and scotopically diminished conditions. The luminance range tested was from 800 to 3700 cd/m^2 and the glare surface was a 3' x 4' rectangle. Objective data was acquired via tiny surface electrodes placed on the orbicularis ocular muscles. We have previously shown that these muscles, which surround the eye, correlate with subjective perceptions of glare. To gather subjective data, subjects were asked to mark a visual analog scale punctuated by four descriptors: perceptible, annoying, disturbing, and intolerable.

The results showed increasing levels of discomfort as the surface luminance

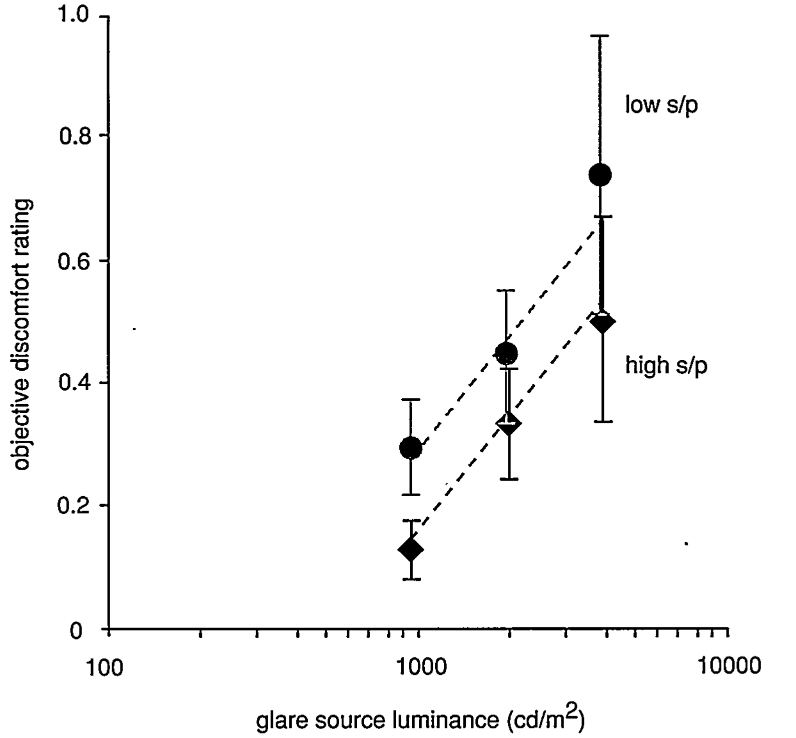

Figure 8. *Measurements on 12 subjects show that, over a broad range of luminances, the low-S/P lighting caused greater objective discomfort than high-S/P lighting. Objective discomfort was measured using the technique described in the text.*

rose, but surprisingly the scotopically deficient illumination showed a significantly higher degree of discomfort both objectively and subjectively. This result implies that a shift in user application to scotopically enhanced lighting may reduce perceived levels of discomfort associated with glare. These significant results were reported at the 1995 annual conference of the Illuminating Engineering Society of North America.

Lamp Spectrum Study

Finally, we undertook a study to identify lamp spectral power distributions that could exploit the implications of the scotopic sensitivity research. As described above, lamps with high ratios of scotopic to photopic content (high S/P ratio) are perceived as being brighter than those with lower ratios and therefore may provide better visual performance at equivalent (photopic) lumen outputs. There is currently no organized procedure for determining how to produce a commercially acceptable high-S/P lamp to take advantage of these properties. As a necessary first step in developing optimal high-S/P lamps, our FY95 goal for this project was to determine optical narrow-band phosphor mixes for fluorescent lamps that will result in (1) high S/P ratio, (2) good color rendering index (CRI), and (3) high photopic efficacy. This data can then be transferred to the lamp industry by providing them with lamp spectral power distributions that can be the basis for a new generation of lamps that can optimally exploit the energy savings potential of scotopically rich lighting.

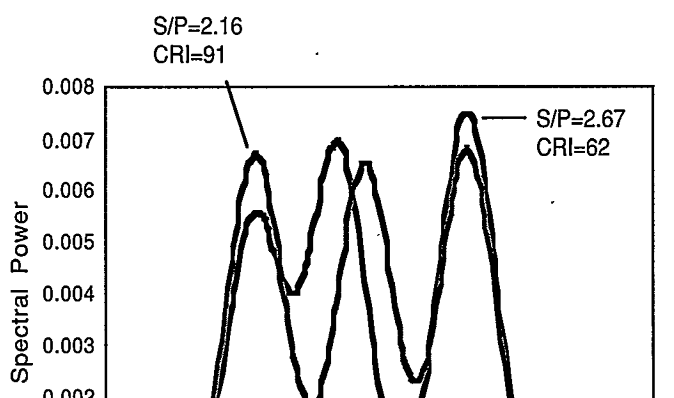

Figure 9.
Two hypothetical lamp spectral power distributions, showing computed S/P ratios and color rendition indices (CRI). Note that a minor shift in the location of the center peak causes marked change in S/P and CRI.

We developed a procedure that can semi-automatically compute metameric matches for Gaussian line-width profiles. Each simulated lamp spectral power distribution was assumed to consist of three Gaussian curves with full width at half maximum (FWHM) selected to approximate the FWHM of rare-earth fluorescent lamp phosphors. A number of the combinations have been evaluated for CRI, photopic efficacy, and S/P ratio. Our initial calculations show that the exact position of the center triphosphor curve has a pronounced effect on the resultant lamp S/P ratio and its computed CRI (Fig. 9). We have computed enough values that we have begun to define the region where high CRI, S/P, and photopic efficacy cluster together.

In FY96 we will further refine our calculations to identify precisely the optimal combinations of these three characteristics. This information will be transferred to industry in FY97 to assist them in rapidly developing new efficient lamps that take advantage of the scotopic research.

Polarized Lighting

For a number of years the possibility of conserving energy through the use of polarized light has been controversial. Our goal in FY95 was to determine whether such energy savings are possible and to make our findings known to regulatory bodies and to the lighting community as a whole.

We continued our participation in the task force appointed by the Illuminating Engineering Society of North America (IESNA) to prepare a draft technical memorandum on the complex subject of polarized lighting. LBNL was instrumental in rejecting a previous draft as it contained a number of inaccuracies. Many of the revisions being made to the new draft are the results of criticisms put forth by the LBNL Lighting Group. In addition, LBNL and Pennsylvania State University prepared a joint paper summarizing many of the important issues surrounding polarized lighting. The paper was presented at the IES Annual Conference in 1995 during one of the more lively technical sessions.

Although our theoretical work in evaluating polarized lighting has led to interesting results, various governmental organizations have shown interest in pursuing field tests on lighting fixtures with polarized panels to determine whether polarized lighting can reduce lighting loads while maintaining visual performance and user satisfaction in realistic building environments. We are exploring the possibility of embarking on such a study in FY96 in partnership with the General Services Administration (GSA), assuming a suitable site can be found.

Visual Performance Modeling

The IES needs a visual performance model for its next iteration of light level recommendations. Our goal was to develop a self-consistent generalizable model for consideration by the IES. These recommendations are used by many government bodies as the basis for energy standards, thus the use of a more accurate model would be reflected in more cost-effective energy and light level standards.

We generalized the Visibility Level (VL) model that we had previously developed to handle a reaction time task. The resulting model is self-consistent and accurate. This work was presented at the IES annual conference and will appear in a forthcoming issue of the Journal of the IES. As a separate effort, we performed a review of the other available visual performance models. This review and work on the LBNL model was presented at an IES forum reviewing all of the available models.

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. 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.

Our building applications research currently focuses on three topic areas: (1) advanced lighting controls, (2) energy-efficient residential lighting, and (3) advanced applications of the RADIANCE computer simulation program.

Advanced Lighting Controls

As the cost of dimmable electronic ballasts drops below $30 per unit, advanced lighting controls that exploit dimming ballasts represent the next significant cost-effective improvement in lighting system efficiency above that obtainable with non-dimming standard electronic ballasts and rare-earth-phosphored T-8 fluorescent lamps. In 1995, we partnered with the General Services Administration (GSA) Region 9 and Pacific Gas & Electric Company to set up an advanced lighting controls testbed on three floors of the Philip Burton Building in San Francisco. As this building was undergoing a massive refurbishment and upgrading of all major energy subsystems, it proved the perfect venue to demonstrate the cost-effectiveness of different lighting control strategies.

With funding through the Federal Energy Management Program's New Technology Demonstration Program, LBNL designed an advanced lighting control testbed at this highly visible site. The objective of this work is to compare the energy savings and cost-effectiveness of different bundles of lighting control strategies against a base-case floor in which only minimal controls were installed. In addition, since this building will be equipped with a BACnet-compatible energy management system in FY96, a secondary objective was to explore the operational improvements possible by integrating the lighting controls system with the building-wide EMS system.

In 1995, the branch circuit wiring serving the overhead lighting on the 3rd, 4th, and 5th floors of the building was modified to allow control and monitoring of appropriate groups of fixtures. Controls equipment from seven industrial partners was selected for installation and testing at this unique site. At the heart of the system are distributed, intelligent controllers that allow precise control of logical zones of lighting fixtures. These controllers, which are strategically

Figure 10. *Dimming system on the 3rd floor of the Philip Burton Building undergoing static test during commissioning. The light patterns on the rear wall show that the row of lights nearest the windows are heavily dimmed.*

located throughout the three floors and connected to photo-sensors, occupant sensors, and switches, exchange data over a twisted pair, forming an elaborate information network. The selected dimming electronic ballasts were installed along with the associated occupant sensors, photocells, and relays. The intelligent distributed controllers and associated networking and control wiring were also installed.

The data collected at the site will not only help GSA to improve the operation of the building lighting systems it manages, but will also help it to better serve its clients' lighting needs while reducing operating costs. Detailed monitoring of lighting energy down to the individual room level will yield a wealth of information for lighting controls manufacturers, utilities, and lighting end-users.

In FY96, we will commission the lighting control system and execute the experimental research plan. We also intend to host a ribbon-cutting ceremony and tour at the Philip Burton Building to coincide with Lightfair, which is being held in San Francisco in May, 1996.

