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FY 1987 Annual Report

Windows and Lighting

March 1988

APPLIED SCIENCE DIVISION

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Prepared for the U.S. Department of Energy under Contract Number DE-AC03-76SF00098.

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LBL-24215

APPLIED SCIENCE DIVISION ANNUAL REPORT

WINDOWS AND LIGHTING PROGRAM

FY 1987

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WINDOWS AND LIGHTING PROGRAM

INTRODUCTION

Over 30% of all energy used in buildings is attributable to two building elements, windows and lighting. Together they account for annual consumer expenditures of over $50 billion. Each affects not only energy use by other major building systems but also comfort and productivity, factors that have a far greater influence on building economics than 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. Lighting systems make it possible to conduct any task of any visual difficulty anywhere in the indoor environment, and at the same time define the luminous qualities of the indoor environment. These two building elements are thus essential components to any comprehensive building science program.

Despite the important achievements in reducing building energy consumption over the last decade, significant additional savings are still possible. These will come from two complementary strategies: 1) better building designs that effectively apply existing technology and extend market penetration, and 2) new advanced technologies to increase the savings potentials with each application. Both the Windows and Daylighting and Lighting Systems Research groups have made substantial contributions in each of these areas. The ongoing research described in the annual summary aims to further advance achievement of these goals.

The Windows and Daylighting Group focuses on developing the technical basis for understanding the energy-related performance of windows. If the flow of heat and light through windows and skylights can be properly filtered and controlled, these building elements can outperform any insulated wall or roof component and provide net energy benefits to the building. The group's investigations are designed to develop the capability to accurately predict 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 in fenestration performance. The Group's three major project areas are optical materials, fenestration performance, and building applications and design tools.

In our studies of optical materials and advanced concepts, we develop and characterize thin-film coatings and other new optical materials that control radiant and thermal flows through glazings. Innovative concepts for large-area envelope enclosures are studied. The program helped accelerate the development and market introduction of windows incorporating high-transmittance, low-emittance coatings for R3-R5 windows. If they sell as currently anticipated, they will save consumers over $3 billion annually in heating bills alone.

Our research on window performance aims to develop new analytical models and experimental procedures to predict the thermal and solar-optical properties of the complex assemblies of glazing materials and shading devices that comprise complete fenestration systems. Thermal performance models are being validated with the Mobile Window Thermal Test (MoWiTT) Facility, now collecting data at a field test site in Reno, Nevada. This unique facility combines the accuracy and control of lab testing with the realism and complexity of dynamic climatic effects. LBL daylighting studies employ a unique 24-foot-diameter sky simulator for testing scale models under carefully controlled conditions, and new experimental facilities for measuring the photometric and radiometric properties of complex fenestration systems.

Building applications studies and design tools help us to understand the complex tradeoffs in fenestration performance as a function of building type and climate. In nonresidential buildings major reductions in electric energy use and peak electric demand can be achieved if the tradeoffs between daylight savings and solar-induced cooling loads are understood. We are developing concepts for an Advanced Envelope Design Tool using new imaging techniques and expert systems.

The research of the Lighting Systems Group is divided into three major areas: advanced light sources, building applications, and impacts on health and visibility.

Our light source research is concerned primarily with developing new concepts for efficiency converting electrical energy into visible light. Areas of interest include mechanisms for reducing the ultraviolet self-absorption in gas-discharge lamps and

the excitation of plasma gas at ultrahigh frequency ranges (approximately 10^9 hertz). Both hold the promise of a more reliable and more efficient conversion of energy into light.

The building applications research concentrates on the design of lighting systems and the effective use of lighting controls, and their interaction with a building's HVAC system.

Research in visibility impacts is focused primarily on gaining basic information needed to define lighting conditions that enhance productivity in a cost-effective manner. It also seeks to determine any possible undesirable visual effects, such as excessive fatigue, associated with using modern office equipment such as visual display terminals in an advanced lighting environment.

Our studies of health impacts extend electric lighting research to a wider class of human activities. In specially designed experimental rooms, conditions can be varied, and nonsubjective responses to lighting variables can be measured by sensitive instrumentation.

The Lighting Group's successes include advancing the development of high-frequency solid-state ballasts for fluorescent lamps and the invention of a new high frequency surface wave lamp with 30% better efficiency than the common fluorescent lamp. A 2-year test of solid-state ballasts in a large office building showed an electricity savings of 40%. Scaled to the entire country, this represents an annual savings of $5 billion. The energy-efficient surface wave lamp promises major reductions in energy use with considerably longer lamp life.

Windows and Daylighting*

S.E. Selkowitz, D. Arasteh, D.L. DiBartolomeo, R.L. Johnson, H. Keller, J.J. Kim, J.H. Klems, C.M. Lampert, K. Papamichael, M.D. Rubin, R. Sullivan, and G.M. Wilde

Approximately 20% of annual energy consumption in the United States is for space conditioning of residential and commercial buildings. About 25% of this amount is required to offset heat loss and gain through windows. In other words, 5% of U.S. energy consumption—the equivalent of 1.7 million barrels of oil per day—is tied to the performance of windows. Fenestration performance also directly affects peak electrical demand in buildings, sizing of the heating, ventilating, and air-conditioning (HVAC) system, and the thermal and visual comfort of building occupants.

The aim of the Windows and Daylighting Group is to develop a sound technical base for predicting the net thermal and daylighting performance of windows and skylights and to accelerate development of new technology that will improve performance and reduce energy use. The group's work will help generate guidelines for design and retrofit strategies in residential and commercial buildings and will help develop new advanced computer-based tools for building design.

One of our program's strengths is 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 use a unique, powerful set of computational tools and experimental facilities. Our scientists, engineers, and architects work in collaboration with researchers in industry and academia.

To be useful, the technical data developed by our program must be communicated to design professionals, industry, and other public and private interest groups. We publish our results and participate in industrial, professional, and scientific meetings and societies, national and international, to ensure that our research results are widely disseminated.

*This work was supported by the Assistant Secretary for Conservation and Renewable Energy, Office of Buildings and Community Systems, Building Systems Division, and Office of Solar Heat Technologies, Solar Buildings Division, of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

Our research is organized into three major areas:

- Optical Materials and Advanced Concepts
- Fenestration Performance
  - —Thermal analysis
  - —Daylighting analysis
  - —Field measurement of performance
- Building Applications and Design Tools
  - —Nonresidential buildings
  - —Residential buildings
  - —Design tools

OPTICAL MATERIALS

Significant reductions in energy consumed by buildings will come not only from better building design, but also from the development and introduction of new glazing materials. Since the inception of our program in 1976, we have worked to identify, characterize and develop promising new optical materials to assist industry with developing the next generation of advanced fenestration systems. We also provide scientific coordination for DOE-funded research projects at universities, private-sector firms, and other national laboratories, and work to transfer our research results to the private sector.

In 1976, we made the development of low-emittance (low-E) coatings a major program objective. DOE-supported research has accelerated market introduction of new high-performance low-E window systems. Several small firms began offering commercial products in 1982, and by 1985 most of the largest glass and window manufacturers offered low-E products. The use of low-E coatings in a conventional double-glazed window provides better thermal performance than triple glazing and makes a lighter and more compact window. In the long term this coating technology could produce windows having heat transfer values as low as those of insulating walls. On an annual basis such windows should outperform the best insulated wall.

CHARACTERIZING COATED GLASS AND PLASTIC SUBSTRATES

To predict the performance of complex window systems, we must accurately know the optical properties of their coatings and glass and plastic substrates. Until recently, scientists did not fully understand these properties for even the most common varieties of glass used in windows. We have completed work on standard clear glasses, glasses having absorbing additives, and high-purity glasses. Our results were summarized in a paper that includes a complete set of optical constants from the near ultraviolet through

the little-studied far infrared for all common window glasses.[1] We also provided spectrally and directionally averaged bulk properties for calculating solar and thermal radiative heat transfer through windows.

Accomplishments During FY 1987

With the increasing marketing of low-E window systems, there is a concern that emittance be properly measured, calculated, and specified. Normal emittance can be measured in a spectrophotometer, but hemispherical values are required for thermal analysis. We previously developed a procedure to determine the hemispherical emittance of a low-E coating if the normal emittance is known. This correlation, shown in Figure 1, was adopted by industry groups as a standard calculational procedure. We also participated in a series of industry-sponsored round-robin emittance measurements.

Planned Activities for FY 1988

We will continue measurement and analysis of coated glazings, seeking generalizable relationships between simple, measurable parameters and the more complex angle-dependent and spectrally dependent behavior of specific coatings. We will also continue collaborative work with an industry group developing voluntary standards for measurement of emittance.

DURABLE LOW-EMITTANCE COATINGS

Since 1976 we have contributed to the development of low-E window coatings that transmit sunlight but reflect infrared radiation, thus suppressing radiative heat transfer. Commercially available coatings based on vacuum-deposited metal-dielectric multilayer films have satisfactory optical properties and a low emittance value, 0.1-0.15, but are not sufficiently durable to be used in nonsealed glazings. Pyrolytic films deposited directly on glass in the float process are more durable but typically have a higher emittance, 0.35, and thus lower energy savings potential. We approach the problem by identifying materials with good intrinsic durability and then attempting to improve the emittance and solar-optical properties.

Accomplishments During FY 1987

We began by studying the titanium oxynitride (TiN_xO_y) system, producing these gradient-index coatings first by plasma-assisted chemical vapor deposition (PCVD) and later by sputtering. To achieve better film properties in FY 1987, we switched to a multilayer coating design, TiO_2-TiN-TiO_2. By varying the TiN thickness and deposition parameters, we were able to obtain coatings with visible transmittances and emittances approaching those of some of the pyrolitic coatings (Figure 2). The coatings were characterized by electron microscopy, Auger electron spectroscopy (AES), and Rutherford backscattering (RBS), in addition to complete optical characterization. Detailed data on deposition parameters and coating properties were developed for industry with the objective of getting our results duplicated on production-scale sputtering machines. We are discussing with developers of sputtering systems the feasibility of modifying existing systems to

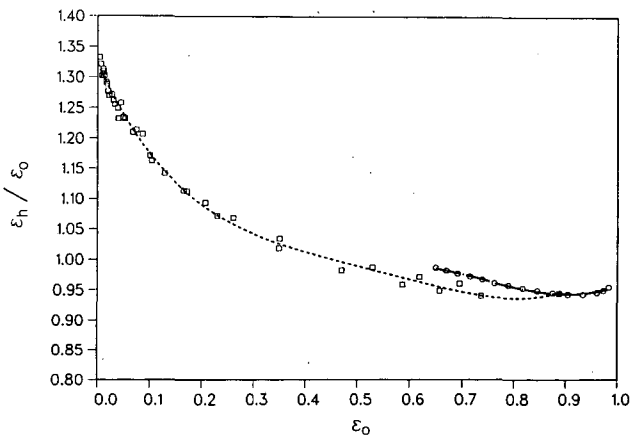

Figure 1. Normalized hemispherical total emissivity versus normal emissivity. Solid curves approximate (□) metals and coatings on glass, and (0), dielectric substrates. (XBL 876-2803)

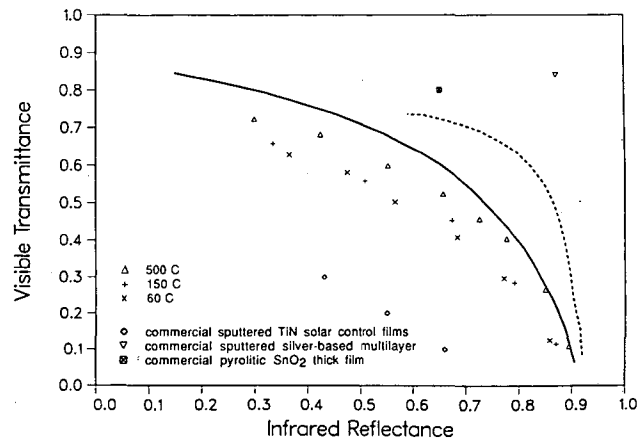

Figure 2. Calculated solar transmittance versus infrared reflectivity of TiN films (solid line) and TiN / TiO_2 multilayers (dotted line). Properties of TiN films deposited at three different substrate temperatures are also shown. (XBL 884-1468)

allow for heating the glass substrate, which is required for deposition of our best coatings.

Planned Activities for FY 1988

We expect to continue collaboration with industrial coaters who are interested in manufacturing TiN-based coatings. Limited durability testing may be undertaken. We have started work on transparent, diamond-like, hard carbon coatings that could serve as a protective overcoat for other optically important coatings.

LOW-CONDUCTANCE GLAZINGS

With the commercial success of R3-R4 low-E windows, the next major challenge lies in developing high-R (R6-R10) glazings. In 1985 we developed a new concept for a high-R window that can be manufactured using existing technology. A DOE patent application was filed and subsequent research and development of the concept was sponsored by the Bonneville Power Administration (BPA).

Our high-R window is based on an innovative modification of conventional triple glazing. Two low-E coatings (emissivities < 0.10) are placed on surfaces facing each of two sealed gaps. To reduce conductive heat transfer and achieve optimum thermal performance, a Krypton or Krypton/Argon gas fill is used instead of all Argon. This allows us to keep the gap widths small and produce a unit with an overall width of 0.75-1.0 inch, small enough to be used in conventional sash and frame designs.