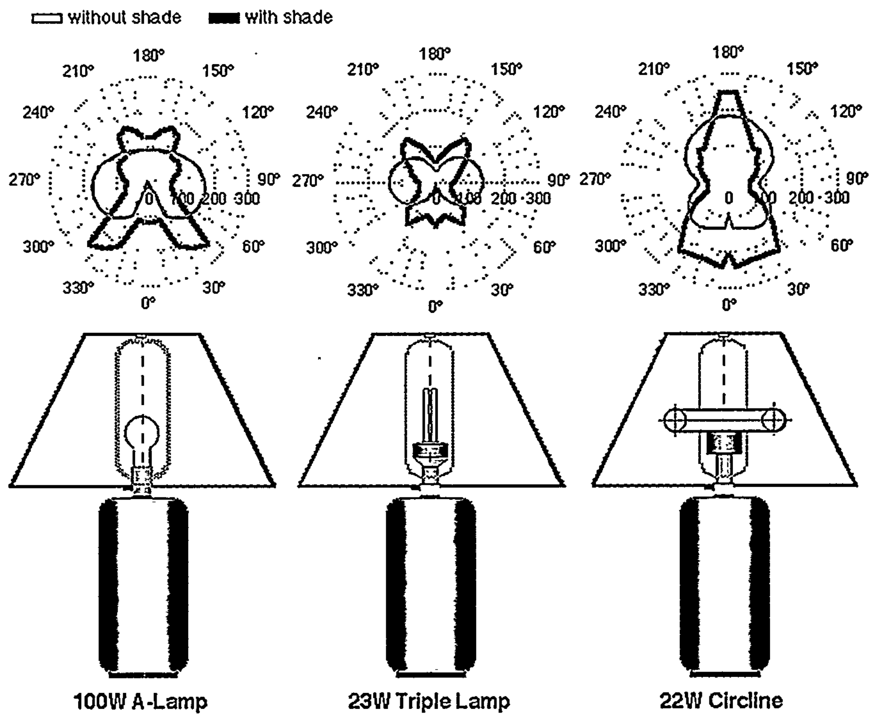

Figure 11. *Candlepower distributions with and without lampshades for a 100-watt incandescent A-lamp, a 23-watt triple-tube CFL, and a 22-watt Circline™ fluorescent lamp, with fixture efficiencies of 83.4%, 81.9%, and 87.2% respectively.*

Residential Lighting

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

Our residential lighting research activities in FY95 focused on (1) measuring how the specific choice of compact fluorescent lamp affects the lumen distribution and perceived brightness from conventional residential fixtures, (2) assisting in the design of a showcase home for demonstrating current and developing lighting technologies that offer energy savings using compact fluorescent lighting and advanced lighting fixture technologies for residential applications, and (3) performing an analysis and market assessment of the residential lighting market.

Advanced Residential Fixtures

When operated in fixtures originally designed for A-lamps, CFLs with equal total lumen packages can appear dimmer due to differences in light distribution. By conducting goniophotometric studies on a broad range of residential fixtures, we sought to identify which CFL lamps best mimicked the light distribution characteristics of the incandescent lamp.

Our studies in FY94 showed that, when used in fixtures originally designed for standard incandescent lamps, CFL lamp position and geometry had a significant effect on total fixture output and light distribution. In FY95 we focused our attention on the effect of specific source type on the distribution characteristics from standard table lamps. The candlepower plots in Figure 11 (gray lines) show the light intensity at all angles for a 100-watt incandescent A-lamp, a 23-watt triple-tube CFL, and a 22-watt Circline™ fluorescent lamp (measured wattages 103.2W, 19.0W and 22.8W respectively). These figures illustrate how different lamp sources can yield widely different distributions.

The black lines in Figure 11 show how the bare-lamp distributions are affected by the addition of the table lamp shade, which in this case was white and fluted. For all lamps, the shade blocks flux in the 50°-140° range and redirects it into the 0°-50° and 140°-180° zones. This tends to block the glare caused by directly viewing the shade and redirects flux upward for indirect lighting (140°-180°) and downward for task lighting (0°-50°). Since shade absorption is roughly inversely proportional to fixture efficiency, we would expect that the more flux a lamp sends into the shade zone, the less total flux leaves the fixture. Consequently, the Circline™ lamp retains 87.2% of its total light output when the shade is added, while the A-lamp drops to 83.4%, and the triple lamp falls to 81.9%.

The CFL fixture with the relatively small twin-tube CFL sources only experiences a 20.0% loss in efficacy with the addition of the diffuser (as compared to 24.3% for the A-Lamp and 34.4% for the Circline™). This horizontal CFL fixture achieves the highest fixture efficiency by having a favorable source/fixture size ratio and by focusing its light vertically.

For this type of table lamp and shade, our results indicate that a predominately horizontally oriented source (in this case a Circline™) outperforms both a vertically oriented, standard incandescent lamp and a triple-tube CFL. On the other hand, other studies conducted at our laboratory and reported in a technical paper in the 1995 IESNA Annual Conference showed that CFL sources that direct flux vertically were found to outperform both A-Lamps and Circline™ sources in kitchen ceiling fixtures. These studies indicate two important findings: (1) the ideal source for a fixture is dependent on the fixture's geometry and the application of the luminaire, and (2) dedicated fixtures that are engineered for the flux of the CFL rather than the typical A-Lamp have the possibility of significantly increasing fixture efficiency and light output.

Ongoing studies with the fixture industry continue to develop new fixture designs that optimize the focused distributions of CFLs. Currently we are working with industry partners to retool table lamps to be "dedicated" CFL fixtures—fixtures that will accept only pin-type CFLs. Analysis of goniometric data from these tilt experiments, in combination with data from a wide matrix of standard vertical, horizontal, and globe CFLs operating in table lamps, will allow us to describe optimal operating characteristics and optimal sources. Thus these new fixtures will be optically optimized and will prevent "snapback," or incandescent reversion.

DOE Energy Demonstration House-Atlanta

To accelerate the deployment of energy-efficient lighting technologies into the residential sector we are assisting in the design and construction of a showcase home where current and developing lighting technologies will be demonstrated. The ECOS House is being constructed in Atlanta and will showcase best residential lighting practice using cutting-edge lighting technologies.

We completed the overall lighting layout and design using a variety of fixture types that exemplify available and emerging technologies, some of which are the result of ongoing technology partnerships between industry and LBNL's Lighting Program. The effort has involved the identification and acquisition of systems from the lamp and fixture industry and represents contributions and participation from a large cross section of American manufacturers. We have been working closely with the industry to develop recommendations for specific product systems and appropriate applications of the compact fluorescent lamp. In FY96 the house and its lighting system will be completed in time for the 1996 Olympic Games in Atlanta.

Residential Lighting Market Assessment

In 1995, we conducted an assessment of the residential lighting market under contract to the Environmental Protection Agency (EPA). In developing the study we drew not only on our own resources, but also a subcontract with Rising Sun Enterprises to provide an analysis of the residential lighting market structure, including a detailed analysis of distribution channels and how this might be affected by increased penetration of CFLs. We completed two reports on the topic and prepared papers for submittal to the IESNA and the American Council for an Energy-Efficient Economy (ACEEE) Summer Study.

We also conducted an important two-day workshop at LBNL in January 1995, gathering together stakeholders in improved residential lighting efficiency to strategize on how best to move the residential market to dedicated compact fluorescent fixtures. LBNL both originated and championed the approach of dedicated compact fluorescent fixtures, in which the fixture is supplied with a CFL pin-based socket and integral ballast, such that the CFL can only be replaced with another CFL, not an incandescent lamp. The workshop was attended by over a dozen fixture manufacturers, numerous utility representatives, environmental advocates, and other stakeholders.

Computer Imaging

The objectives for the computer imaging project this year were (1) to demonstrate the use of advanced computer technology for improving lighting quality and energy-efficient design, and (2) to continue the transfer and dissemination of the RADIANCE software package into the private sector.

In FY95 we started a major new project funded by the Federal Aviation Administration to study lighting design and visibility in air traffic control towers. In Phase I of this contract we are demonstrating the capabilities of lighting simulation and computer graphics for improving the safety and comfort of air traffic control towers. As part of this contract, we have developed a computer model of the San Francisco tower, which we will render under different lighting and daylight conditions to simulate the creative use of fixtures and shades to control visual comfort and improve visibility for air traffic controllers. Next year we hope to continue work under Phase II of the FAA contract, which will focus on developing actual design tools and methods for air traffic control towers.

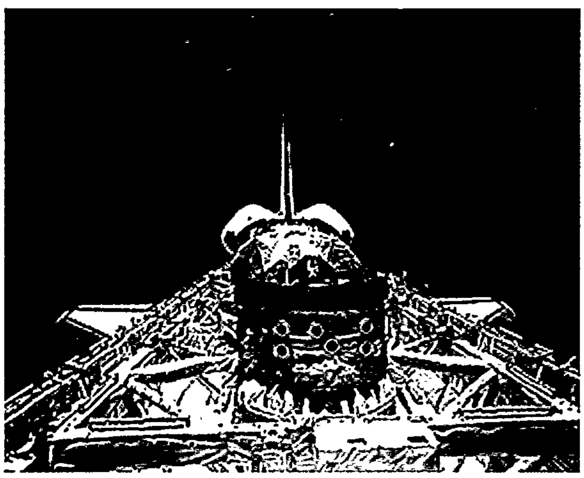

Figure 12. *Shuttle photograph.*

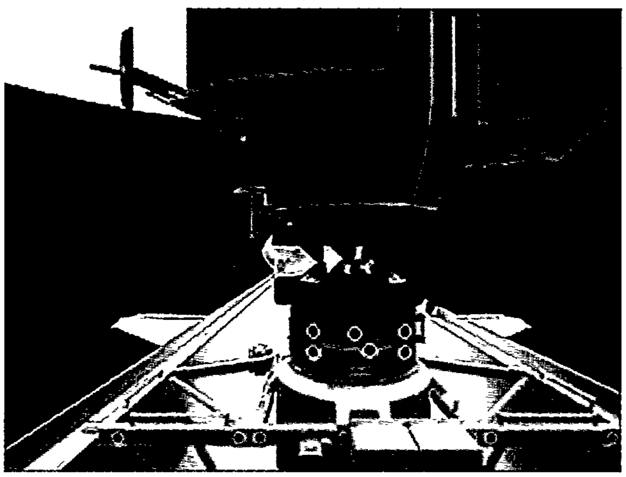

Figure 13. *RADIANCE simulation.*

Another significant accomplishment for this year was the initiation of distribution of the ADELINE software package for lighting design on IBM PC-compatible computers. This package contains an MS-DOS port of RADIANCE, and is therefore of interest to designers who have no access to UNIX workstations. In addition, we have set up a user discussion group (mailing list) and a world wide web site for the software: http://radsite.lbl.gov/adeline/HOME.html.

In general, the popularity of RADIANCE continues to rise as users from different fields recognize the software's unique ability to produce radiometrically accurate predictions and renderings of realistic environments. Figure 12 shows a photograph of a NASA space shuttle fitted with a docking platform for the Russian Mir space station. Figure 13 shows a RADIANCE simulation of the shuttle during the docking procedure. This simulation was used to check the software for the Canadian Space Agency computer vision system designed to control some of the delicate maneuvering required to bring the two spacecraft together.

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Building Energy Simulation

Investigators

F.C. Winkelmann
B.E. Birdsall
W.F. Buhl
W.L. Carroll
K.L. Ellington
A.E. Erdem
R.J. Hitchcock
R. Meldem
J.M. Nataf

Our simulation research effort develops accurate, well-validated computer programs to assist in the design of energy-efficient and cost-effective buildings. This work includes development and maintenance of current-generation energy analysis programs—DOE-2 and PowerDOE, an easy-to-use version of DOE-2—and development of an advanced building performance calculation tool—the Simulation Problem Analysis and Research Kernel (SPARK).

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. 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.

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

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.

PowerDOE and DOE-2

The PowerDOE program is under joint development by the LBNL Simulation Research Group (SRG) and James J. Hirsch & Associates (JJH), Regional Economic Research (RER), and Southern Company Services (SCS), 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 architects and engineers, 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.

Features of the PowerDOE interface include on-line help, 3-D building view, building component libraries (walls, windows, lighting systems, operation schedules, HVAC equipment, etc.), dynamic defaults, "on-the-fly" equipment sizing, automated parametric runs, and graphical results display. PowerDOE will also be linked to the Building Design Advisor (described elsewhere in this report), which will simplify the use of PowerDOE in conceptual design. Figure 1 is a sample PowerDOE screen that shows a rotatable 3-D view of the building as input by the user.

In 1995 RER completed work on an alpha version of the PowerDOE user interface. SCS and RER finished an alpha version of the PowerDOE results display module, which allows graphical display of the PowerDOE calculations and creation of customized tabular reports. SRG and JJH modified the DOE-2 input processor to allow it to work interactively with the new user interface and began work on integrating the Systems and Plant programs based on hot water, chilled water, and condenser water loops to provide more accurate simulation of HVAC equipment. In addition, SRG, JJH, and EMPA (Switzerland) expanded the simulation capabilities of the PowerDOE/DOE-2 engine by adding new calculation features, including:

- mean radiant room temperature calculation
- ground source heat pumps
- duct and piping losses
- hot and chilled water reset
- exhaust fan scheduling
- primary and secondary pumping in Systems and Plant
- residential space heating by DHW heater
- residential hydronic heating
- cooling towers with heat exchangers
- dual-fan, dual-duct, variable-air-volume system
- cool recovery from relief air
- residential system with options including evaporative cooling, forced ventilation, natural ventilation, and air-to-air heat recovery.

In collaboration with the EMPA Building Physics group and University of Karlsruhe, work began on a DOE-2 solar/thermal model of window blinds, which can have a large impact on cooling loads.

A beta version of PowerDOE will be released in mid-FY96 for outside testing. The first general release of PowerDOE and of DOE-2.2, its mainframe equivalent, is expected in late FY96. PowerDOE will also become a key component of the Building Design Advisor, described in the Advanced Building Systems section of this report.

Merger of BLAST and DOE-2

Preliminary planning began in 1995 to combine the BLAST and DOE-2 building energy analysis programs. BLAST was developed at the University of Illinois for the Department of Defense's Construction Engineering Research Laboratory. BLAST and DOE-2 are similar programs, but each has important calculation features not found in the other. The combined program, scheduled for release at the end of 1997, will become the US national building energy model.

Simulation Problem Analysis and Research Kernel (SPARK)

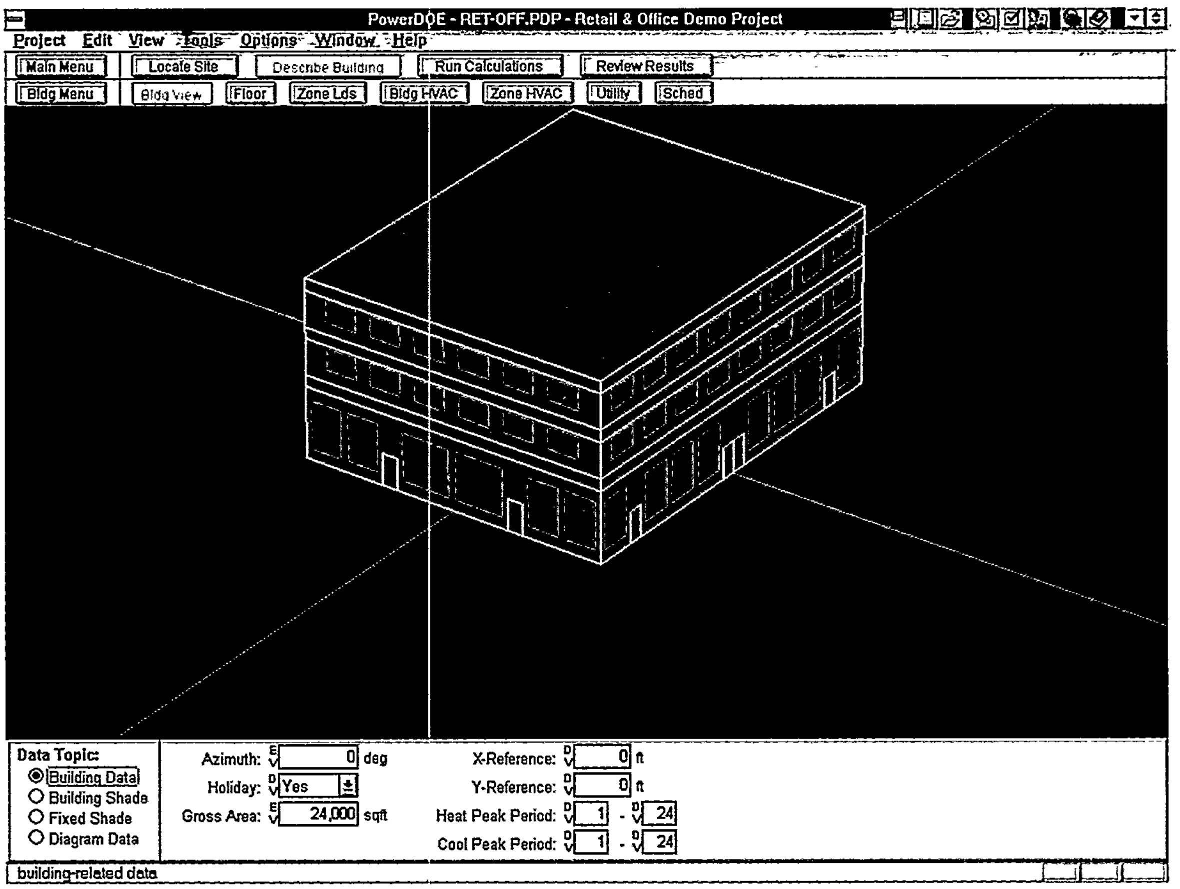
SPARK allows users to quickly build models of complex physical systems by linking calculation modules from a library. SPARK is aimed at simulation experts who need to create detailed models of building components and systems to aid in research and analysis of innovative technologies. SPARK is being developed by SRG, with assistance from California State University Fullerton (CSUF) and Chapman University.

In 1995, work continued on the SPARK graphical editor with which users connect building components into networks that represent building systems. CSUF completed development of 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 Ecole des Ponts et Chaussées in France continued work on an improved translator to SPARK from Neutral Model Format (a new, standard way of expressing component models) and completed work on "zonal" modeling methods for SPARK. SRG, CSUF, and Chapman University began work on speeding up the SPARK calculation and improving the program's ability to handle difficult simulation problems.

In 1996 a beta version of SPARK will be released for outside testing, and work will begin on linking SPARK to PowerDOE for simulation of complex HVAC systems and controls.

SPARK is also being used as the engine in a new tool development effort whose goal is assuring optimal performance of the building over its life cycle. This prototype performance evaluation and tracking tool is described in the Advanced Building Systems section of this report.

Figure 1. *PowerDOE screen showing 3-D view of building being modeled.*



Alternatives to Compressor Cooling

DOE-2 predictions were compared with measurements in the Pala test houses near San Diego. This work is part of the California Institute for Energy Efficiency "Alternatives to Compressor Cooling in California Transition Zones" project in which DOE-2 is being used for parametric analysis of cooling strategies that reduce peak electrical power in hot, dry climates. To establish the validity of DOE-2 for this kind of analysis, the program was compared with room air temperature measurements in a "low-mass" house with conventional insulated stud wall construction and a "high-mass" house with insulated concrete walls. To test different aspects of the DOE-2 calculation, four different unconditioned thermal configurations of these houses were considered: unshaded windows, shaded windows, white exterior surfaces, and forced night ventilation. In all cases DOE-2 agreed well with the air temperature measurements, with a mean deviation between simulation and measurement ranging from 0.2 to 1.0°K depending on configuration and type of house. A sample comparison is shown in Figure 2 for night ventilative cooling, one of the alternative cooling strategies. Good agreement was also seen between DOE-2 and inside surface temperature measurements.

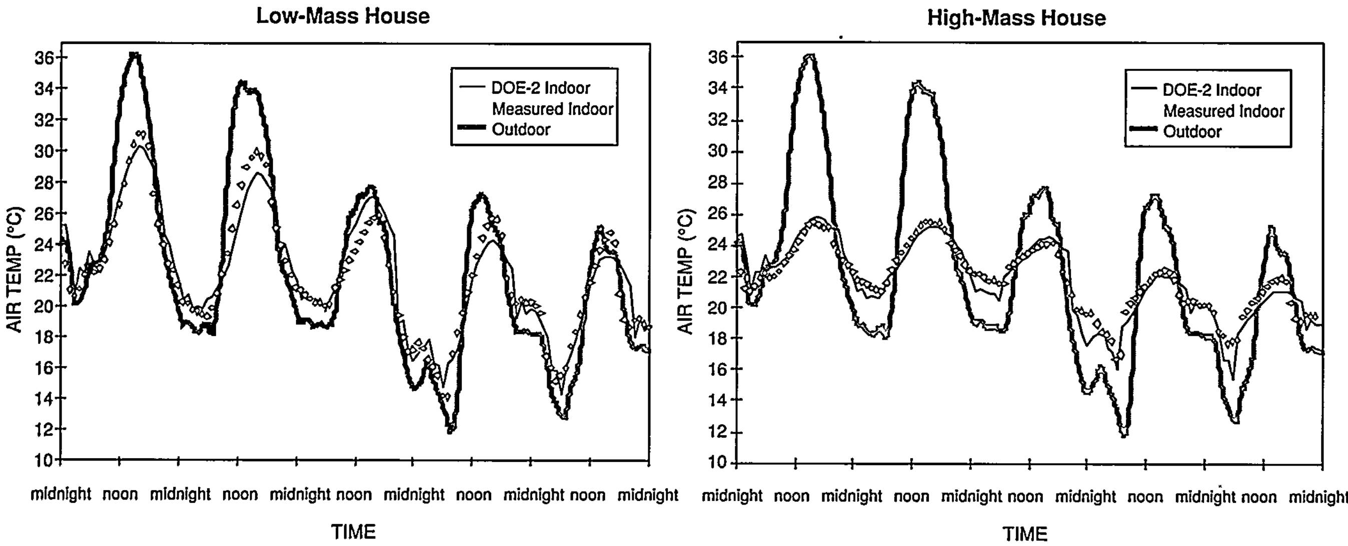


Figure 2. *DOE-2 vs. measurement for Pala, California low-mass house (left) and high-mass house (right) for Configuration 4: white outside color, shaded windows, and night ventilation, for a five-day period in September, 1994.*

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, Energy-10, that provides an interactive environment in which to explore the energy impacts of various building design decisions. LBNL is providing technical support in the development of this design tool, primarily in the area of daylighting.

The design tool is being developed to operate on an IBM-compatible PC under the MS-DOS and Windows operating system. This tool is meant to go well beyond the type of energy evaluation programs which are currently available. Innovative features include the initial generation of a complete building simulation model from minimal input data, intuitive access to and modification of the design details of the building, automated specification of energy-efficient strategies for improving the overall performance of a building, and a variety of criteria for evaluating the relative performance of alternative building designs.

Current LBNL support efforts, which will continue on into 1996, relate to the building design issues of daylighting and electric lighting. In prior fiscal year efforts we provided algorithms for evaluating simple daylighting energy-efficient strategies (EES) that can be applied to building designs (vertical glazing and skylights). These algorithms were implemented as a Windows dynamic link library for easy integration with the other modules of the tool. We also designed and implemented the user interface dialogs for describing the daylighting aspects of a building.

During FY95, we developed an approach for automatically specifying building description modifications that add daylighting features to a reference building. This approach has now been implemented with a user interface (Figure 3) and integrated into the July 1995 beta-version of Energy-10. Feedback from beta testers has resulted in modifications to correct identified problems and other updates to the underlying code. We look forward to the initial release of Energy-10 Version 1.0 during this calendar year.