Accomplishments During FY 1987

During the past year, computer analyses and lab and field tests have shown that a window with an overall effective R-value of R6-R8 (R8-R10 center of glass) can be commercially produced using low-E coatings and krypton-based gas fills. At gap widths of 0.35 inch, the differences between 100% Kr and 50/50 Kr/Ar are small, but the difference between using two standard low-E coatings (emissivity of 0.15) and two high-performance low-E coatings (emissivity of 0.05) is large. Proposed window designs would therefore concentrate on using the better low-E coatings available today with emissivities under 0.10 (Figure 3).

In small quantities, pure Krypton is too expensive to use in gas-filled windows. However, the prospects for much lower prices for large quantities of "crude" Krypton are good. Improved filling techniques under development will reduce gas waste. At present very little data exists on the expected lifetime of gas fills in insulated glazings. European experience

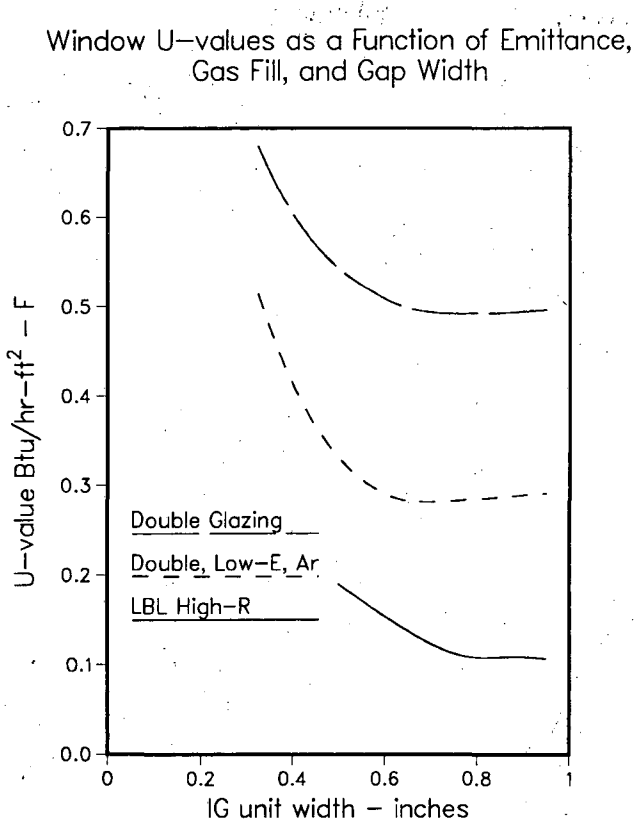

Figure 3. Window U-values as a function of insulated glass unit width for conventional double glazing; low-E (e = 0.15), Argon-filled double glazing; and an LBL high-R design (two e = 0.05 coatings, two krypton-filled gaps). Nominal 1/8-inch glass assumed for all glazing layers. (XBL 884-1469)

suggests that with the proper sealant and sealing procedure, gas leakage should not be a problem. Argon has been the primary gas examined for this purpose; Krypton's rate of diffusion should be significantly lower because of its comparatively larger molecular size.

A finite-element computer analysis showed that the structural stresses in such a window system should be within design constraints. A window with thinner Krypton-filled gaps will create less stress and smaller deflections than a wider Argon unit. Future work will address the thermal bridging effect from the use of conventional metal spacers in a highly insulating window, and gas diffusion rates through alternative nonmetallic spacers.

Planned Activities for FY 1988

We will continue to study specific technical problems, such as the influence of different frame and edge materials on overall U-values, gas retention, gas-filling processes, gas costs, center glazing-

layer materials and structural performance. Second-generation technical proof-of-concept prototypes of the most promising options will be built and field tested. In these field tests, we hope to show that high-R glazings can outperform insulated walls. We expect to work with industrial partners in the production of windows to be used in field tests and a demonstration program. The overall program will be supported by BPA and DOE.

CHROMOGENIC MATERIALS RESEARCH

Optical switching materials or devices can be used to dynamically control transmission of solar radiation through a window by changing its optical properties in response to light, heat, or electrical field. Initial results of energy simulation studies of office buildings suggest that an automatically controlled switchable coating can provide substantial economic benefits by minimizing cooling and lighting energy use, reducing peak electrical demand and HVAC system size, and improving thermal and visual comfort. Thermochromic and photochromic systems may have less universal application than actively controlled electrochromic coatings, but may be simpler and cheaper to produce and perform equally well for specific building applications.

Electrochromic Materials

Electrochromism is exhibited by certain metal oxide and organic materials.[2] We are studying hydrated nickel oxide films and complete devices that include component layers such as polymer ion conductors. An anodic electrochromic material such as hydrated nickel oxide undergoes an intense color change after dual ionic and electronic extraction. An example of this reaction is: $Ni(OH)_2$ (transparent) <---> NiOOH, brown bronze+ H^++ e^-. This reversible reaction occurs at applied potentials below 1 Volt, and the material does not require a constant potential to remain colored.

Accomplishments During FY 1987

Our investigations have emphasized (A) developing a detailed understanding of the behavior of electrochromatic films to improve their operating properties, and (B) developing prototype electrochromic devices.

We have performed in-situ solar and FTIR spectroscopic studies on hydrated nickel oxide films in KOH electrolyte. These films were made by electrochemical deposition directly onto doped tin-oxide-coated glass substrates. We determined that in the bleached and colored states these films exhibit distinctive molecular vibrational states corresponding to $Ni(OH)_2$ and NiOOH, respectively. Also we determined the rate kinetics for specific conditions.[3]

In our device studies we developed a basic polymer electrolyte that conducts hydroxyl ions and used it to make the first prototype devices.[4] The devices are of the configuration: glass/SnO_2/$Ni(OH)_2$/polymer/SnO_2/glass. An example of the optical response of this device is shown in Figure 4. We also completed a study for the International Energy Agency (IEA) on the stability and durability of the most commonly known electrochromic devices.[5]

Planned Activities for FY 1988

The major objective in FY 88 will be fabrication of a complete optical switching device based on hydrated nickel oxide. We will continued to characterize and improve the polymer electrolyte and will develop better electrolyte deposition methods. We will expand our study of counter electrodes for ion storage and perform studies on optimizing and improving overall device properties. Our IEA studies

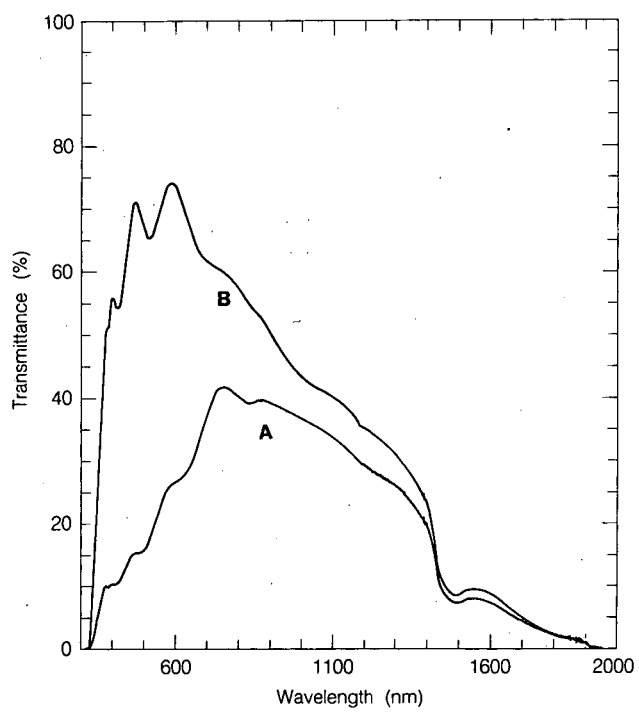

Figure 4. Normal solar spectral transmittance of the nickel oxide electrochromic device in colored (A) and bleached (B) states. The integrated solar and photopic transmittances are T_s (bleached) = 0.50, T_s (colored) = 0.23, T_p (bleached) = 0.70, and T_p (colored) = 0.23. (XBL 879-11135)

will investigate degradation and stability of generalized electrochromic devices.

Thermochromic Materials

Simpler thermochromic coatings that switch in response to heat or light may also be useful, particularly if these coatings can be fabricated and installed less expensively than more complex electrochromic coatings. A thermochromic material might, for example, be used in sun-belt residential windows.

Accomplishments During FY 1987

In FY 1987 we started work on a thermochromic vanadium oxide coating. Prior work by Honeywell suggested that VO_2 was a promising material, although its transition temperature was too high for use in buildings. Jorgenson successfully demonstrated that the transition temperature could be reduced by doping the oxide. We studied the optical and long-wave IR properties of the coating to determine its suitability for a combined low-E/thermochromic coating for windows in sun-belt residences. We concluded that the emittance was not low enough to provide useful insulating properties. The optical switching effects in the solar spectrum were disappointingly small for coatings that were thin enough to provide good light transmission in the clear state.

Planned Activities for FY 1988

There are several possible ways to increase the switching ranges. However, at this time we have decided not to pursue further research on this materials system.

MATERIALS FOR IMPROVED USE OF DAYLIGHT

Conventional methods of controlling daylight in buildings rely on architectural elements and shading devices. Greatly improved performance would result from materials or systems that could: (1) transmit maximum daylight with minimal cooling load impact (i.e., reject solar infrared radiation); (2) collect and distribute daylight beyond the perimeter zones in buildings; and (3) provide angular selectivity in accepting and redirecting incident light at the building envelope.

Light Guide Systems

Though daylighting can reduce electricity use and peak electric demand in buildings, its application is currently limited to work areas close to windows and skylights. Sufficient daylight falls on the exterior skin of a building to provide adequate illumination throughout any building—the technical challenge is to collect, transmit, and distribute the light where it is needed. We believe that light collection and transmission systems are the critical optical elements for successfully developing core daylighting systems. We are developing the system design concepts and performance data necessary to evaluate the economic feasibility of such systems.

Accomplishments During FY 1987

Previous simulation studies have shown that several types of solid and hollow light guides can transmit significant fractions of incident light. Performance is a function of materials, geometry, and incident sun conditions. Guide transmittance of greater than 50% is possible over a distance of 50 ft for a 2-ft-square guide. Optical measurements on a scale-model guide have corroborated these findings. We continued our mathematical studies of total optical system performance including the coupling between collector and guide optics. We established several baseline collector systems that could be coupled to each of several different guide systems.

Planned Activities for FY 1988

We will continue modeling studies to determine the overall performance of alternative optical system designs. We will complete a survey of several existing installations and will review the most promising optical systems from the perspective of costs and architectural integration. We will begin design studies for a core daylighting test facility that could be used by researchers or developers to test promising new systems.

ADVANCED GLAZINGS FOR AUTOMOBILES

Solar load control is an increasingly important problem to the auto and glass industries because styling trends and customer preference are dictating ever-increasing glass areas on car bodies. Also, the automobile industry and government have recently become concerned about auto air conditioners as a source of chlorofluorocarbon (CFC) in the atmosphere. Increased cooling loads associated with larger glazing areas demand larger air conditioners, which exacerbates the CFC problem. Our objective is to define the potential reductions in solar load and air conditioner size by using new high performance glazings.

Accomplishments During FY 1987

A series of parametric studies were compiled to document the effects of glazing properties on the cool-down characteristics of an auto air conditioning system (Figure 5). Using the computer program ESP,[6] we also analyzed interior air, dashboard, and seat surface temperatures as a function of exterior and interior surface absorptances, interior thermal mass, and air infiltration. We explored the possibility of cooperative studies between LBL and automobile and glass manufacturers and we established a working relationship with the Environmental Protection Agency, which is now formulating policy on the CFC problem.

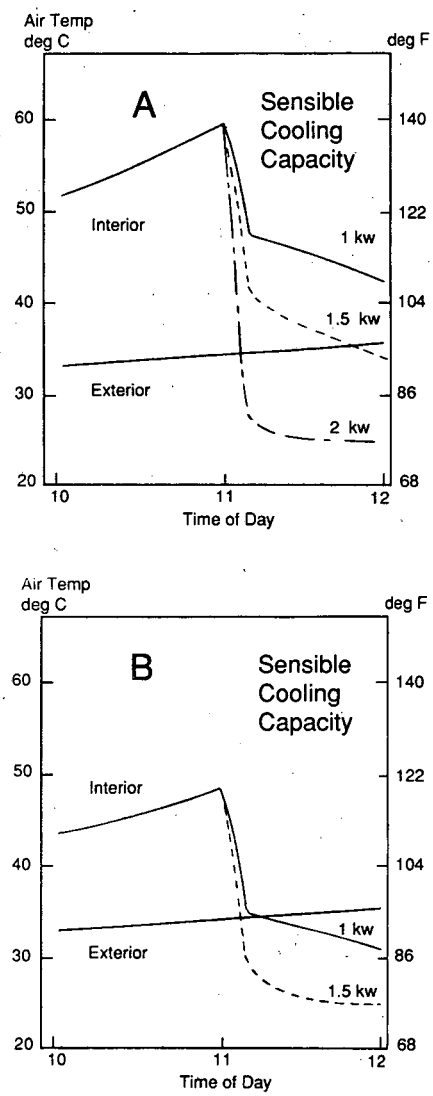

Figure 5. Interior air temperature in sports model as a function of time for varying air conditioner cooling capacity under static soak conditions. Air conditioner is turned on at 11 a.m. In A, glazing transmittance is 0.83; in B, 0.43 for front windshield and 0.23 for side and rear windows. (XBL 885-1480, XBL 885-1481)

Planned Activities for FY 1988

We plan combined analytical and experimental investigations of static-soak, cool-down, and city-driving conditions. We will revise the ESP simulation program to more accurately predict auto air conditioning performance. We will test the ESP program during our experimental measurements of air and surface temperatures, solar radiation, and air flow.

FENESTRATION PERFORMANCE

Research activities in this area are intended to characterize the performance of fenestration components and complete systems over the entire range of operating conditions in any climate or building type. The research will develop and refine experimental techniques and analytical models for accurately determining heat transfer and solar-optical properties of fenestration components and systems and will validate these models in field test facilities and occupied buildings. Many of the new algorithms and data sets are designed to be incorporated into hour-by-hour building energy simulation programs such as DOE-2.1. These data will not only improve the accuracy of our predictions but will also allow us to predict the performance of new fenestration systems and novel architectural designs. Our plan for developing and implementing these new analysis capabilities in energy simulation models is shown schematically in Figure 6.

THERMAL ANALYSIS

With the increased use of low-E coatings and gas fills, the number of possible window configurations is expanding rapidly. The continuing development of new products and their combinations necessitates an objective, accurate, easy-to-use calculational procedure to determine standard thermal properties. We developed and released WINDOW 2.0 in July 1986 to meet this need. It has been adopted by industry as a virtual de facto standard for window thermal calculations.

Accomplishments During FY 1987

During FY 1987 we completed work on WINDOW 3.0, which is to be publicly released in mid-1988. WINDOW 3.0 can now analyze certain gas mixtures, include the resistance of the glazing

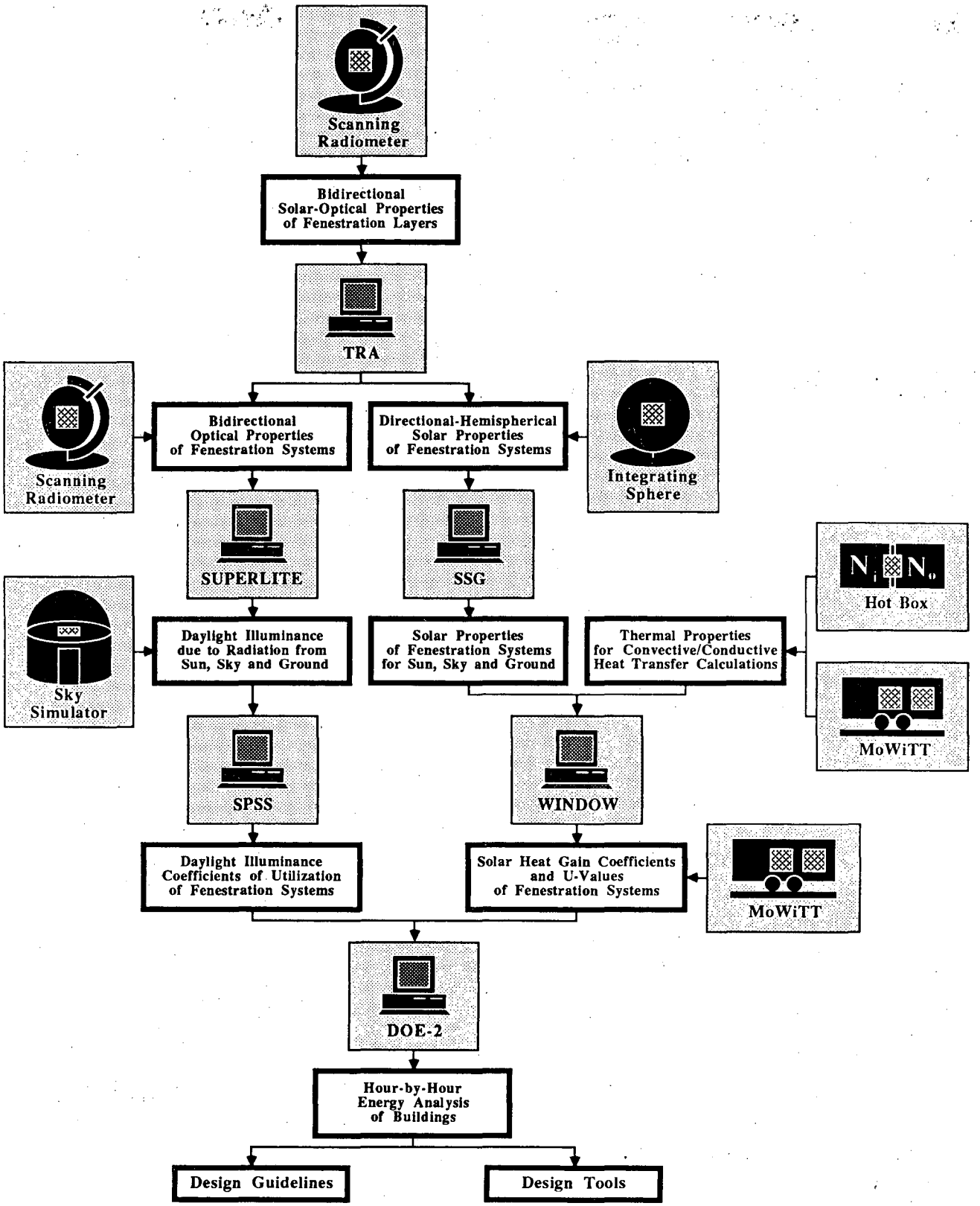

Figure 6. Schematic diagram of overall fenestration modeling capabilities under development including new measurement facilities, computer models, and intermediate calculated and measured results. Direct measurement of some intermediate calculated results provides a validation check. (XBL 885-1479)

material itself, use a multiband spectral-properties model, calculate two-dimensional edge and frame effects, and analyze nonvertical glazings. With the program's new interactive format, the user can make changes and see new results quickly. A new glass library allows the user to choose standard or user-input glass types and then quickly specify glazing choices by library number.

We distributed WINDOW 2.0 to approximately 200 users, including all major glass and window manufacturers. A major insulating glass sealant manufacturer has distributed over 500 copies of the program to interested recipients on their mailing list.

We also developed and distributed a spectral properties analysis program, SPECTRUM 1.1. This program calculates UV, visible, total solar, and IR average properties for a given wavelength-dependent glazing property. These results can then be used in WINDOW to calculate shading coefficient.

Planned Activities for FY 1988

During FY 1988 we will release WINDOW 3.0 to the public and continue to support and upgrade it in response to industry requests. The capability to analyze IR-absorbing gases will be added. The algorithms used in SPECTRUM 1.1 will be incorporated into a multilayer program compatible with WINDOW and will be distributed to interested users.

DAYLIGHT AND SOLAR HEAT GAIN STUDIES

Providing daylight to building interiors is one of fenestration's most important functions, both from an energy perspective and from an occupant's point of view. But the solar heat gain associated with daylight can be a benefit or cost, depending on circumstances. Analyzing the trade-offs to arrive at an optimum solution for simple glazings is difficult; for complex fenestration with sophisticated sun control systems it is virtually impossible with currently available tools. Our objective is to develop the experimental facilities and analysis models to accurately characterize the daylight and solar heat gain from fenestration systems of arbitrary complexity. We conduct a wide range of activities to establish the facilities, tools and data to address these problems.

Solar-Optical Properties of Complex Fenestration Systems

A quantitative understanding of the solar-optical properties of fenestration systems is essential to accurately predict their luminous and thermal performance for any sun, sky or ground conditions. "Luminous performance" refers to daylight illuminance and luminance levels used to determine electric lighting requirements and luminous comfort. "Thermal performance" refers to direct and diffuse solar heat gain levels used to determine heating/cooling requirements and thermal comfort.

The method that we are establishing (Figure 6) is based on treating fenestration systems as radiation sources of varying intensity distribution that can be calculated from their bidirectional solar-optical properties. The solar-optical properties of fenestration systems are determined from the bidirectional solar-optical properties of their component layers, using the computer program TRA (Transmittance/Reflectance/Absorptance). The bidirectional solar-optical properties of component layers are determined experimentally, using our scanning radiometer (Figure 7).

The output of TRA is used by the component programs SUPERLITE and SSG (Sun/Sky/Ground). SUPERLITE determines daylight illuminance and luminance coefficients. SSG determines direct (from the sun) and diffuse (from the sky and the ground) transmittance and absorptance (by component layer) coefficients for any sun, sky, and ground conditions.

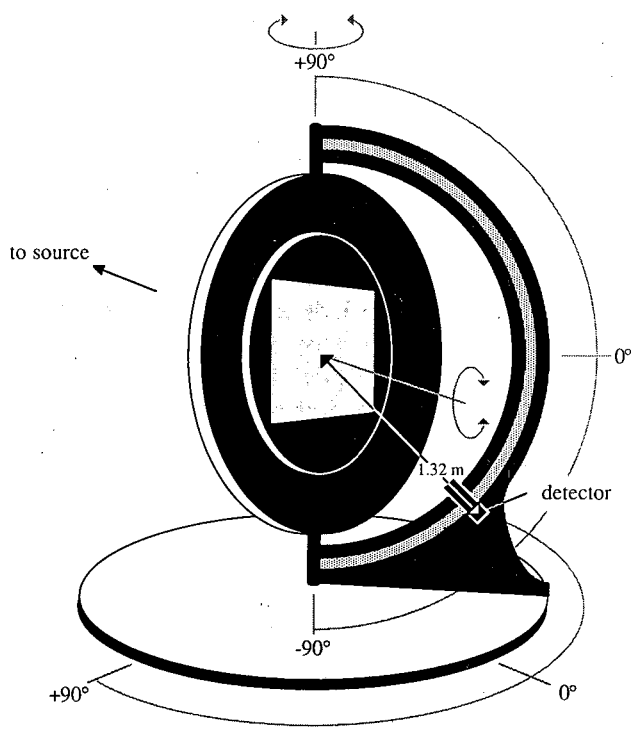

Figure 7. The scanning radiometer for measuring the bidirectional transmittance and reflectance of fenestration components and systems. (XBL 884-1472)

These direct and diffuse transmittance and absorptance coefficients are then used by the computer program WINDOW to determine solar heat gain coefficients.

Finally, the output of SUPERLITE and WINDOW is used by the computer program DOE-2.1 to determine hourly energy requirements for lighting, heating, and cooling and luminous and thermal comfort.

Accomplishments During FY 1987

Our work concentrated on the development of the scanning radiometer and the software for its operation, data acquisition and analysis. We also worked on the development of the computer programs TRA, SUPERLITE and SSG.

The scanning radiometer was fully automated and was used to determine the bidirectional optical properties of diffusing and slat-type shading systems (Figures 8 and 9). These measurements were used for identifying the limitations of our experimental techniques, as well as for validation of the computer program TRA. The scanning radiometer data analysis computer program and the computer program TRA were developed to operate on the same library of solar-optical properties of fenestration components and systems. A new version of SUPERLITE was developed to directly use the bidirectional transmittance coefficients produced by TRA.

The computer program SSG was developed for vertical and horizontal shading applications and was used with directional-hemispherical transmittance coefficients of venetian blinds (Figure 10) that were determined using our integrating sphere (Figure 11). SSG operates on the same solar-optical properties library as TRA and accounts for the CIE standard overcast and clear sky luminance distributions and uniform luminance distribution for the ground.

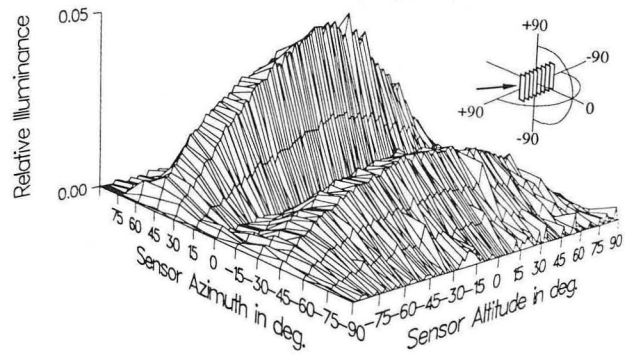

Figure 9. Transmitted distribution through a slat-type sample of 60-degree incident angle of incoming radiation on a plane normal to the slat direction. (XBL 884-1471)

Planned Activities for FY 1988

We plan to finalize our method for the simulation of luminous and thermal performance of fenestration systems. We will concentrate on installing the scanning radiometer in its new location in Building 70, and completing the final version of the operation and data acquisition/analysis hardware and software. Using scanning radiometer and integrating sphere measurements, we will validate our experimental procedures and the computer program TRA.