During FY96 we will enhance the capabilities of the daylighting analysis engine by incorporating algorithms for evaluating complex fenestration system types such as light shelves and geometrically complex roof monitors. We will also develop algorithms for the description and evaluation 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.

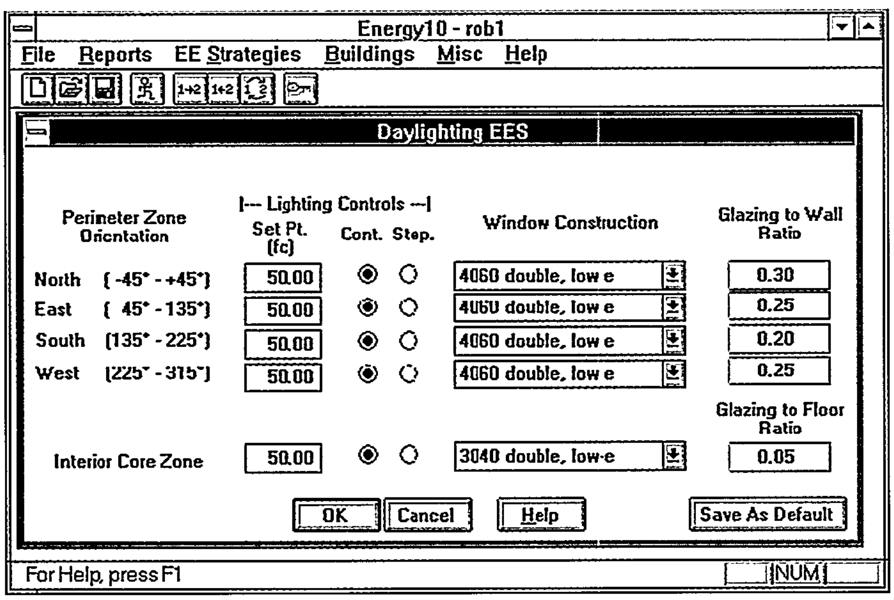


Figure 3. *User interface for specifying characteristics of automated daylighting EES.*

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Advanced Building Systems

The Advanced Building Systems activity has grown from a realization that changes in the building sector often require an R&D focus that transcends individual building technologies, a narrow focus on energy efficiency, or even a single point in the life cycle of a building. We have increasingly turned our attention and perspective to integrated building systems where "integration" occurs between building technologies, across performance parameters, among the building professionals, and over the building life cycle.

The goal of one of our commercial building projects is to develop a series of integrated envelope/lighting systems where the building facade has been developed in conjunction with the lighting/daylighting systems to minimize cooling and lighting energy use and to maximize comfort, productivity, and occupant satisfaction. Although these latter issues are more difficult to assess, they can be critical factors in the successful adoption of new design strategies. Using a similar philosophy, we are developing an integrated window system for residential applications that combines multiple functions (e.g., high tech frameless glazings, movable insulation, solar control) in a single manufactured package which substitutes engineered wood products for conventional framing. In our development of a new type of advanced insulation we are looking beyond the improved insulating value to the overall design of an appliance in which the appliance shell plus insulation is optimized for thermal performance and for ultimate recycling.

As we examined the obstacles to widespread implementation of energy efficiency strategies in buildings, we identified the problem of information management and lack of cost-effective tools designed to meet the needs of different professions throughout the building life cycle. We are engaged in three interrelated activities to address this need.

The first activity is the Building Design Advisor, a new concept for a design tool that is focused on meeting the needs of designers early in the design process. This new tool is built around a new, integrated building data model and a versatile user interface with multimedia capabilities that allows the user access to many different information resources and multiple simulation engines. We are also exploring the feasibility of using BDA as a platform to integrate life-cycle environmental impact information into design decisions, thus making it useful in the design of a new generation of "green buildings."

The second activity is the Building Performance Assurance project, whose goal is the development of an expanded set of tools, the Building Life-Cycle Information Systems, that assist in assuring energy efficiency, comfort, and productivity over the life cycle of the building. This activity was initiated as an internally funded exploratory development effort using staff from all three Energy and Environment Division programs in the Center for Building Science and from the Information and Computing Sciences Division. We are developing a design intent tool that captures and archives key design performance requirements and rationales for design decisions and makes them available for inspection and updating throughout the life cycle. We have created a prototype commissioning tool that helps manage the process of commissioning chillers, establishes data links to the building energy management system, and updates the building design model. Our new performance tracking tools incorporate a chiller emulator that allows continuous comparisons of actual performance to benchmark data and exploration of the impact of alternative control strategies.

These tool development efforts complement our third activity, participation in the Industry Alliance for Interoperability (IAI), a non-profit industry group whose goal is to bring software interoperability to architecture, engineering, construction, and facilities management. IAI is developing Industry Foundation Classes, a software library of commonly defined "objects" that can be shared across disciplines by diverse software applications throughout the building life cycle. These should facilitate the sharing of information between energy tools and the wide range of other software tools used by the building community.

Integrated Envelope and Lighting Technologies for Commercial Buildings

S.E. Selkowitz, L. Beltrán, D. DiBartolomeo, J.H. Klems, E.S. Lee, and F. Rubinstein

The practice of window and lighting systems design in commercial buildings is typically a non-interactive process. Architects who are responsible for the shell of the building rarely explore the full integration of the solar heat and daylight-admitting window system with their lighting and mechanical system consultants. Survey data reveals the shortcomings of the resulting built product in terms of energy efficiency and comfort. For example, 55-65% of office workers in the Pacific Northwest had complaints regarding thermal or visual discomfort due to the envelope design, despite the provision of space conditioning.

Energy-efficient electric lighting, glazing, and daylighting control technologies have the potential to significantly reduce the peak demand and total electricity use of commercial buildings if these technologies are designed as integrated systems and supported by appropriate design tools. Since lighting and cooling in commercial buildings constitute the largest portion of peak electrical demand, promotion of such integrated systems could become a cost-effective option for owners and utilities. As an additional significant benefit, although difficult to quantify, these integrated systems can also provide better, more comfortable work environments for occupants and higher value space for building owners.

Since 1991, this multi-phase R&D program has focused on bringing together viable envelope, daylighting, and lighting solutions from traditionally disparate trades. This research is primarily supported by the California Institute for Energy Efficiency, a consortium of California utilities and agencies. As such, the approach differs substantially from much conventional research in that it cuts across traditional areas of basic research but also seeks to derive near-term practical solutions for commercial buildings. Initial prototype designs derived from R&D studies have been developed to meet more complex and realistic environmental and building conditions as the project has progressed; e.g., field tests have supplemented computer simulations, and in-situ building installations have followed physical scale model testing.

Two systems have been developed for cooling-load dominated commercial buildings: dynamic systems and advanced optical systems. Dynamic systems, such as automated venetian blinds (precursors to switchable electrochromic glazings) with a dimmable lighting system, actively balance daylighting and thermal heat gains while addressing comfort issues. Advanced optical systems, such as light shelves and light pipes, passively extend the depth of daylighting penetration to approximately 10 m beyond a conventional sidelight window. Daylight is distributed more uniformly to achieve a higher level of visual comfort.

Dynamic Systems. DOE-2 simulations of an automated venetian blind with daylighting controls indicate that 16-26% total energy savings can be attained with the blind system compared to an un-

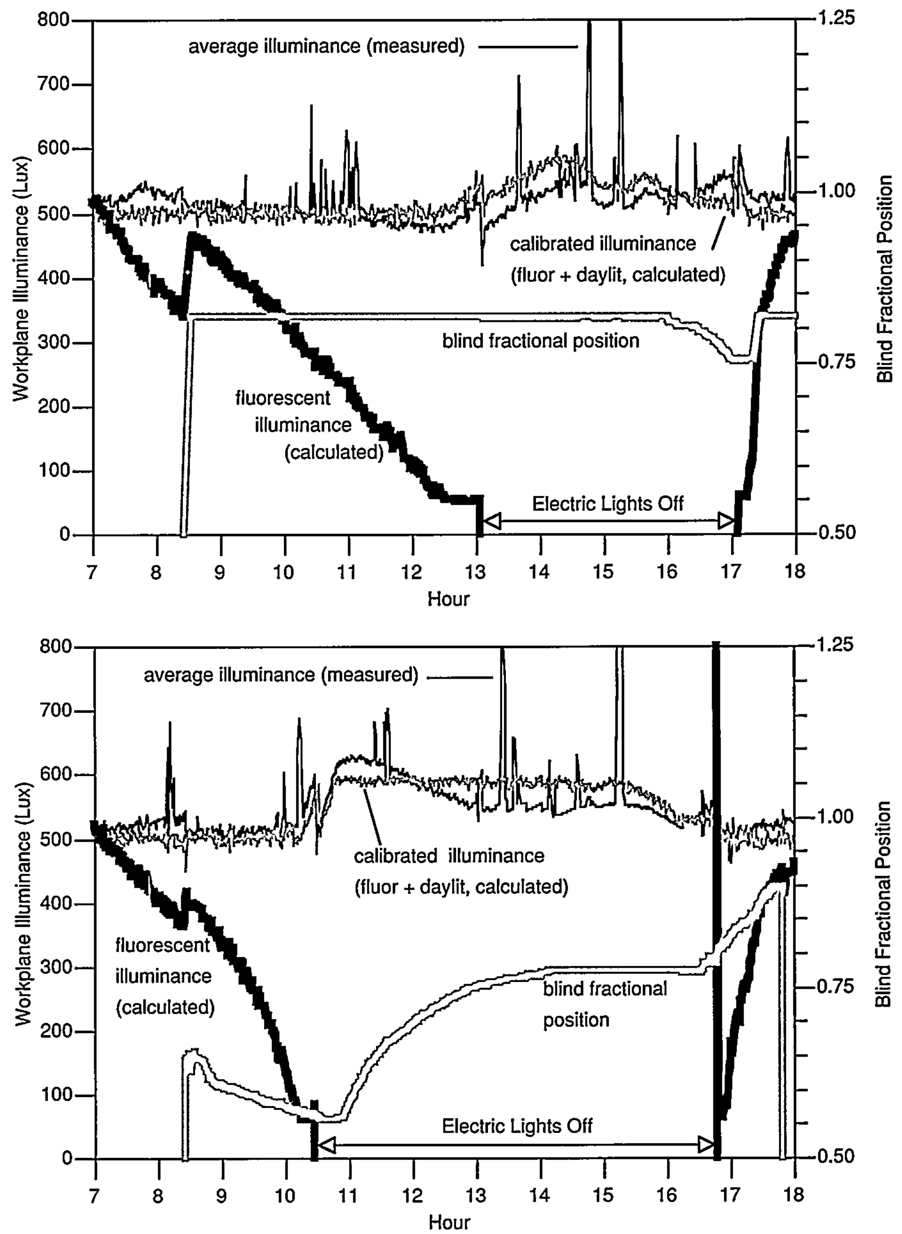

Figure 1. *Average workplane illuminance, fluorescent lighting workplane illuminance, and blind fractional position for a clear day in February. The fixed blinds (top) were held at a near horizontal position until late afternoon, when the position was adjusted to a slightly more open position. The dynamic blinds (bottom) were controlled to block direct sun and meet the design workplane illuminance level using the ceiling mounted photosensor for control.*

shaded low-E insulated window system in Los Angeles. These savings have been corroborated with outdoor field test data gathered this past year in the LBNL 1:3 reduced-scale office module. If the blinds are operated to block direct sun and optimize interior daylight levels, lighting energy savings of ~34% (winter) and 42-52% (summer) are achieved on clear sunny days compared to a fixed blind system for south to southwest-facing windows. These savings were accomplished using as-is or modified commercial lighting products or prototype solutions (Fig. 1).