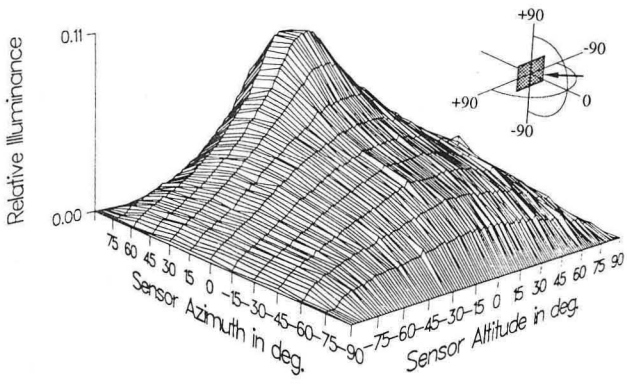

Figure 8. Reflected distribution by a diffusive sample for 45-degree incident angle of incoming radiation. (XBL 884-1470)

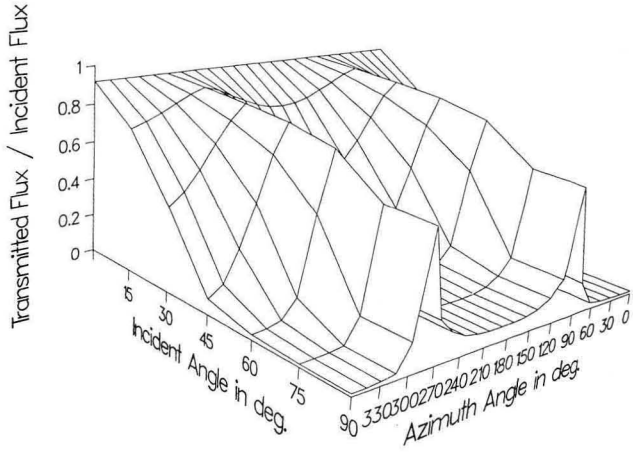

Figure 10. Directional-hemispherical transmittance of grey aluminum venetian blinds. (XBL 884-1473)

Figure 11. The integrating sphere for measuring the directional-hemispherical transmittance of fenestration components and systems. (CBB 837-6399)

DAYLIGHTING ANALYSIS

The prediction of lighting quantity and quality in the luminous environment is essential for energy-efficient lighting design. Over the years we have developed a range of daylighting design tools to expand our modeling capabilities and improve calculation accuracy. In the process, we have developed a state-of-the-art daylighting analysis model, SUPERLITE 1.0, which is widely used by researchers and to a lesser extent in lighting design. While continuing to expand SUPERLITE 1.0 to model more sophisticated daylighting systems such as complex fenestration systems, we enlarged the scope of our design tool development to include tools that can assist lighting designers in making qualitative assessments of luminous environments.

Accomplishments During FY 1987

We continued development of SUPERLITE and made progress toward modeling complex shading systems by incorporating measured bidirectional transmittance. We modified SUPERLITE to enable it to model optically complex fenestration systems with a bidirectional transmittance data set temporarily limited to 100 incoming and 100 transmitted light directions.

We collaborated with the ABACUS group, University of Strathclyde, Scotland, in developing an advanced lighting model to be incorporated into the three-dimensional color-rendering program DIM (Dynamic Illumination Model) that will not only produce numerical illumination levels but also display realistic images of a lighted space. The preliminary graphic images produced indicate a great potential for qualitative analysis of luminous environments (Figure 12).

Planned Activities for FY 1988

We will move beyond SUPERLITE's limitation on bidirectional transmittance data sets to enable us to model complex fenestration systems. We will begin validation of the new SUPERLITE model by comparing calculated results with data from scale model measurements. We will also develop the capability to display SUPERLITE output as three-dimensional shaded surfaces. We will also continue to collaborate with ABACUS to improve the new multichromatic lighting model.

Coefficient-of-Utilization Model for Energy Simulation Models

Computer models for building energy analysis must be able to predict the daylighting performance of the complex designs commonly used by innovative architects. The models should either internally calculate the daylight illumination or be supplied with data calculated by other illumination models or measured in scale models. The first approach, internal calculation of daylight illumination, is generally impractical for complex designs because of the significant computational cost and complexity required to obtain reasonably accurate answers. We are therefore developing a coefficient-of-utilization (CU)

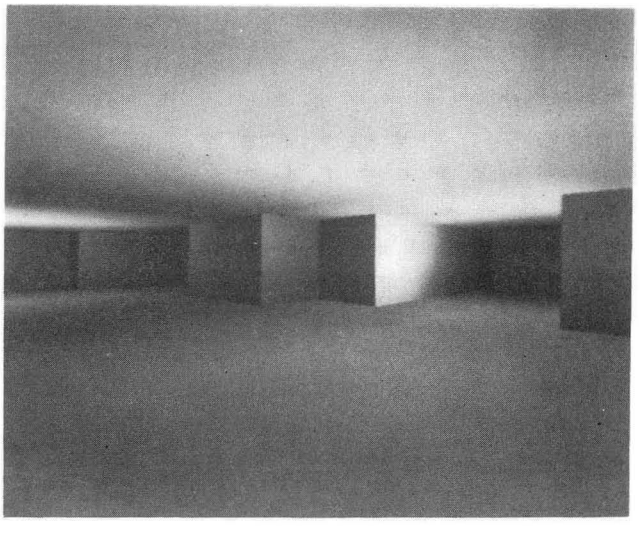

Figure 12. Image of a test space having surface luminance values calculated by DIM and plotted by a three-dimensional rendering program to display realistic images of the lighted space. (XBB 884-4095).

model that will be compatible with an hour-by-hour simulation model but still retain the flexibility and accuracy of more complex computational models.

Accomplishments During FY 1987

During FY 86 we developed the framework of our new daylight coefficient-of-utilization model; we identified seven indoor illuminance components based on the light sources (the sun, overcast sky, clear sky and ground) and the pathways (direct and indirect) to a location indoors. We also produced a new version of SUPERLITE 1.0 to be the primary source of indoor illuminance data.

Developing simple regression equations that can provide indoor daylight illuminance for a wide range of sun and sky conditions and for a variety of building configurations is a formidable task. During FY 1987 we focused on generating a CU equation for each illuminance component of a geometrically simple room. We generated seven principal forms of CU regression equations, aiming for expressions that are easily expandable and can handle the CU data from geometrically complex spaces in the future. The regression equations for direct components include variables relevant to window geometries, while those for reflected components include variables for room geometry and surface reflectances. Limited validation tests were also done.

Planned Activities for FY 1988

The improvements and detailed validation tests for the CU regression equations will be initiated. We will work with the DOE-2 group to add the new daylighting model to the DOE-2 program.

The Sky Simulator and Daylight Photometric Laboratory

A 24-ft-diameter hemispherical sky simulator (Figure 13) was designed and built on the University of California's Berkeley campus in 1979. In operation since 1980, it can simulate uniform, overcast, and clear-sky luminance distributions. Sky luminance distributions are reproduced on the underside of the hemisphere; light levels are then measured in a scale-model building at the center of the simulator. From these measurements we can accurately and reproducibly predict daylighting illuminance patterns in real buildings and thereby facilitate the design of energy-efficient buildings. The facility is used for research (Figure 14), for educational purposes, and on a limited basis by architects working on innovative daylighting designs.

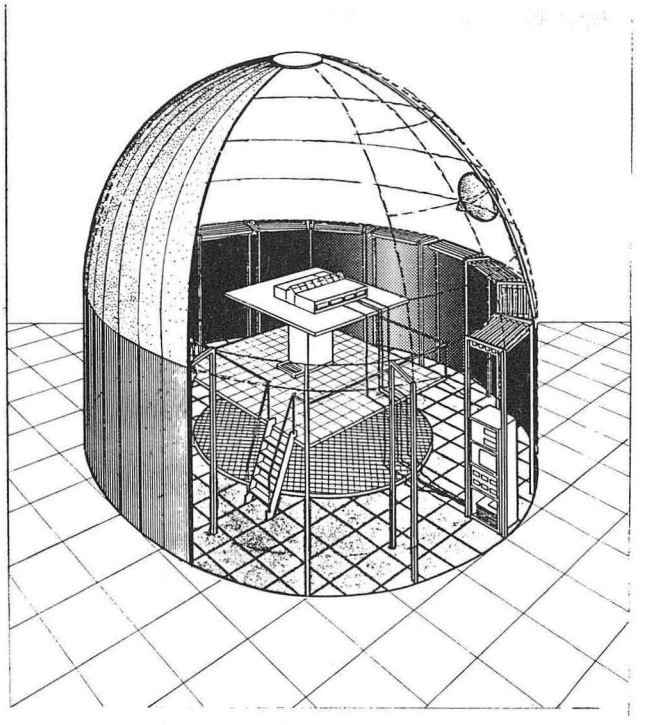

Figure 13. Schematic of 24-ft diameter sky simulator with model on platform. (XBL 8412-5328)

Daylight Availability Studies

Accurate daylight availability models are necessary for many design and energy analysis simulations. However, a widely accepted generalized model of availability in the U.S. has yet to be developed. We began work on this topic in 1978 and published three papers analyzing daylight availability data for San Francisco.[7-9] Analysis focused on the relationship of measured illuminance and irradiance to atmospheric parameters such as turbidity. New functional relationships were developed for an illuminance turbidity for visible radiation analogous to the conventional turbidity terms used with solar radiation and for zenith luminance as a function of turbidity. We found that our clear-sky luminance distribution data agree well with data from currently accepted European models.[10]

Our focus then shifted to developing a better understanding of the nature of partly cloudy skies. Although some progress was made using a sky luminance mapper, this activity was terminated due to budget limitations. We continue to collaborate on daylight availability with Florida Solar Energy Center (FSEC) where a new instrumentation package for detailed sky measurements is now in operation.

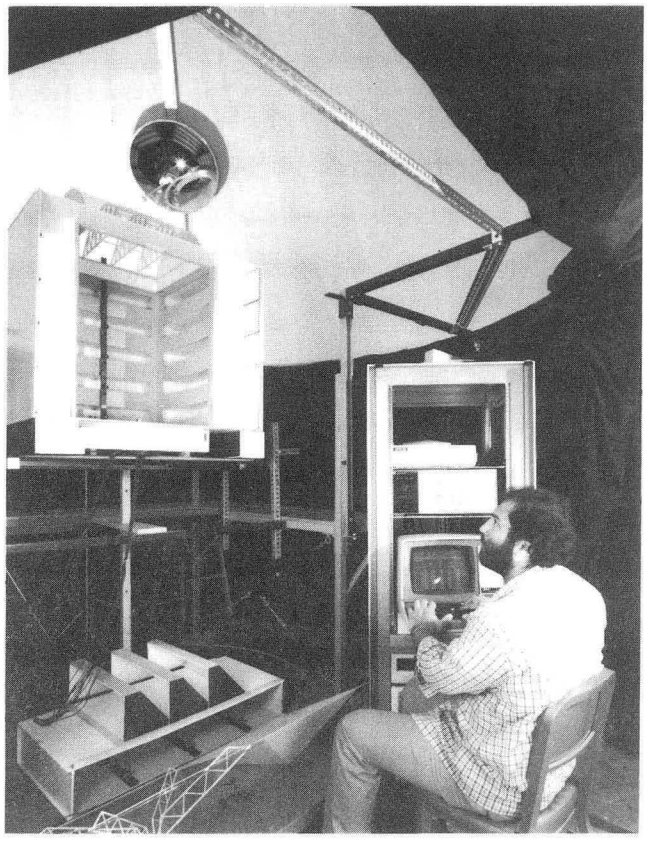

Figure 14. Interior of sky simulator showing reconfigurable scale model of a five-story atrium (with one side removed). (CBB 848-5926)

FIELD MEASUREMENT OF FENESTRATION THERMAL PERFORMANCE

We have known for some time that wintertime solar heat gain through south-facing windows in conventional buildings is a significant source of "free" energy. Subsequent calculations have indicated that it is technically possible, for any orientation in any U.S. climate, to optimize windows to the point that they become positive contributers to a building's energy needs.

This claim is not likely to be widely accepted without firm experimental verification. However, to measure the performance of highly optimized window systems in a realistic way is a formidable measurement task, requiring specialized non-steady-state calorimetry on a scale never before attempted.

To perform these measurements, a unique facility, the Mobile Window Thermal Test (MoWiTT) facility, was designed, built, and calibrated. In developing this facility it was necessary to solve the problem of doing calorimetry on a room-sized enclosure (which would normally require careful maintenance of constant equilibrium conditions) in the presence of the solar fluxes and changing outdoor temperatures that control the behavior of a fenestration system. We solved this problem with a large-area heat-flux sensor and a very sophisticated measurement of the heat extracted from the calorimeter by its cooling system. The MoWiTT, shown in Figure 15, began operation in 1986 at a field test site in Reno, Nevada.

Accomplishments During FY 1987

One of our first tasks was a study of newly commercialized low-emissivity insulating glazings. Though these glazings are offered by nearly every major U.S. glass and window supplier, there had been no convincing demonstration of their predicted energy savings in actual use, and the many products with different emissivities (hence, different U-values) had engendered considerable confusion in the marketplace.

A definitive study using the MoWiTT is ending this uncertainty. During 1986 we showed that these low-E insulated glazings show the expected improvement in U-value: a 35% reduction in nighttime heat loss. Further measurements of the net heat flow through the window demonstrated the effects of solar absorption in the low-E coating. Because of this absorption the overall effect of adding a low-E coating to double glazing is not simply the difference in nighttime heat loss: daytime solar heat gain is also

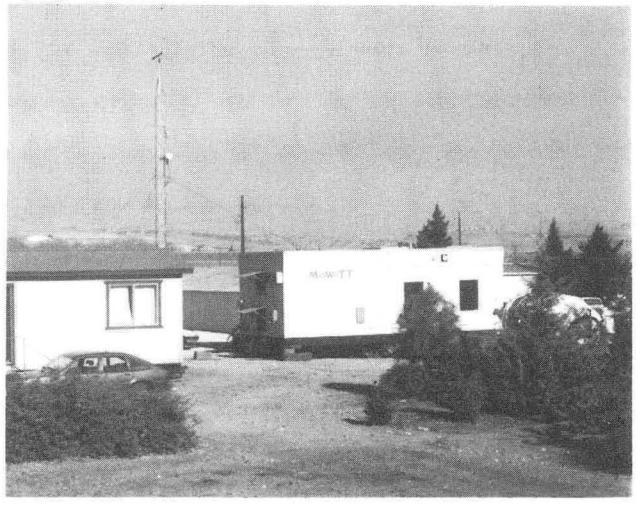

Figure 15. The MoWiTT facility at its field test site in Reno, Nevada. Two sealed insulating glass units are mounted in the two calorimeters. The portable building at left contains the computer that controls the facility and records data, including data from the on-site weather tower. (CBB 8611-10756)

reduced. The net effect of the fenestration on a building's energy balance depends on the extent to which the solar gain is beneficial or detrimental, and this depends on climate, orientation of the fenestration, and the building's heating and cooling demand and thermal storage capacity. Thus, knowledge of the true heat transfer through the window as a function of time is necessary to utilize the new window product in an optimal way.

During 1987 we extended these measurements to include cold winter conditions and other orientations. In Figure 16 the measured net heat flow through the fenestration over time shows the effect of U-value improvements for different orientations. Part (a) shows simultaneous measurements of low-E double glazing (points) and single glazing (solid curve) in a southern orientation (January 1987). Both fenestrations are large energy gainers during daytime; to the extent that this solar gain is useful, the lower transmission of the low-E tends to offset its nighttime advantage. The smaller daytime gains in the northern orientation (b) enhance the advantage of low-E (February 1987).

We studied the performance of a high-R, triple-glazed window incorporating two low-E coatings and a heavy gas fill. Figure 16 (c) shows that this window provides further improvement in a northern orientation. The shift in daytime net heat flow of the single glazing (solid curve) is a result of lower solar transmittance of the window and the higher daytime temperatures during these measurements (March 1987). The sharp daytime peaks in the single glazing curve are the result of transients in the measuring equipment and should be disregarded.

A systematic field study of the overall thermal performance of conventional glazing systems is also under way. Because window characteristics such as U-value are affected by ambient conditions, laboratory testing of window properties to predict the heating or cooling energy use attributable to the windows has been controversial. The impact of solar gain through windows adds further complications. Beginning with simple frameless windows and working toward progressively more complex systems, our study will test current methods (such as DOE-2) of calculating window performance in detail, and will delineate how useful simplified models as can be.

During 1987 we conducted extensive tests of windows with frames (a cooperative project with support from the Bonneville Power Administration). When completed, this study will demonstrate the importance of frame design and the accuracy of hot-box measurements for prediction of window thermal performance. Exploratory studies of air infiltration through windows were also begun.

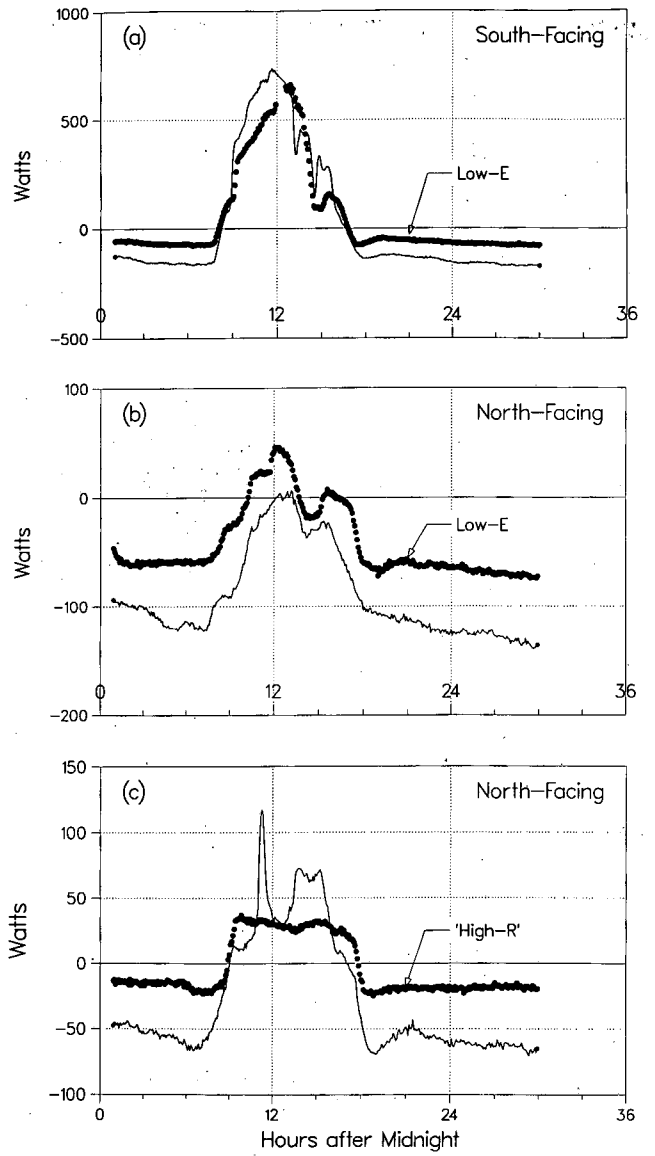

Figure 16. Measured net heat flow as a function of time. (a) Low-E (points) and single glazing (solid curve), south-facing. (b) The same pair of windows, north-facing. (c) High-R window (points) and single glazing (solid curve), north-facing. (XBL 884-1475)

Planned Activities for FY 1988

During FY 1988 we will further explore the relationship between thermal losses and solar gain with measurements of glazings of various transparencies and on managed fenestration systems. We will complete the study of windows with frames and begin a new study, in cooperation with ASHRAE, of solar heat gain through complex fenestrations including nonspecular shading devices. These and future measurements with the MoWiTT have the potential

for removing uncertainties about window performance that have slowed progress in energy conservation for a decade.

BUILDING APPLICATIONS AND DESIGN TOOLS

Research to develop new glazing materials and to better understand fenestration performance will provide real energy savings only if the technology is effectively applied in buildings. Using the technology requires that we have a detailed understanding of how a wide range of fenestration systems can be optimally used in different building types and climates, and that we pass this understanding, through design tools, to building design professionals.

SIMULATION STUDIES: NONRESIDENTIAL BUILDINGS

While most building energy simulation studies have focused on minimizing total energy consumption, other issues are equally important. Peak electrical demand affects both user costs and the utilities' required generating capacity. A complete study of the cost-effectiveness of fenestration systems, particularly those incorporating daylighting strategies, must include their impact on peak electrical demand as well as on energy savings. In addition, issues such as comfort and convenience affect the user acceptance and, consequently, the net energy efficiency of these systems. Our studies explore the interactions of these issues.

Accomplishments During FY 1987

During the past several years the effects of a wide range of glazing properties, window sizes, lighting loads, orientations, and climates on the energy performance of a prototypical office building have been simulated with DOE-2.1.[11, 12]

Initially we examined the impact of fenestration properties and daylighting strategies on office building energy performance and peak electrical demand. Lighting energy savings resulting from daylighting were examined for a range of fenestration properties and lighting control systems. Annual energy consumption of an office module was found to be sensitive to variations in U-value, shading coefficient, and visible transmittance, as well as glazing area, orientation, climate, and operating strategy. Sample results from our simulation studies are shown in Figure 17.

We conclude that, in almost all instances, it is possible to design a fenestration strategy that outperforms a solid insulating wall or roof, and that daylighting is almost always an essential component of energy savings. If the installed electric lighting power density is high, the energy savings potential is large. More efficient electric lighting systems reduce daylighting benefits.

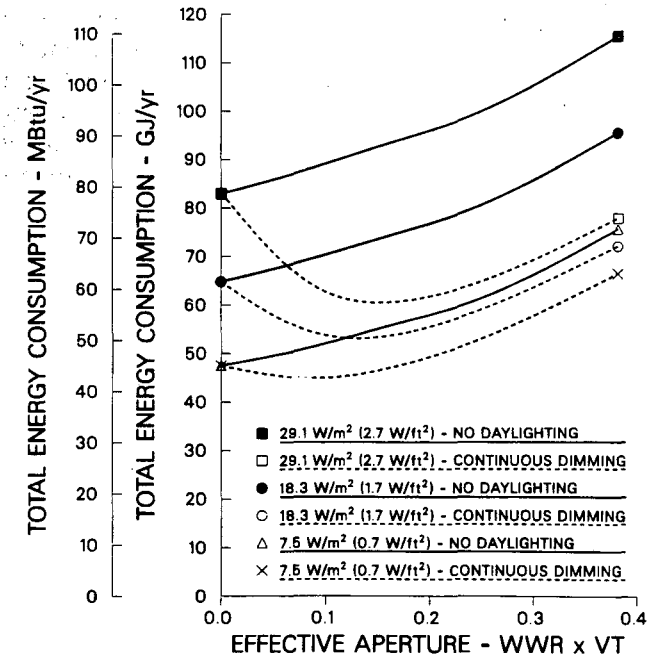

Figure 17. Annual energy consumption in the south zone of an office building in Madison, WI, as a function of window area. "Continuous dimming" indicates controlled reductions in electric lighting response to daylight; "no daylighting" indicates no dimming. (XBL 876-2796)

The net benefits of fenestration are highly dependent on the trade-offs between daylighting savings and cooling loads resulting from solar gains.[13] Visible transmittance properties, improved shading design, and window management will thus assume increasing importance for maximizing energy benefits from daylight. Our studies have demonstrated that the common assumption that daylighting is a "cooler" source of light than electric lighting is not necessarily true. In Figure 18 cooling loads for daylighting with several fenestration options are compared with cooling loads from electric lighting. We have developed and are refining a methodology[14] for comparing cooling loads imposed by daylight (or electric light) through the use of an index derived as a fraction of three parameters:

(1) the relative T_{vis} and SC of the glazing or shading system;
(2) the distribution of daylight within the space; and

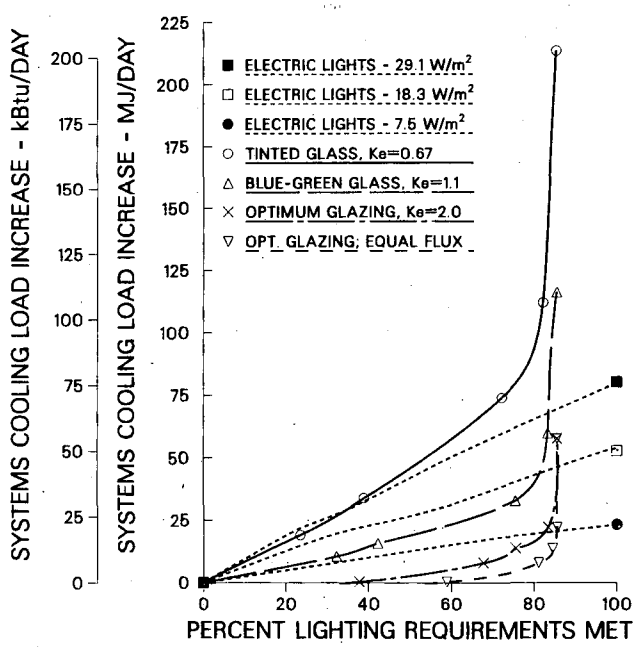

Figure 18. Increase in cooling requirements as a function of lighting strategy and glazing properties in a south zone on a clear March day. The "optimal glazing" has good selection properties (high K_c) and distributes the transmitted flux uniformly throughout the space. (XBL 884-1474)

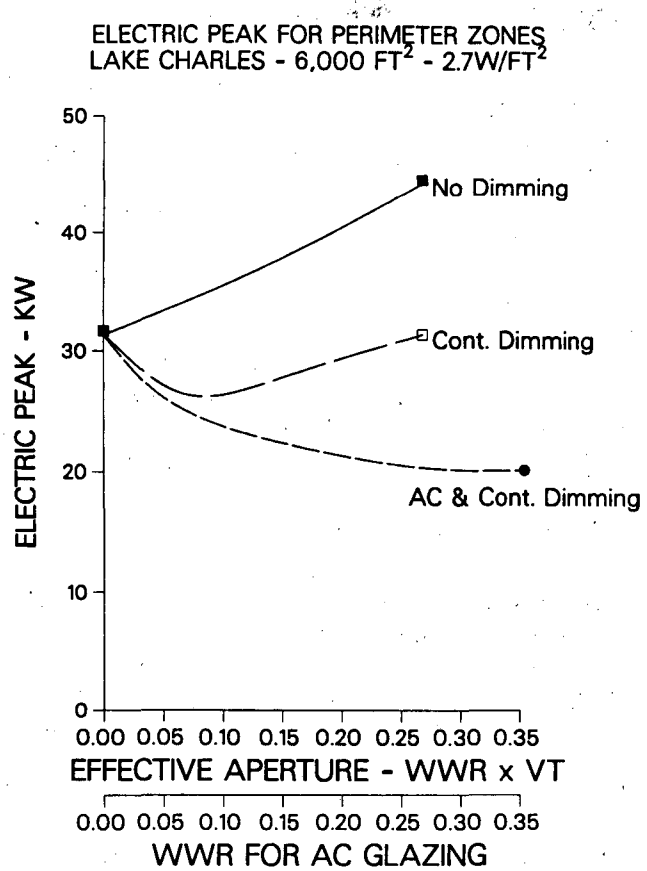

Figure 19. Results from DOE-2.1B energy simulations of a 6000-ft^2 office building in Lake Charles, LA, showing the effect of daylighting on peak electrical demand as a function of effective aperture. "AC" stands for a hypothetical glazing with transmittance actively controlled in response to solar gain level. (XBL 876-2802)

(3) the time-dependent absolute transmitted solar intensity.