On the cooling side of the equation, results from the Mobile Window Thermal Test Facility (MoWiTT) indicate that the blind system with a less-than-optimal control algorithm was still more than twice as effective at reducing solar heat gains under clear sky conditions as a static, unshaded bronze glazing, while providing approximately the same level of useful daylight.

Continuing to resolve full-scale implementation details, quantifying energy performance, and addressing other practical cost and occupant issues will be critical to achieve full-scale commercialization of these systems. Office space was acquired for full-scale measurement and verification at the Oakland Federal Building in California, in cooperation with Pacific Gas and Electric and the U.S.A. General Services Administration. The testbed will be operational in March 1996 after which a detailed series of unoccupied and occupied testing will take place.

Advanced Optical Systems. Using measured bi-directional illuminance data in combination with mathematical algorithms, the daylight output of several advanced optical technologies was shown to be significantly more effective at distributing useful daylight than conventional technologies. For example, the south-facing lightshelf produced daylight illuminance levels that were two to four times greater than a conventional flat light shelf at a depth of 8.38 m from the window wall, during clear sky conditions from 9:30-14:30, February to October. Cooling loads were of minor concern since the daylighting aperture was 40% smaller in area than the base-case light shelf.

A prototype skylight system, a derivative of the light-redirecting concepts of the basic perimeter daylighting systems, was demonstrated at full-scale at the Palm Springs Chamber of Commerce, in collaboration with Southern California Edison (Fig. 2).

The design was highly effective at distributing daylight throughout the entire room cavity and produced a uniform workplane illuminance throughout a partly cloudy winter day. Practical experience gained working with the contractor, 3M, and SCE led to further refinement of the underlying conceptual designs and a greater understanding of the practical issues surrounding fabrication and construction. Occupant feedback has been very positive with respect to the quantity and quality of daylight delivered by the system.

Figure 2. *Palm Springs Chamber of Commerce skylight system.*

Design Tools. The demonstration in Palm Springs not only facilitated the development of the advanced optical skylight system, it also incorporated other state-of-the-art window, lighting, and cooling systems. The integrated approach was also used on several Federal buildings in cooperation with the Federal Energy Management Program. Findings will be compiled for use by Energy Managers throughout the country.

A twelve-section daylighting design guideline has been compiled that provides a quick reference to integrated design principals and practices. The approach has been tailored to the architectural design process, from programming through building occupancy, in a series of concise how-to bullets and supporting reference material. In FY96, we hope to begin new work on computer-based tools by initiating development of a design advice module to work with LBNL's Building Design Advisor (BDA).

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Integrated Window Systems

D. Arasteh and P. LaBerge

Our research activities in the field of high-performance windows (see Windows & Daylighting - Superwindows) led us to conclude that even by using high-performance insulating glass units, low-conductivity frames, and warm-edge spacers, there are still untapped sources for improving energy-efficiency in the design and use of residential windows. While such high-performance windows are a dramatic improvement over conventional units, they do not reduce conductive losses through wall framing around the window, nor do they offer guarantees against excessive wall/window infiltration or adapt to the daily and seasonal potentials for night and summer shading.

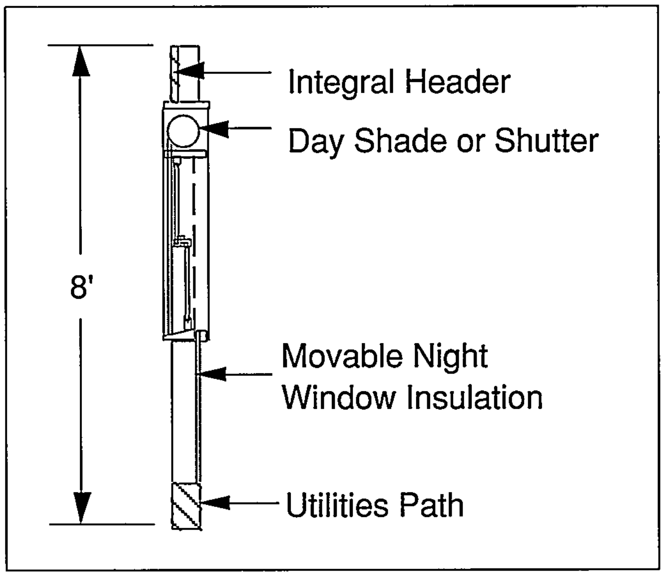
To meet this need, we have been working on the design, development, and prototyping of Integrated Window Systems (IWS) since 1993. Integrated Window Systems are a form of panelized construction where the wall panel includes an operable or fixed window sash, recessed night insulation, integral solar shading, and is built in a factory setting in order to minimize thermal short circuits and infiltration at joints. IWSs can be built in modular lengths to facilitate their installation with conventional wood-frame stick construction or other forms of panelized construction.

Our prototype IWS uses the wall framing to anchor the window sash, thereby doing away with the window frame (Fig. 3). The use of supporting lumber (jack studs, headers) is also minimized. Thin, high-performance night insulation is installed in the outer inch of the cavity below the window; when deployed, the window's insulation doubles to approximately R12 while the wall remains well insulated. A retractable solar shade screen, installed above the window in space freed up by the replacement of the conventional header with a compact engineered header, can be operated either manually or by an electric motor.

During FY95 we refined our prototype design and built the first prototype IWS. Laboratory IR thermography on the prototype IWS and a conventional wall section confirmed the energy savings potentials of the IWS prototype. As part of the prototype construction process, we developed contacts with component manufacturers and with window manufacturers who might market IWSs. The completed prototype was displayed and well received at the Pacific Coast Builders Conference; comments from builders are being addressed in the development of new prototypes.

In FY96 we will work with builders to demonstrate an IWS or selected IWS themes in prototype energy-efficient modular homes. In future years we plan to work with manufacturers and builders to outfit an entire house with prototype IWSs and to monitor performance.

Figure 3. *Integrated window systems combine several energy efficient features and resource-efficient construction practices into a modularized residential window product.*



Gas-Filled Panel Insulation

D. Arasteh, C. Goudey, B. Griffith, and D. Turler

Better thermal insulation will reduce energy flow through the shells of buildings and appliances. We have developed a fundamentally new, opaque insulation system known as Gas-Filled Panels that can achieve R12 per inch or higher, more than twice the insulating value of the best traditional insulation materials. Our objective is to perform basic research and development on this new technology to facilitate its adoption by industry, so that a new generation of products can provide increased thermal efficiency for buildings and appliances.

We realized in 1989 that we could design a high-performance opaque insulation by applying the same concepts we developed for use in high-performance windows. The result would be a more efficient and cost-effective insulation product. With financial support from CIEE and DOE, in 1990 we began developing and testing these opaque panels composed of thin polymer films with low-E surfaces and low-conductivity gases. The main uses of these Gas-Filled Panels (GFPs) include refrigerator/freezer appliances and the cavities in building walls and roofs. The new insulation system delivers higher levels of insulation per unit thickness, which allows for more energy-efficient design but avoids costly changes in shell thickness dimensions.

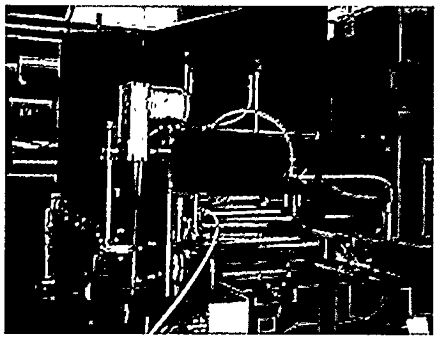


Figure 4. *This gas-filled-panel fabrication machine was assembled in 1995 to allow faster and better prototyping of insulation panels.*

Last year's efforts to develop advanced refrigerator doors proved successful this year through measured energy savings that were conducted in cooperation with Oak Ridge National Laboratory. They used the standard procedure for rating refrigerator energy usage to evaluate alternative top and bottom doors on a top-mount refrigerator/freezer. Our advanced doors used the original inner liners and gaskets fastened to prototype polymer outer shells and had about 98% of the internal volume filled with prototype krypton-GFPs. The measurements showed a 6.5% savings in electricity from these doors; modeling predicts a 25% energy savings from using the technology throughout the rest of the cabinet. This research was presented to the appliance industry at the 1995 International Appliance Technical Conference.

Our prototype GFPs were tested at the National Institute of Standards and Testing this year in cooperation with their efforts to develop an improved method of testing advanced insulations. We took this opportunity to also measure GFPs filled with xenon which resulted in whole-panel performance measured at about R-19 per inch. Krypton panels were also measured at R-12.5 per inch. These tests measured the entire panel including the barrier material and showed that the thin polymer material used in GFPs does not degrade performance, unlike many competing vacuum panel technologies.

This year we designed and assembled new machinery and tooling for fabricating prototype panels (Fig. 4). The equipment will allow us to ramp up prototyping capabilities to enable widespread evaluation of GFP prototypes in the future. This effort has also allowed us to evaluate the industrial adhesives that would be used to bond the thin polymer films in the manufacture of the cellular baffle component.

In FY96, we expect to fabricate improved prototype GFPs and to further develop their application in refrigerators and buildings. Additional development and demonstration of advanced refrigerator/freezer doors is planned in cooperation with major refrigerator manufacturers. We also plan to conduct standard thermal testing on a 2x4 wood-frame wall insulated with low-cost, argon GFPs. Ongoing basic research will increase our understanding of barrier material longevity and other design parameters that have cost implications for the final products.

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Industry Alliance for Interoperability

S. Selkowitz, V. Bazjanac, D. Collins, J. LaPorta, K. Papamichael, and F. Winkelmann

Only a small fraction of buildings are designed using computer-based energy simulation tools, such as DOE-2, in part because of the time and effort needed to enter descriptive and performance data. Much of this needed information already exists in other building design tools (e.g., CAD tools contain the required geometric data) but it is not readily accessible since there is no agreed upon procedure for sharing such information between tools.

In the fall of 1994 LBNL joined 11 private sector companies, each a major force in the building industry, and formed an alliance whose goal was to bring interoperability to architecture, engineering, construction, and facilities management. The other founding members are ARCHIBUS, AT&T Bell Labs, Autodesk, Carrier Corporation, Helmuth Obata & Kassabaum, Honeywell, Jaros Baum & Bolles, Primavera Systems, Softdesk, Timberline Software Corporation, and Tishman Research Corporation.

In the building industry, the goal of "interoperability" means concurrent access to project/building information and information sharing: a single building model that is shared by all participants in a building's design, construction, and use. Interoperability supplants the current sequential data exchange; information is no longer lost in the process. Data compatibility across applications and platforms is no longer an issue. Software users will benefit from enhanced communication among disciplines and across project teams, reduction of inconsistencies from decisions made by different disciplines, and direct links of CAD data to non-CAD applications. The industry will see major cost savings through more efficient information management, tracking of project/building decision-making, and the ability to add to previously made decisions. To illustrate the potential for savings in the industry, the Latham Report challenged the UK construction industry to use new information technology and save up to 30% in the cost of building projects over the next five years.