We continued our general studies on the peak-shaving potential of daylighting with results that show—despite solar gains—daylighting can significantly reduce peak electrical demand during summer months. The critical trade-offs—between electric lighting reductions from daylighting and cooling load increases from solar gain—help determine the combination of window properties that minimize building peak loads. In Figure 19, annual peak electrical demand is shown for our prototypical building in Lake Charles, LA.

The most significant potential improvement in commercial building energy performance lies in the use of advanced glazing materials having dynamic optical properties and active response functions to control daylight and solar transmittance. Simulation results using these materials are shown in Figure 19 and compared to results with conventional glazing.

Skylights can also provide significant energy and cost benefits. Daylighting benefits are maximized with relatively small ratios of skylight effective apertures areas (0.01–0.04). Because skylights provide more uniform daylight distribution, the cooling load impact of daylighting may be less than with vertical fenestration. As effective aperture is increased beyond the optimum, cooling loads in most climates rise to adversely affect net annual energy performance.

A large number of DOE-2.1 runs for window and skylight studies have provided enough data for multiple regression techniques to develop analytical expressions of energy requirements as functions of glazing parameters; from these we may be able to develop a generalized expression to accommodate climate variables. The simple expressions correlate well with DOE-2 results and may become a design tool to assess energy and cost trade-offs among fenestration options. We have incorporated the regression equations developed in our skylight studies in a skylight design handbook sponsored by AIA, AAMA, and NFC,[15] and this procedure is the basis for the LRI fenestration performance indices described in the next section.

Planned Activities for FY 1988

New studies will examine the performance of more complex shading systems for which adequate solar optical data do not now exist. Optical properties of shading devices measured in our new laboratory facilities will be used in these studies. We will also continue to look at variations in window management strategies, issues of daylight luminous efficacy, advanced glazing materials, the effects of fenestration performance on HVAC, and the effects of various HVAC options on fenestration performance. The costs of fenestration design and daylighting as influenced by peak electrical demand, annual energy use, and chiller size will be examined.

FENESTRATION PERFORMANCE INDICES

We have completed the first phase of a two-part study to develop numerical indicators that can be used by architects, designers, builders, and others to determine the energy and comfort performance of fenestration systems[16]. Sponsored by the Lighting Research Institute, (with support from Electric Power Research Institute and New York State ERDA) the work was done in collaboration with the Florida Solar Energy Center. In Phase 1 we developed the basic methodology for determining the performance indicators in nonresidential buildings and tested the techniques for a few sample fenestration systems. In Phase 2, we will perform the measurement and analysis tasks required to construct a large data base of indices for most of the common generic fenestration systems. We also plan to develop a microcomputer tool to embody the project's results.

Accomplishments During FY 1987

We developed the concept and methodology for a fenestration performance design tool that will enable users to evaluate the fenestration systems of nonresidential buildings using a microcomputer. Performance indices for electric energy usage and peak demand, fuel usage, and thermal and visual comfort were established and a procedure proposed for the definition of an overall figure of merit. The figure of merit incorporates user-defined weighting factors that assign relative weights to each performance index. Figure 20 shows sample figures of merit for evenly weighted performance indices for four glazing types. We developed a prototype computer design tool so that potential users can evaluate the methodology and offer recommendations for improving the final tool in Phase 2.

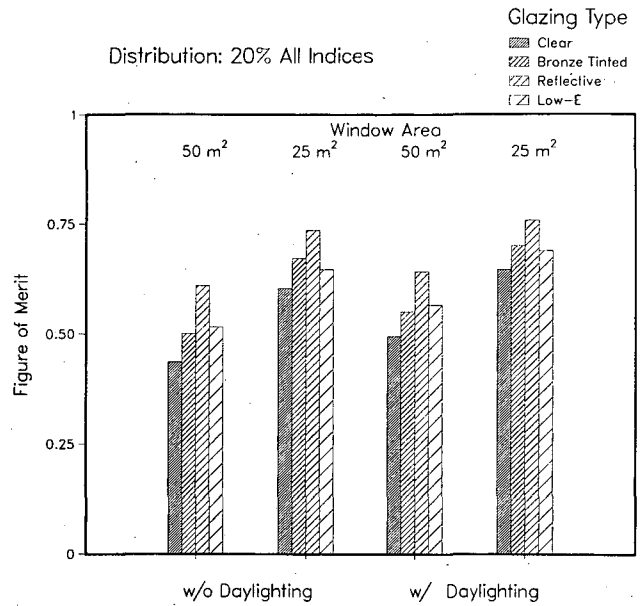

Figure 20. The figure of merit compares the performance of fenestration systems. Here the five performance indices are equally weighted (20% each). Results are shown for four glazing types and two window sizes, with and without lighting controls and daylighting. (XBL 884-1476)

Planned Activities for FY 1988

We will begin Phase 2 during FY 1988. Performance data will be calculated and a computerized data base constructed for conventional fenestration systems and complex operable shading systems. The primary Phase 2 product will be a microcomputer tool to access and process the fenestration data base and to apply user-defined weighting functions. The specific form and capabilities of the final tool will be based on extensive consulation with the project sponsors and feedback from professional user groups.

SIMULATION STUDIES: RESIDENTIAL BUILDINGS

The growing number of new window technologies in the residential sector make window selection a difficult task. Over the last few years we developed analytical techniques to predict window performance for a wide range of technology options and climates.[17] We have developed a regression analysis method to translate an energy use data base into algebraic expressions to directly calculate which window properties will optimize energy use or other values. Our analysis efforts are beginning to show potential for developing powerful new tools for determining residential fenestration performance.

Accomplishments During FY 1987

We continued our analytical studies to simplify the procedures for predicting the energy effects of windows in residences. We concentrated on determining the relationship between different residential prototypes so that in the future we can significantly reduce the number of required computer simulations. We continued studying our regression expressions to better understand the component load and incremental costs associated with windows. Extensive data on low-E window performance were generated for Madison, WI, Lake Charles, LA, and Phoenix, AZ (Figure 21).

Reliable and accurate data on energy performance are needed by builders in a form that is easily accessible and useful in building design. Working with representatives of the residential building industry, we began efforts to make our technical information available to designers by translating it into accessible formats.

Planned Activities for FY 1988

Our objective is to develop handbooks, charts, nomographs, and computer software to help builders and suppliers assess window strategies. The immediate goal in FY 1988 is to develop a series of informative "design notes" for builders and to create a prototype residential fenestration design tool to stimulate building industry interest in collaborative development of a comprehensive tool.

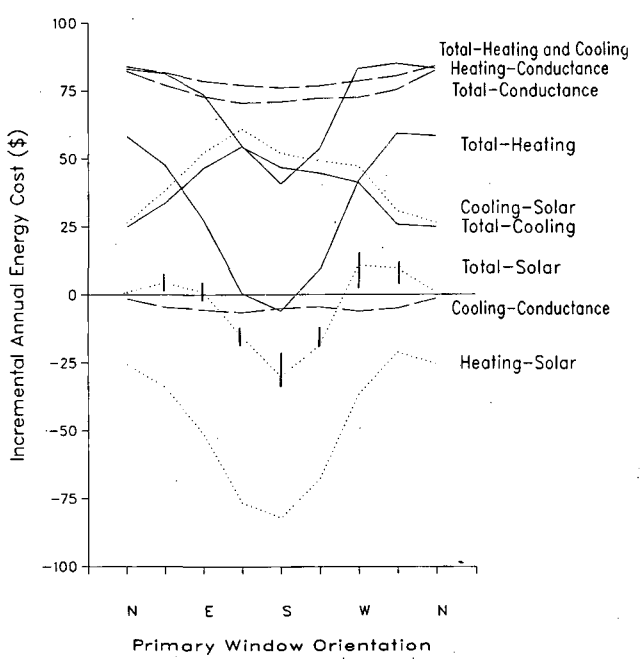

Figure 21. Incremental annual energy cost components for varying orientation of a double-pane window with low-E coating with an area of 18.39 m^2, U-value of 1.94 W/m^2C, and shading coefficient of 0.73, in Madison, WI. Positive values represent heating costs, negative values heating savings. (XBL 885-1478)

DESIGN TOOLS AND TECHNOLOGY TRANSFER

To influence energy consumption trends in the United States, it is critical to communicate our results to other researchers and professionals. We use a variety of media to reach a widely varied audience: other research and development groups, educational institutions, and professional and industrial societies. We have developed improved daylight analysis and design tools and handbooks, carried out design assistance studies, and sponsored workshops and meetings with manufacturing and design firms and public utilities.

Technology Transfer

We continually communicate research results to design professionals and industry through conferences, workshops and seminars.

Daylighting Conferences. At the conclusion of the 1986 International Daylighting Conference, we assisted in promoting the conference's general proceedings[18] to professional and industrial societies and educational institutions. The refereed technical proceedings will be published in 1988.[19]

Daylighting Network of North America. After several years of organizational growing pains the Daylighting Network of North America (DNNA) has established an active membership of 35 universities with research and instructional interests in daylighting. The DNNA has expanded the avenues for transferring daylighting research results to professionals, educators, and students.

In FY 1987 faculty and students from several DNNA centers worked at LBL on daylighting projects. We plan to continue these informal exchanges in FY 1988. LBL also supported an electronic network of eight authors from different universities jointly writing a handbook, *Simulating Daylight with Architectural Models.*[20]

The Network makes a concerted effort to plan and implement professional educational and design assistance programs. One successful vehicle has been the *DNNA News,*[21] currently published at the University of Michigan. SUPERLITE 1.0 and DOE 2.1B and C continue to be disseminated to faculty

and practitioners by one of the regional centers. Of special significance is a three-year major research and education effort at the University of Minnesota DNNA Center. Faculty will be developing professional workshop curriculum, computer course demonstrations, and daylighting information data bases for students and building professionals in the state, using many daylighting tools and data bases developed at LBL.

The Network will continue to distribute design software and promote joint research projects. Establishing a sabbatical-timed program for visiting researchers at LBL will be a priority.

Design Tools

The Windows and Daylighting Group and subcontractors develop and distribute daylighting design tools to industry and educational institutions. Private-sector software firms continue to introduce new design tools for daylighting, but evaluation and comparison are difficult. There is a need: (1) for a comparative matrix identifying the capabilities of existing tools, and (2) for photometric data and evaluation procedures to compare these tools.

Accomplishments During FY 1987

We continued distribution of the Daylighting Design Tool Survey,[22] SUPERLITE, Daylighting Nomographs and other tools and data.

Skylight Handbook/Design Guidelines. The *Skylight Handbook,*[15] based on technical research done by LBL, was completed and published by the Skylight and Space Enclosure Division of the American Architectural Manufacturers Association (AAMA), and distributed to building professionals. The handbook's energy design data worksheets will be converted to a microcomputer program during the coming year. The *Skylight Handbook* is expected to serve as a model for joint development of handbooks and design guides with other public and private professional organizations.

Advanced Design Tool. Our long-term interest is in the development of the next generation of sophisticated hardware and software design tools. The Advanced Envelope Design Tool (AEDT) development has moved on several levels over the past year. The computer data base of hardware and software continues to track market trends. We have formed professional liaisons with major architectural firms, software manufacturers, and building organizations for the purpose of developing joint activities. Believing imaging technology to be a key to any future design tool, we have explored CD-ROM technology for possible use in the AEDT. We also continued investigations of knowledge-based systems and advanced simulation models at a low level.

Planned Activities for FY 1988

We plan to form a Berkeley working group of research projects at the University of California and LBL. With combined resources and expertise, the development of a prototype interactive microcomputer-based tool to illustrate the potential of the AEDT could be realized.

We expect to integrate our interest in the Advanced Envelope Design Tool with a broader DOE-sponsored effort on advanced tools for whole-building design.

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Lighting Systems Research*

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We estimate that 50 percent of the electrical energy consumed by lighting, or about 12 percent of total national electrical energy sales, could be saved by gradually replacing existing lighting with energy-efficient lighting. This would amount to a yearly savings of some 220 billion kilowatt-hours of electricity.

The objective of the Department of Energy's National Lighting Program is to assist the lighting community (manufacturers, designers, and users) in achieving a more efficient lighting economy. The program carried out at Lawrence Berkeley Laboratory (LBL) represents a unique partnership between a national laboratory-university complex and industry, facilitating technical advances, strengthening industry capabilities, and providing designers and the public with needed information.

To implement its objectives, the Lighting Program's efforts are divided into three major categories: advanced light sources, building applications, and impacts on human productivity and health.

The advanced light sources component undertakes research and development projects that are both long-range and high-risk, leading to more efficient sources of light. These are projects in which the lighting industry has an interest, but which it does not pursue on its own, and from which significant benefits could accrue to both the public and industry. These efforts involve the disciplines of physics, chemistry, and electrical engineering.

The building applications component undertakes research on the electromagnetic compatibility of high-frequency lighting with building functions, including machinery, computers, and other electrical and electronic systems; the interaction of lighting with building energy systems; and the use of lighting controls and fixtures to optimize lighting benefits. These efforts combine the disciplines of engineering, architecture, and lighting design.

The impacts component examines relationships between humans and lighting, looking to ensure that energy-efficient technologies contribute positively to human productivity and health. These efforts are interdisciplinary, involving engineering, optometry, physiological optics, and medicine.

Since its inception in 1976, the LBL Lighting Program has produced more than 124 reports and publications. These reports are available to the public and document research on subjects such as solid-state ballasts, operation of gas-discharge lamps at high-frequency, isotopically enriched fluorescent lamps, energy-efficient fixtures, lighting control systems, and visibility and human productivity. In addition to its research activities, the internationally recognized interdisciplinary staff is involved in a variety of professional, technical, and governmental activities.

The Lighting Program combines the facilities and staff of LBL with those of the University of California College of Environmental Design and School of Optometry, both on the Berkeley campus, and the School of Medicine in San Francisco (UCSF). Because the research is directed at both enhancing the capabilities and long-term viability of the lighting industry, and providing the design profession and the general public with needed information, the program is unique in the United States and the world.

Described below are highlights of the accomplishments realized in FY 1987 and activities planned for FY 1988 by each of our three major efforts: advanced light sources, building applications, and health impacts. Publications and conference presentations from the past year may be found in the publications list at the end of this chapter.

ADVANCED LIGHT SOURCES

The advanced light sources effort promotes new lamp technology and light source development. To see what can be accomplished in this area, consider that the most efficacious four-foot fluorescent lamp, operated at high frequency (20 kHz), has a luminous efficacy of approximately 100 lumens of light output per watt of electrical power input. Although this is more than five times as efficient as an incandescent lamp, still greater efficacies are possible. White light can, theoretically, be produced at almost 350 lumens per watt. The advanced lamp technology program is developing the engineering science that will help us achieve a target efficacy of 200 lumens per watt within the next few years. Table 1 lists the series of technical improvements that are proposed to reach that goal.

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Eliminating three significant loss mechanisms—self-absorption of ultraviolet (UV) radiation, electrical losses, and energy loss in lamp phosphors—in fluorescent lamps will improve their efficiency. In the first case we would like to reduce self-absorption of UV radiation, a process that occurs within the lamp plasma before the radiation strikes the phosphor-covered inner wall (the phosphor converts UV radiation into visible light). If, we decrease UV self-absorption, we increase the amount of UV radiation available to be converted into light, and therefore increase the lamp's light output.

In the second case, energy losses associated with electrodes can be eliminated by exciting the lamp plasma at radio frequencies (RF). The problem is to find an efficient method for coupling the RF energy into the lamp without causing new losses.

In the third case, we would like to develop a more efficient phosphor matrix that will convert one energetic UV photon into two visible photons. Reductions in self-absorption and electrode losses could provide a significant improvement, and a two-photon phosphor could double lamp efficacy.

LBL is studying several ways of reducing UV self-absorption. The first method is altering the isotopic composition of mercury. In its natural state mercury has seven stable isotopes, each with slightly different resonance UV emission spectra. Altering the naturally occurring isotopic composition can provide more escape channels for the resonance radiation, thereby reducing the probability of quenching collisions and increasing the amount of UV radiation reaching the phosphor. The most promising possibility is isotope alteration-enrichment with ^{196}Hg, which is being pursued in a joint effort by LBL and GTE Lighting. Should isotopic alterations prove economical, modified lamps would enter the market quickly. Lamps would simply be loaded with isotopically enriched rather than natural mercury, with other lamp manufacturing processes remaining the same.

Another method of reducing UV self-absorption was recently discovered at LBL based on the application of a d.c. magnetic field having a direction parallel to the main current. Axial magnetic field strengths of about 600 gauss can increase light emission by about six percent. LBL and major firms in the lamp industry are studying practical ways to apply this technique.

A highly promising mechanism developed at LBL uses a plasma coupling principle that eliminates the need for electrodes, it allows for lamp plasma excitation to occur primarily near the inner lamp wall and thereby, reduces both the electrode losses and the likelihood of entrapment loss. This surface wave mode of operation occurs at high frequencies, in the radio frequency (RF) range between 100 and 500 MHz, permitting efficient lamp excitation without electrodes. The surface wave lamp shows approximately 40 percent increased energy efficacy over normal fluorescents, operates without starting circuits, and should be very long lasting because of the absence of electrodes.

Reducing the effects of energy loss in the phosphors requires altering a lamp's phosphor material. The materials used today convert each UV photon into, at most, one visible photon. Improving this conversion rate would increase the efficacy of low-pressure discharge lamps. Although a UV photon has sufficient energy to permit the cascade conversion of the UV photon into two visible photons, this process must occur quickly to prevent heat-producing collisions. The intermediate level in the cascade must be tuned carefully, ensuring that both emitted photons are in the visible spectrum. LBL is examining the possibilities of a program in phosphor chemistry designed to discover whether the two-photon phosphor is feasible. The lamp industry, long aware of the complexity of this problem along with the extensive research required to provide solutions, is extremely interested in a cooperative effort.

If these research projects at LBL come to technological and commercial fruition, future fluorescent lamps should operate at high frequency and be isotopically enriched, magnetically loaded, and coated with a two-photon phosphor. Such lamps would have an efficacy of more than 200 lumens per watt, doubling the efficiency of today's best fluorescent lamps.

Other lighting technology research concentrates on high-intensity discharge (HID) lamps, which could be made both more efficient and dimmable if operated without electrodes. High-frequency operation is required to excite the lamp plasma in an electrodeless mode; it may also permit lamps to function with just one or two metal halides and no mercury or sodium. Electrodeless operation would also enable us to use compounds that have desirable light output and color, but that are excluded today because they would harm electrodes. Finally, an electrodeless lamp that could be dimmed without observable spectral changes and that could provide instant restrike could be used in many new ways improving energy efficiency and is therefore attractive to lighting designers. Table 1 summarizes our goals.

To address the lack of data on the plasma discharges, a program on plasma diagnostics has

Table 1. Targets of opportunity in lighting technology.

Technology	Comment	Total efficacy (lm/W)	Year entering market
Fluorescent lamps			
High-frequency operation		90	1980
Narrow-band phosphors		100	1983
Isotopically enriched	LBL/DOE	110	1988
Magnetically loaded	technical	120	1990
Two-photon phosphor	initiatives	180	1995
Gigahertz/electrodeless		230	1995
HID Lamps			
Today with (high-freq. ballast)			
400-W high-pressure sodium	(CRI-25)	100	1984
400-W metal halide	(CRI-66)	80	1984
400-W mercury	vapor	50	1984
Electrodeless/high/freq.			
1000-W lamps	10-15% improvement		1989
Low-W lamps	30% improvement		1989
New gases	20-25% improvement		1990
Color-constant/dimmable	20-25% improvement		1993

been initiated. It will measure a number of characteristics of both optically thin and thick plasmas (see Fig. 1).

Accomplishments During FY 1987

Mercury Isotope Separation and Enrichment

Continued progress has been made in assessing the feasibility of photochemical separation of natural mercury to produce mercury enriched in the isotope mass 196Hg. Three significant accomplishments achieved during FY 1987 are discussed below.

Basic to the photochemical process is the establishment of a high flux source of nearly pure 196Hg photons. This source is a centrally located quartz lamp that is filled with as pure a charge of 196Hg as possible. However the initial sample of mercury is not 100 percent pure and because the 196Hg hyperfine resonance line has some overlap with other isotopes, added frequency filtration is required to assure a pure product. As part of the separation system, frequency filtration has been successfully added that achieves the desired high photon flux with good isotopic selection.

The second accomplishment was measuring the overall transmission of the inner annulus wall of the reactor chamber, as a function of time and material deposition rate, to study the possibility of reducing in the incoming photon flux.

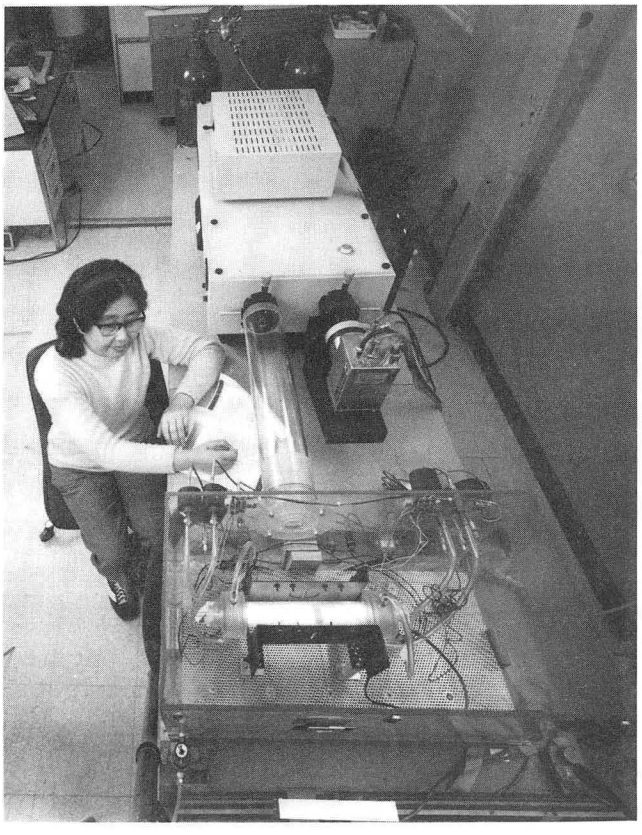

Figure 1. A test fluorescent quartz lamp loaded with a particular admixture of mercury isotope is examined spectroscopically at the UV resonance line. (CBB 870-9874)

The third accomplishment was the development of a new practical means of removing the product separated isotope in a continuous, rather than batch, process.

Magnetic Enhancement

The luminous efficacy of a 7-inch fluorescent lamp immersed in a nearly uniform axial magnetic field has been examined. We made provisions to isolate the electrode power loss from the total observed lamp dissipation in order to assure that the actual positive column luminous efficacy was indeed being determined. Data were taken for cold spot temperatures in the range (30 T < 48) and applied magnetic fields in the range (0 B 965 gauss). We found that the luminous efficacy of the positive column showed a maximum, with a cold spot temperature of 40.7° C and an applied magnetic field of 845 gauss. These data represent a 6.14 percent increase over the positive column luminous efficacy in the absence of an applied axial magnetic field. All measurements were made with constant arc current.

We observed that the total dissipation of the lamp under test increased with increases of applied axial magnetic field. Evaluation of the electrode power losses indicated that most, if not all, of the increased power requirement was dissipated at the electrodes, while the positive column dissipation remained approximately constant for all values of magnetic field studied herein.

The establishment of the size of the magnetic effect completes our investigation. Any further effects would be directed toward developments of viable methods of bringing a magnetic field into a lamp's environment.

Surface Wave Lamp (SWL)

Many detailed technical problems have been solved during FY 1987. In particular the thermal control system, the optical detection system, and the RF detection system have all been upgraded. We constructed a modular RF cage a modular RF cage to handle tubes from seven inches to four feet in length. The cage's wire geometry allows most of the light emanating from the lamp to be visible.

The surface wave lamp demonstration for display in the U.S. Senate building has been completed. We overcame a number of technical problems so that a non-technical person can operate the demonstration system and show the surface wave lamp's 40 percent improvement, in efficiency over an a.c. fluorescent lamp.

Our development of a special facility for high-intensity operation of a surface wave lamp has continued on schedule during the past year, including completion of the RF shielding, the optical collimator system, and the RF power measurement system. In addition, the high intensity launcher has been designed and should be fabricated during FY 1988.

End Fall Diagnostics

Further diagnosis of the end fall power losses by the movable cathode technique has been delayed because the test lamp was not fabricated according to specifications. A new test lamp is expected in early FY 1988. Using the imperfectly fabricated lamp, we compared measurements of voltage by moving the cathode with and untested current variation method yielding consistent but somewhat limited results. Tests with the new lamp are expected to clear up the present uncertainties.

Planned Activities for FY 1988

Mercury Isotope Separation and Enrichment

We will begin designing and constructing the next reactor of increased size and capacity, which will be capable of producing several grams of enriched mercury per day. We will use knowledge gained from using the smaller reactors to help us design the new one. Access, geometrical configuration, as well necessary spectrographic instruments will be taken into account in the new design so we will be able to measure the emission and absorption line profiles of the ^{196}Hg under conditions of variable reactant pressures and temperatures. Thus, the new design will permit thermodynamic sensitivity studies on the ^{196}Hg production as it depends on the HCl, Hg, and rare gas conditions. The new design will also permit measurement in-situ of performance and allow continuous monitoring of the processes. These efforts should lead to the production of enough enriched mercury that we can evaluate high-speed production of fluorescent lamps with the enriched product.

Electrodeless High Intensity Discharge (HID) Lamp

This project will start during FY 1988; first we will set up an induction system for operating experimental low wattage HID lamps at frequencies of 6.87, 13.56, 27.12, and 40.68 MHz. We will be able to introduce new gas fills to compare the new experimental lamps with existing low wattage electroded lamps. Special care will be taken to assure the accuracy of power measurements at these high frequencies; these measurements have been a major prob-

lem. Previous work by General Electric for LBL, has shown that bromide and chloride salts can produce good color and high efficacy in electrodeless HID lamps at high powers (1000 watts). After geometrical configuration permitting low power operation have been established, experimentation will begin on the applicability of the new gases in these low power configurations.

Surface Wave Diagnostics

The radial distribution of electrons (or ions) and excited mercury atoms is expected to be more skewed toward the lamp wall in the surface wave lamp than in the standard 60 Hz a.c. fluorescent lamp. General Electric Corporate Research and Development has a laser diagnostics which can measure mercury excited state radial distributions by the method of induced fluorescence in the a.c. lamp. We expect to negotiate a subcontract with GE asking them to extend their laser diagnostics capability to the surface wave lamp.