The basis for information sharing and interoperability in the building industry is a common approach to describing a building, the Industry Foundation Classes (IFCs). IFCs comprise a library of commonly defined "objects" that depict building components, features, and events, and which can be shared by diverse applications throughout a project's/building's life cycle. All IFCs are to be defined by the industry and are open; i.e., not owned by any vendor. They are to be implemented incrementally, and would continually evolve to meet industry needs. If they

Figure 5. *Demonstration of interoperability at the AEC Systems show in Atlanta, June 1995: The high-resolution image of a computer classroom is generated by RADIANCE with information drawn from the architect's and facility manager's descriptions of the space.*

become widely accepted and implemented, IFCs are likely to become a de facto new industry standard.

In June 1995, Alliance partners gave a demonstration of software interoperability at the AEC Systems Show in Atlanta. The demonstration showed how an office building may be designed in the future when interoperable design tools are available (Fig. 5). LBNL participated in the demonstration with the Building Design Advisor (BDA), DOE-2, and Radiance, which were shown used in a fully interoperable building design environment.

After the June demonstration, the initial efforts of the private alliance of 12 companies was reorganized as the non-profit Industry Alliance for Interoperability (IAI), which now has 70 members. IAI is an international organization, with new chapters in Europe and Asia.

IAI's main task is to define, publish, and promote Industry Foundation Classes (IFCs). It is currently developing version 1.0 of IFCs, which it will publish in mid 1996. Specifically, IAI will publish the reference object model definition (IFCs), IFC conformance criteria, IFC implementation guidelines, and specifications for model exchange requirements. LBNL is a Board member of IAI, chairs IAI's Research Committee and is participating in the integration of objects defined by the various disciplines. By late 1996, LBNL plans to make one of its tools fully IFC 1.0-compatible. If IAI can successfully accomplish its goals in the next few years, it opens the possibility of all energy related tools being able to communicate and share information with each other, as well as with the CAD, cost estimation, and facilities management software that is at the heart of the building industry. This has the potential to significantly enhance the impact of energy tools on building design and operations.

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Advanced Design Tools: The Building Design Advisor

K. Papamichael, H. Chauvet, D. Collins , J. LaPorta, S.Selkowitz, J. Thorpe, T. Trzcinski, and F.Winkelmann,

The Building Design Advisor (BDA) is a computer program that allows designers to quickly and effectively use multiple analysis and visualization tools and integrate their output to support informed multi-criterion decision-making (Fig. 6). The development of BDA started in FY94 with funding from the Pacific Gas & Electric and Southern California Edison through the California Institute for Energy Efficiency, as well as the US Department of Energy.

The objective of the BDA development efforts is to promote energy efficiency and environmental awareness in the design of new buildings, particularly in the schematic design phase, by providing means for decision-makers to analyze and evaluate the potential performance of their designs. Unless energy and environmental benefits can be accurately predicted, along with other non-energy performance aspects—such as comfort,

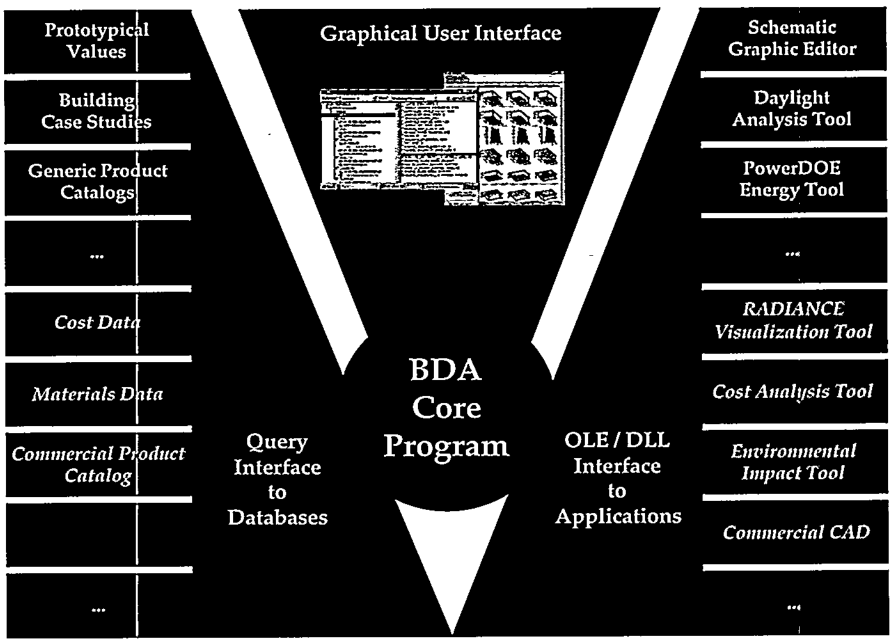


Figure 6. *Schematic diagram showing the Building Design Advisor software environment.*

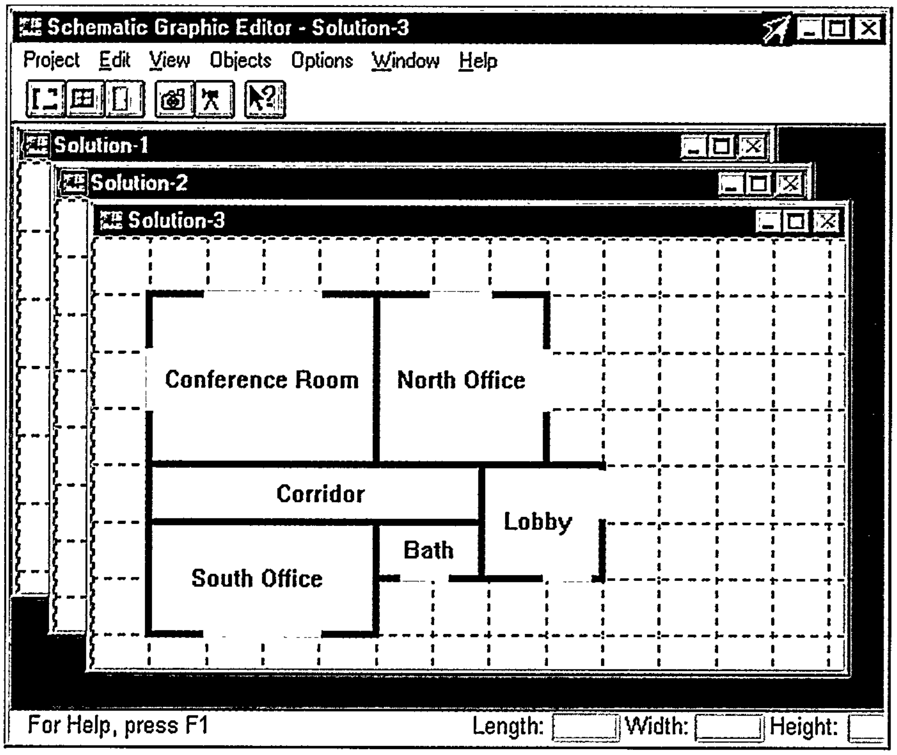
esthetics, and economics—most building designers will not risk the implementation of new energy efficiency strategies and technologies in their designs.

The currently available tools for accurate prediction of energy and environmental performance are very hard to use because they require preparation of complicated text files to describe the building and its context and provide output in the form of numerical tables that are hard to review and understand. Moreover, such tools use building modeling representations that are incompatible with each other and thus require multiple, specialized descriptions of the building and its context. As a result, such programs are generally used only by experienced consultants for large projects that can justify and support the high associated costs. Our initial goal is to move these decision-making capabilities to the architect's office early in the design process and to make its use cost-effective as viewed by designers.

To facilitate the integrated use of multiple analysis tools—such as DOE-2 for energy simulation, and RADIANCE for lighting analyses and photo-realistic rendering—BDA uses a real-world, object-oriented representation of the building and its context, mapped onto the specialized representations of the analytical models linked to it. In this way, BDA shields building designers from the modeling complexities of the individual analysis and visualization tools, allowing them to concentrate on design decisions.

BDA allows the user to quickly specify the basic geometric attributes of spaces, windows, doors, etc. through a CAD-like Schematic Graphic Editor (Fig. 7) while it automatically assigns default values from a Prototypical Values Database to all non-geometric parameters (such as thermal properties of walls and occupancy schedules) required for energy and other analyses. The default values are assigned based on location, building type, and space type and can be reviewed and changed at any time using BDA's Browser. Using the Browser, the user can select any number of input and output (computed) parameters for display in BDA's Desktop for decision-making (Fig. 8).

In addition to the Prototypical Values Database, BDA is linked to a multimedia Case Studies Database that allows building designers to compare their designs to existing buildings and create an appropriate, realistic context to set performance goals and evaluate performance. The Case Studies Database serves as an electronic magazine and supports the use of images, sound, and video for enhanced coverage of buildings.



The major development effort to create a working prototype of BDA began in FY95. BDA is implemented as a windows-based application for personal computers. The initial version will be linked to PowerDOE, the new version of the DOE-2 building energy simulation program, and a Daylight Computation Module. Future versions will be linked to additional analysis DOE-supported and visualization tools, as well as commercially available computer-aided design (CAD) software and electronic product catalogs. The overall vision for the future of BDA includes the development of context-dependent advice modules, support for collaborative design over local- and wide-area networks, and coverage of the information needs of the whole building life cycle. Some of these future capabilities were addressed in 1995 through collaborative efforts with groups from the Center for Integrating Facilities Engineering at Stanford University and the Industry Alliance for Interoperability, an industry consortium whose goal is to standardize the object-oriented representation of building components and systems to serve the needs of all building-related industries.

An alpha version of the software was released in mid FY95 and a beta version just after the end of the fiscal year. FY96 will see the completion of release 1.0 based on comments from our beta testers and the initial development of new modules to extend the functionality of the tool to environmental issues, cost issues, and to a broader role in the building life cycle. We are exploring the use of BDA as an educational tool, and examining how the internet might be used to support BDA development, distribution, and training.

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Figure 7. *Through a Schematic Graphic Editor, BDA users can quickly specify the basic geometric attributes of building components and systems, such as spaces and windows.*

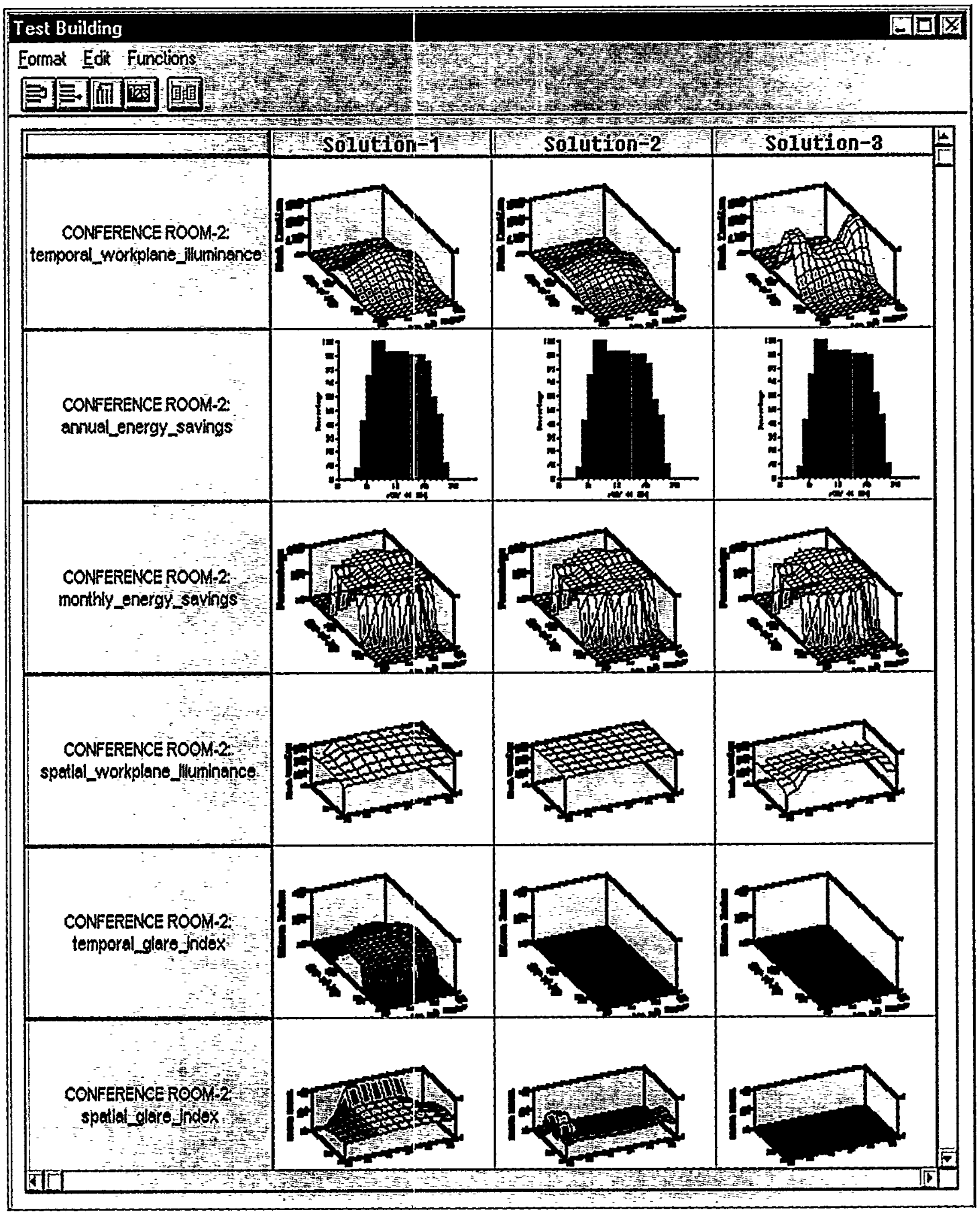

Figure 8. *The Decision Desktop is a spreadsheet-like element that allows building designers to compare multiple design solutions (occupying the columns) with respect to multiple design considerations (occupying the rows).*

Building Performance Assurance

S. Selkowitz, K. Heinemeier, K. Kinney*, S. Meyers†, F. Olken‡, K. Papamichael, M. A. Piette*, D. Sartor†, O. Sezgen*, M. Sherman§, and B. Smith§*

Despite significant advances in building technology and the promulgation of tighter building codes, commercial buildings consume about 15% of all energy used in the US at a cost of $85 billion annually, half of which is wasted compared to what is cost-effectively achievable. Assuring total building performance (which includes health, comfort, and productivity in addition to operating expense such as energy costs) is a priority in an increasingly competitive world. Achieving this goal requires a careful examination of the process by which buildings are designed, built, and operated. A life-cycle perspective on how information is managed in the building sector provides useful new insights and opportunities for achieving performance potentials.

In FY95, members of all three division programs involved in buildings R&D, with the participation of colleagues in the Information and Computing Sciences Division, were successful in obtaining internal R&D funds from the Laboratory Director's office to explore solutions to this problem. The goal of the project is to initiate the development and standardization of an interoperable set of tools that enhance building performance by facilitating information transfer in the building life cycle. These tools are individually optimized to respond to the specific needs of each phase of the building's life, but are linked by a shared information infrastructure, the Building Life-Cycle Information Systems (BLISS). Our project strategy was to develop workable, cost-effective prototype solutions to assuring building performance as a springboard for developing future private sector partnerships and new funding sources to implement our complete vision.

Our initial effort has focused on the conceptual development of BLISS and the development of a series of prototype tools: a tool for capturing Design Intent, a Chiller Commissioning toolkit to assist in the process of verifying and documenting installed chiller performance, and a Performance Evaluation and Tracking Tool, which incorporates a chiller emulator and data visualization module. In this exploratory project we have focused our efforts on chiller system performance, beginning in the design phase and extending through commissioning and operations. In order to ground the proof-of-concept in reality, all of the software models under development have been driven by measured data from Soda Hall, a newly occupied building on the UC Berkeley campus. As part of this project we have added additional instrumentation to the existing building energy management system and have tapped into these data streams (approx. one gigabyte per month) as needed by our software tools. In addition to the tool development efforts, we have created a computer-based mockup that demonstrates key elements of our entire BLISS vision and have begun a marketing and feedback effort with utilities, manufacturers, building owners, and government agencies, all with prospective interests in the successful completion of this effort.

Several of the specific project elements are outlined below and progress in FY95 is reported in the following articles.

Building Life-Cycle Information Systems. The goal of this effort is to create a software infrastructure that can be used for information sharing across disciplines and can be used to link interoperable software tools throughout the building life cycle. The project has three major elements: (1) to specify the distributed software architecture, (2) to build a life-cycle database, and (3) to develop a mechanism to capture and update "design intent" throughout the life cycle (see below). The distributed systems architecture describes how various building software components communicate and the database schema specifies the structure and semantics of the database. An initial version of this software will be built as an extension of the Building Design Advisor data model (see section in this annual report). In addition, our plan is to make this software consistent with the evolving software standards from the Industry Alliance for Interoperability (see report section).

Design Intent Tool. This software tool will assist in documenting design intent as expressed in a set of performance objectives that are initially generated during the early phases of design, but then revised and altered in both planned and unplanned ways over the building life cycle. The performance objectives can take the quantitative form of a performance metric with target values or the qualitative form of a text-based descriptive statement. The rationale behind the initial decisions and later alterations, which is typically lost, will be archived by the software for later retrieval as needed.

Computerized Chiller Commissioning Tools. The focus in this project is to explore the general structure of commissioning tasks and their implementation, plus the development and testing of commissioning procedures for one specific component, chillers, in a new, well-instrumented building. Our prototype commissioning toolkit includes test procedures as well as software to assist in the commissioning of chillers. The software contains a component library and test plans, and it archives results from the commissioning tests. The test results serve as the starting point for a calibrated cooling plant model used in performance tracking.

Building Performance Evaluation and Tracking Tool. The focus of this project is the development and testing of performance tracking tools, again focusing on cooling plants. We prepared a conceptual design for integration of PETT with our life-cycle database, with particular emphasis on data needs, time series analyses, and data flow. The bulk of the effort was in the development and calibration of a component-based SPARK simulation model of our case study building to evaluate chiller performance. This model in turn will be the starting point for a controls optimization and retrofit tool.

*Energy Analysis Program
†Center for Building Science
‡Information and Computing Science Division
§Indoor Environment Program

Design Intent Tool

R. Hitchcock

The design, construction, and operation of a building is a complex undertaking that spans many disciplines over long time durations. Although virtually every element of the building life cycle has become more complex over time, the building information management methods used to support and integrate the wide variety of project participants and their activities have not kept pace. In current practice, the bulk of building design-related information is still documented and communicated in the traditional forms of paper-based specifications and graphical drawings with text annotations. Much valuable information, in particular the intent behind the myriad design decisions made by all project participants, is altered or lost due to inadequate documentation and poor information management.

We have been examining the issue of documenting design intent from a life-cycle perspective so that this information can be made accessible to all project participants throughout the life cycle to better assure that a building achieves the functional and operational needs of its owners and occupants. We have developed a formal methodology for identifying and documenting the required building-related information. We then developed a prototype of an early vision of a software tool for documenting design intent.

The prototype software assists in explicitly identifying and documenting the performance goals (explicit global objectives, EGOs). EGOs are organized in a user-defined hierarchical structure as shown in Fig. 9. An individual EGO may take the quantitative form of a performance metric with its target value or the simple qualitative form of a text-based descriptive statement. We also specify Context Parameters which define the operating environment within which the building has been designed to achieve the stated explicit global objectives; e.g., the design day cooling load used to size an HVAC system chiller. A series of Design Rationale Records document the basis for design decisions in which building components, systems, and operation procedures are synthesized to achieve identified objectives under stated operating contexts. A single Building Design Version is thus comprised of a complete set of objectives, context parameters, design records, and other supporting information. The initial Building Design Version then changes over time to reflect life-cycle variations of a building, which can include alternative design solutions, the as-specified design that is sent out for construction bidding, the as-built building, the post-commissioned building, and the building at various stages in its ongoing operation. In the coming year this early prototype will be extended and tested using real building data sources.

Reference

Hitchcock, R.J. 1995. "Improving building life-cycle information management through documentation and communication of project objectives," CIB Proceedings Publication 180. pp. 153-162. August 21-23, 1995. Lawrence Berkeley National Laboratory Report LBL-37602, August 1995.

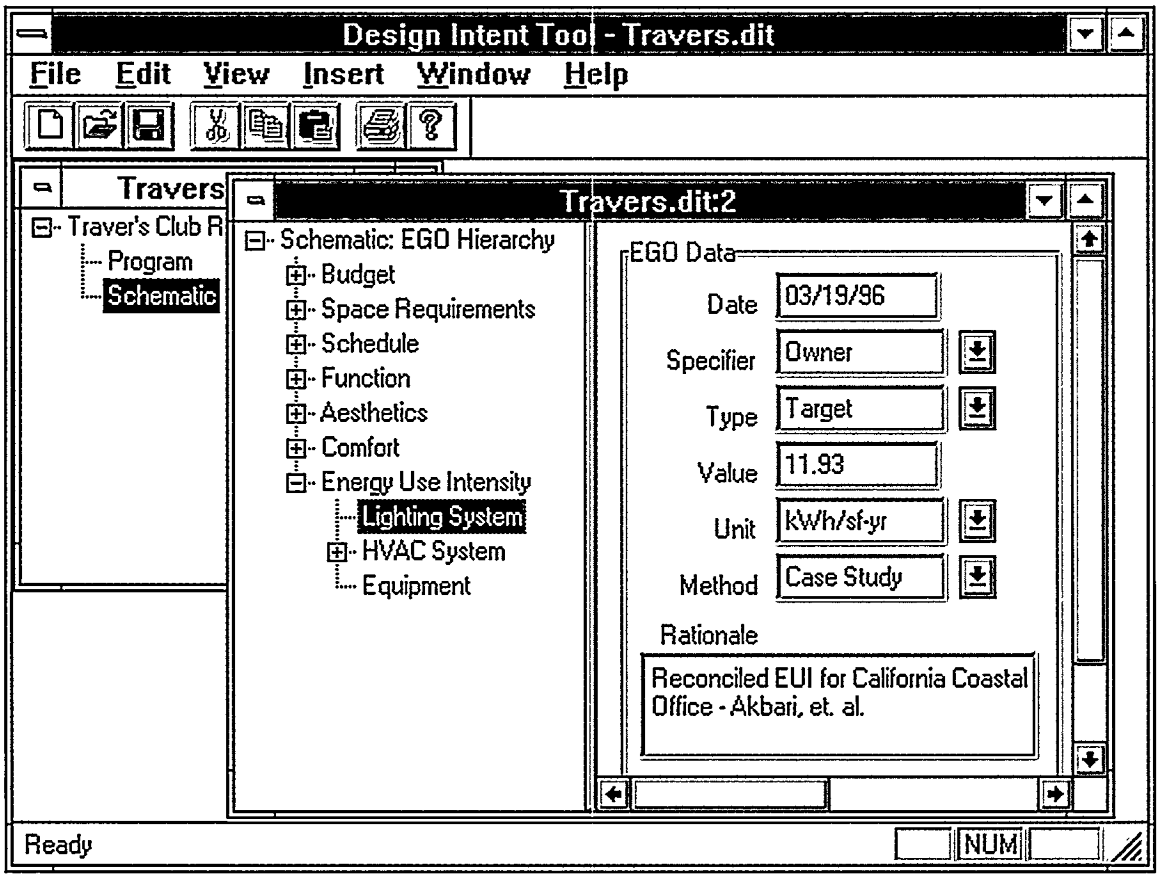

Figure 9. *Screen image of Design Intent Tool objectives hierarchy.*

Computerized Commissioning Tools for Commercial Buildings

M. A. Piette, K. Heinemeier, K. Kinney, F. Olken, D. Sartor, S. Selkowitz, and M. Sherman

Commissioning is a set of processes to ensure that building components and systems are installed and operated in an optimal fashion to meet or exceed design intent. Most buildings are not commissioned in a structured manner, resulting in significant problems such as defeated energy-efficiency strategies, incomplete control sequences, and poor documentation on as-operated conditions. While recent LBNL analysis of the benefits of commissioning has shown it is often cost-effective on energy savings alone, efforts to reduce costs are needed to encourage more widespread use of commissioning processes and techniques.

Computer-based information technology is one approach to address the loss of information that occurs as a building moves from design to operations. LBNL has developed a prototype chiller commissioning tool to assist in the development, customization, execution, and archiving of commissioning plans. This tool was developed as part of the Building Performance Assurance project to develop Building Life-Cycle Information Systems (BLISS).

Part of the first year FY95 efforts have focused on chiller commissioning, since chillers are the largest single energy-using component in buildings with central plants. As shown in Figure 10, the first step in applying the software is to describe the characteristics of the chiller components, such as chiller size, type, design efficiency, flow rates, and operating temperatures. The software contains a general description of chiller commissioning activities and a module to record specific test plan methods, customized for a particular building (Step 2). Laptop computers can be used to track changes to test plans and collect data during plan execution (Step 3). Test results are recorded and outstanding issues and deficiencies are tracked to ensure that the chiller is fully functional (Step 4). Long-term performance tracking methods are also defined for ongoing evaluation over the life of the building.

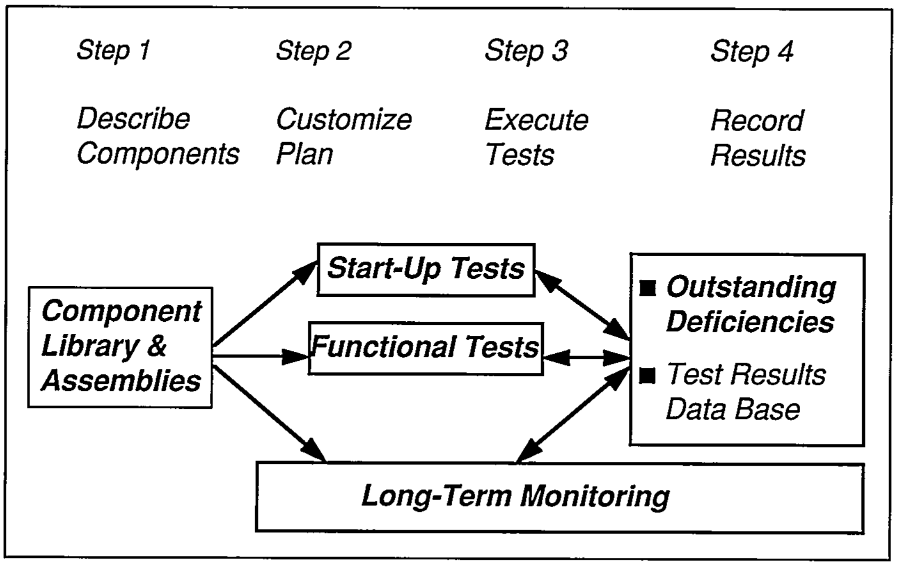

Figure 10. *The four steps of commissioning and the use of a computer-based chiller commissioning tool.*

Second year activities in FY96 will include four primary areas. First, we will obtain feedback on the software from commissioning agents to evaluate its usefulness and value in cutting commissioning costs and improving building performance. Second, we will expand the tool to be interoperable with other computer-based building life-cycle information tools. These include design tools such as PowerDOE and the Building Design Advisor, and model-based performance tracking tools such as a calibrated (equation-based) SPARK model. Third, we will refine the tool based on user comments. Finally, we plan to increase the scope of the software to include additional cooling plant components, such as cooling towers. These improvements will culminate in the development of a prototype cooling plant life-cycle information system.

Reference

M.A. Piette, B. Nordman, and S. Greenberg, "Commissioning of Energy-Efficiency Measures: Costs and Benefits for 16 Buildings," prepared for the Bonneville Power Administration, LBL Report 36448, November, 1994.

Building Performance Evaluation and Tracking Tool

O. Sezgen, K. Kinney, S. Meyers, and B. Smith

Numerous proxies—such as equipment coefficient of performance (COP) at standard conditions, annual integrated part load efficiency, and seasonal integrated part load efficiency—have traditionally been used to measure the energy performance of HVAC systems in buildings. These proxies describe the performance of a building HVAC system in a very limited fashion. More detailed information about performance must involve the dynamic behavior of the HVAC and other building variables.

Measured HVAC time-series data are descriptive of the performance, but only under the strict boundary conditions that the building was exposed to during the monitoring (such as weather conditions during monitoring, the control strategies that were applied, etc.). When one wants to estimate performance under other possible conditions, measured time-series data of the past is of limited use. However, a dynamic model of the HVAC systems calibrated to monitored data can facilitate such estimations.

Our objective during this project was to develop a prototype tool using a dynamic model of the chiller system to track system performance in a testbed building and optimize chiller operations as required over time. This tool development effort was part of a larger Building Performance Assurance project to develop building life-cycle information systems.

We used the Simulation Problem Analysis Research Kernel (SPARK) (see Building Energy Simulation section of this report) to build our emulation model. SPARK may be viewed as an object-based differential and algebraic equation solver. The models are represented as mathematical graphs (as opposed to linear data structures) in SPARK, and this feature facilitates emulation of sub-models without substantial changes to the model. This is also a crucial feature which facilitates emulations with changes in control strategies.

In our methodology, during the *design phase*, the HVAC model is built using the design documents and manufacturer-supplied data on equipment performance. If the building is still not built at this stage, it is possible to emulate several design options (such as different equipment sizes, efficiencies, etc.), compare the energy performance of these different options, and feed information back to the design process. This would be a "traditional" use of SPARK as part of the PowerDOE tool.

During the *commissioning phase*, the SPARK model built using the design data is calibrated to represent the dynamic behavior of the system as it actually performs. For this purpose, after the acceptance of the building, time-series data on the HVAC variables are used to revise the SPARK model parameters. At this point, the emulation results and the real data from the building should be very close.

We developed application software which allows the use of the above calibrated model in numerous ways during the *operations and retrofit phases*. The Building Performance Evaluation and Tracking Tool can be used for performance tracking, for analysis of different control strategies, and also for the analysis of different options during the retrofit phase.

Using the *performance tracking* options, data from the building can be compared to benchmark data from other similar buildings, to historic data from the same building during other time periods, or most significantly to the emulated data using the HVAC model (Fig. 11). Deviations of the building data from the simulated data may indicate problems in the HVAC system. At this stage, this project is not aimed at pinpointing the source of such problems. While this in not a diagnostics application, other related research projects are addressing those issues.

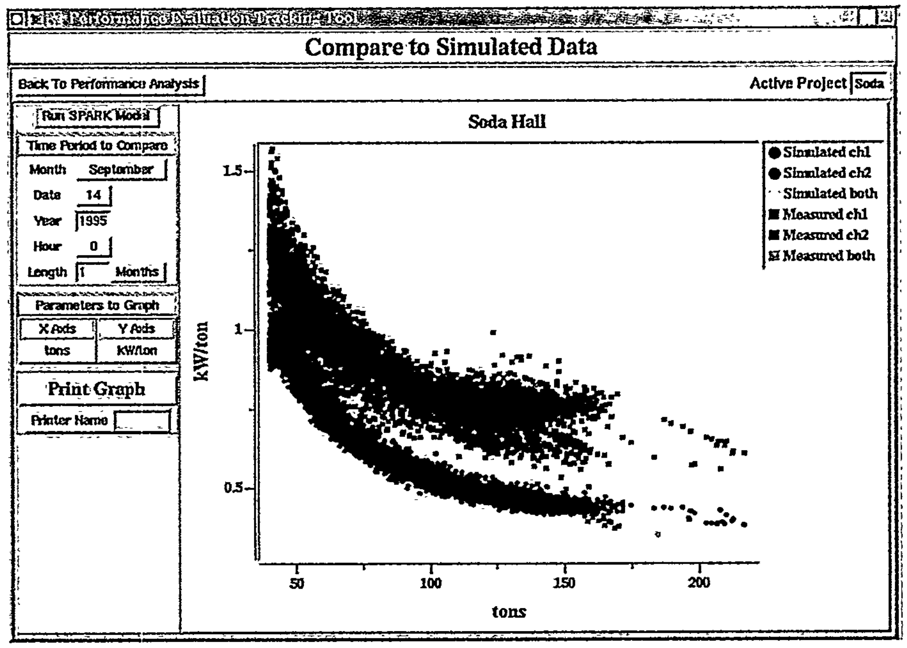

Figure 11. *Measured and simulated data for the chillers of a case-study building.*

Options related to *control strategy analysis* facilitate changes to the control logic that is actually used during the measurement and comparison of the emulated results to the actual measured data. The environmental conditions and the building loads are maintained at the reported levels, but changes are made on the control choices, such as temperature set points or equipment status. Although at this stage, these control strategy analysis options serve as a "what-if" type of analysis facility, capabilities here can be expanded to include optimization. In such an application, the tool would return an optimal set of choices for all of the control options.

Finally, longer-term actions can be analyzed using the *retrofit analysis* options of the tool. Here changes that would require implementation of new equipment and hardware are analyzed. A typical example would be a chiller replacement project. Using the retrofit analysis options of the tool, one can compare the performance of the overall system under different chiller sizing and efficiency choices.

During the first year of this project, we focused our attention on the SPARK chiller model. This was mainly for demonstration purposes and this setup served as a testbed for the development of the Performance Evaluation and Tracking Tool. Clearly, optimization of chiller performance cannot be conducted independently of the effects of such action on the energy performance of the rest of the system. For example, reducing the condenser inlet temperature reduces the chiller electricity, but it increases the energy consumption of the cooling towers. Having demonstrated the concepts on the chillers, in FY96 we are now expanding our models to include the cooling towers, the coils, and possibly the air distribution system.

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