Surface Wave Lamp (SWL)

Optimization of the SWL parameters such as mercury and argon pressures, glass thickness, as well as operating frequencies is fundamental to establishing lamp efficacy. These measurements require several hundred test lamps, all of which will be fabricated by an outside vendor because we currently cannot produce them in house. Toward the end of FY 1988, subsequent to the addition of more laboratory space, a new lamp fabrication facility will be designed and installed as part of the lighting laboratory. In addition, when the optimum frequency characteristics have been established, an RFP will be developed to interest the electronics industry in a low-power high-frequency power supply.

BUILDING APPLICATIONS

Real energy savings depend on the transfer to the lighting community of energy-efficient technologies and strategies. The building applications activities aim to assess and, develop energy-efficient lighting technologies and combine their technical performance characteristics to model energy-efficient and cost-effective lighting geometries and controls. Our analysis uses knowledge of the relationship between visual performance and physical aspects of lighting, such as illumination level, distribution, contrast, and glare. As part of this effort, a computer program has been developed that provides accurate simulations of illuminated spaces with their contents. The simulated scenes are visibly indistinguishable from real photographs; using them, we can model effects of changes in the illumination systems. Validation of luminance values produced by these simulations requires physical measurements of luminances in complex environments. Therefore, the project uses a number of novel techniques for luminance mapping of interior environments with complex objects to obtain actual luminance values. The technology development component of this program examines engineering approaches to reducing light losses associated with conventional lighting fixtures. The conclusion of these efforts will be a combination of lighting systems technologies and analysis with a visual simulation of the proposed application representing the most compelling tool for promoting the implementation of energy efficient lighting. (see Fig. 2).

Accomplishments During FY 1987

Advanced Lighting Design

We selected a workspace for the Lumen-Micro computer program, which includes input from a variety of luminances and control systems. The program is then augmented and used to calculate the two principal metrics for assessing the value of a lighting environment: the average relative visual performance (RVP), and the visual comfort probability (VCP), a measure of glare present in the system design. These metrics, along with lighting energy economics, are the basis for a cost benefit analysis that can incorporate the engineering parameters of lighting systems.

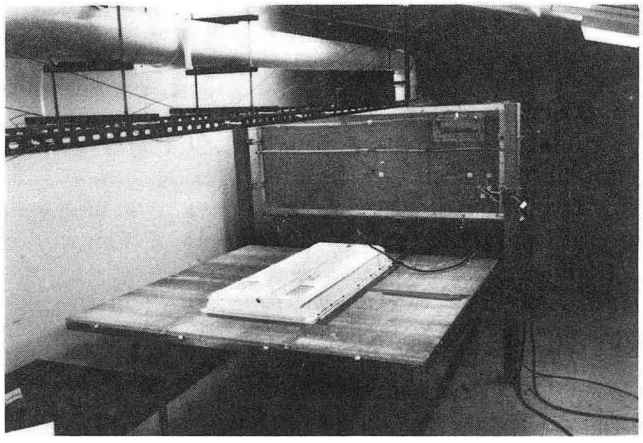

Figure 2. The testing facility for determining the heat generated by a typical combination lamp and luminance. (XBB 855-4074)

Progress in FY 1987 included gathering basic information on luminance types and lighting distributions, types of control systems and the variables needed for utilization of visual performance and visual comfort metrics. Workspaces were examined to locate a one with a good balance of reality, complexity, and feasibility for the Lumen-Micro program.

Computer Imaging

Computer logic has been developed capable of presenting visual images of illuminated spaces. The images show how different lighting equipment and techniques can change the appearance of illuminated spaces. The program has been developed to handle specular and diffuse reflecting surfaces. It can also handle complex objects in the space. An initial validation for simple spaces was performed by comparing luminance results with Lumen-Micro, a commercially available program that also computes luminances, but only for empty rooms with purely diffuse reflecting walls. Further validation is required based upon physical measurements of real interior objects such as furniture. (see Fig. 3).

Thermally Efficient Luminaires

Several years ago we demonstrated that luminaire performance could be improved by applying multiple dielectric coatings to reflecting surfaces. Further work was directed toward understanding the thermal performance of luminaires. It was found that fluorescent lamps in most fixtures operate well above the optimum temperature, which decreases light output and system efficacy. In a pilot study during FY 1987, we have shown that air handling luminaires can increase light output by as much as 20 percent. Demonstrations have shown that proper venting of enclosed ceiling mounted fixtures can increase output and efficiency by 15 percent.

Peltier Device

Virtually all fluorescent lamps in fixtures operate at temperatures above the optimum, which decreases light output and efficacy by 15 to 20 percent. A Peltier Device has been used to control lamp wall temperatures and reduce losses. The current systems are designed to be positioned on the external surface of the lamp wall. This design has been as a useful tool in the laboratory for characterizing fluorescent lamp systems.

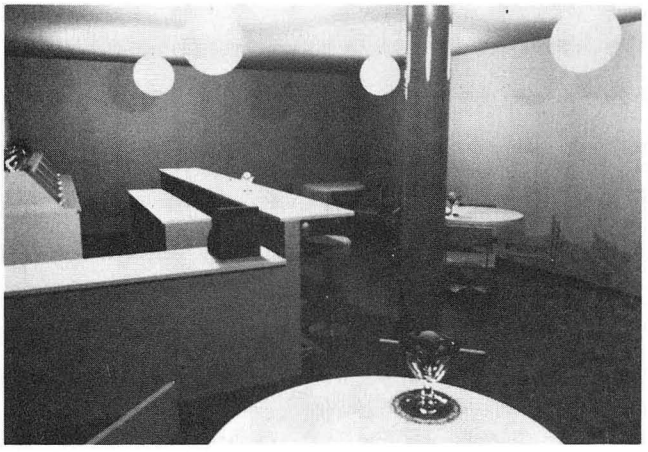

Figure 3. A computer generated "photograph" of an ice cream parlor. (CBB 878-6585)

Planned Activities for FY 1988

Advanced Lighting Design

During FY 1988 these elements will be brought together and a complete assessment of the totality of lighting factor will be performed. Cost of lighting energy, as well as costs of providing a given level of performance and comfort will be established, as will their sensitivity to choices of technical lighting system parameters.

Computer Imaging

The principal activity for FY 1988 will be the validation of the imaging logic for complex objects. In cases where directional reflection coefficients for surfaces are known, a direct comparison can be readily made. However, we expect that known coefficients are not sufficiently representative and part of the FY 1988 effort will be devoted to measuring these coefficients for selected typical indoor and outdoor surfaces. This effort will need some equipment development.

Thermally Efficient Luminaires

The principal effort will be devoted to determining methods for introducing convective cooling in four-lamp, wrap-around, ceiling-mounted fixtures. We will determine the quantitative benefits of various technical and strategies. Considerable effort will also be expended to upgrade and rehabilitate the thermal test chamber, which has deteriorated during

the past year. Calibration, painting, and improved photocell systems will be part of this rehabilitation.

Peltier Device

In a potentially more practical system the device would be an integral part of the lamp, and could be driven by the ballast. Further research will develop such a Peltier Device. A number of technical problems will be examined in FY 1988. In particular, the size and geometry of the Peltier Device system needed to cool and maintain a 40° C temperature in a four-foot fluorescent lamp will be determined along with specification of the required electrical power, voltage, and current range of operation.

Subsequently, we will begin constructing of an experimental test set up in which the environment of a Peltier Device in a lamp can be simulated. This test set up will facilitate measuring of the required performance of the Peltier Device, and determine the amount of heat to be dissipated, and the means to drive the device. Possible methods of dissipating the heat from the Peltier Device located in the lamp will be examined, based on the electrical requirements for operating the Peltier Devices. A system will be designed that provides the Peltier Device power and is compatible with a core or an electronic ballast.

IMPACTS OF NEW LIGHTING TECHNIQUES ON PRODUCTIVITY AND HEALTH

The idea that lighting might negatively affect health has appeared often in the lay press during the past few years. Scientific data are lacking, especially to ascertain whether new energy-efficient technologies adversely affect human health and productivity.

Performance and productivity may be influenced by the lamp electronics and associated controls, the fixture, or the geometry and location of the lighting system. We classify these lighting factors as: color variations; glare; intensity fluctuations; spectrum variations, including the ultraviolet region; electromagnetic fields generated by the lamp, ballast, or controls; and flicker. All of these could evoke a variety of human responses (behavioral, psychophysical, physiological, or biochemical).

Our research seeks to assure that new energy-efficient lighting technologies do not adversely affect human health and productivity. We are investigating whether any aspect of new technologies can produce responses in humans. If we identify responses, we will characterize the effects and identify the necessary changes in lighting technologies. Although subjective responses of workers provide some information, such responses are generally confounded by a mix of sociological factors and individual motivations. The investigations carried out by LBL use objective responses to establish cause and effect, and ensure repeatability.

The impacts program is divided into two areas: (1) direct effects of lighting on the human autonomic system (carried out at University of California, San Francisco and LBL), and (2) interactions of lighting that affect visual performance and productivity or comfort (carried out at the UC School of Optometry and LBL), which are termed here "lighting ergonomics".

In the first area of this program, lamps to be evaluated include: incandescent, cool-white fluorescent, high-pressure sodium, and metal halide. Human responses to various lighting conditions will be assessed by monitoring autonomic responses, including heart rate, galvanic skin response, muscle strength, exercise tolerance, facial expression, and pupillary response. Behavior measures to be used include memory (Wechsler Memory Scale and Sternberg's Memory Scanning Time), cognitive function (mental arithmetic), time estimation, and simple reaction time. Other behavioral tasks will probably be included.

Data-gathering and subject control are supervised by trained medical personnel. A national technical advisory committee oversees and reviews the project. First results of this effort concern the effects of visible-spectrum and low-frequency radiation on human muscle strength, and, as described previously, they indicate that psychological factors are the likely cause of reported effects. A second set of experiments using pupillometry has, however, shown very robust and surprising effects of spectrum on pupil responses to different lamps.

The second area of this program studies primarily issues of glare resulting from lighting systems, and, to a lesser extent, flicker. In addition to these principle concerns, theoretical studies and comparative analysis are undertaken on models of visual performance particularly as they relate to understanding the benefits of more energy-efficient lighting.

Present knowledge and prescriptions by the lighting community for dealing with glare are based on subjective responses, without support by objective criteria. It is reasonable to implicate pupil responses as relevant to glare discomfort since pain receptors are present in the iris and the nervous pathway necessary to signal pain is present in the fifth trigeminal cranial nerve. Some studies by vision scientists have suggested pupil response as a possible to the sensation of discomfort but this conclusion is not

generally accepted in the vision community. We have undertaken a series of studies to clarify the possibility that pupil dynamics can be used as an indicator of glare response.

Accomplishments During FY 1987

Direct Effects of Lighting on the Human Autonomic System

Accomplishments for FY 1987 were in methodological studies, brightness studies, and PC computer development. The methodological studies primarily addressed validation of our pupillometer, including the effects on the pupilometer's accuracy resulting from test lamps; determining reliable threshold settings of the pupilometer in order to understand and avoid possible erroneous measurements because of conflicting or antagonistic threshold settings; exploring potential effects of eye movement on area measurement; examination of behavioral effects such as the subject initiating data collection by pressing a button; and potential effects of subject viewing a color verses black and white television. Several pilot studies led to two subjective brightness studies, both designed to correlate pupil size to subject report of brightness between metamerically matched pairs of fluorescent lamps over a range of low intensities; a second study looked at a range of higher intensities.

Summary of Methodological Studies

1) *IR Studies.* Several pilot studies designed to evaluate effects of additional infrared energy on the output of the MMI pupilometer were accomplished. These studies evaluated various combinations of lamps, especially those with high IR content such as High Pressure Sodium with and without an additional IR source lamp for the MMI on various threshold settings of the instrument. The results indicated the lamps used, and those expected to be used in this research, all failed to introduce sufficient IR energy to effect the output of the MMI under normal operation.
2) *Threshold Effects on the Pupilometer.* Studies were designed to explore the range of various threshold and sensitivity settings of the MMI in order to establish optimum settings, and define the outside limits of these settings to ensure accurate operation of the instrument.
3) *Eye Movement Studies.* Studies were implemented to determine whether eye movement affected the area recording of the instrument, and, if so, what range of eye movement is tolerable. The results indicate that eye movement of less than ten degrees vertically and horizontally failed to alter the area output. Movement greater than 15 degrees produced artificial changes in the area output.
4) *Behavioral or Button Press Studies.* Two variables in our methodology were suspected of contaminating the dependent variable (average pupil size over time); instructions to the subject to press the button (initiating the data collection period), and the performance of pressing the button. Results of these studies showed a systematic pupillary dilation just prior to pressing the button (anticipatory response), with the approximate amplitude of 0.4 mm diameter and a return to baseline in approximately 2.5 seconds. This response appeared to habituate over repetitions.
5) *Color Versus Black and White TV Viewing.* We anticipate evaluating visual performance under various lighting conditions with a contrast sensitivity task utilizing a black and white monitor. Therefore, we wanted to compare its effects to those of a previously used color monitor. The results indicate the black and white monitor used in this study emitted intermittently high levels of scotopic intensity. This emittance of large scotopic intensity is in direct conflict with our research concerning the scotopic/photopic ratio of various lamps.

Summary of Subjective Studies

1) *Low Range Intensity Study.* This study investigated the correlation between pupil size and subjective report of brightness, comparing photopically matched pairs of metamerically matched lamps across three intensities. The results showed a strong relationship between subjective report of brightness and pupil size elicited by scotopic intensity, and compared to photopic intensity.
2) *High Range Intensity Study.* This study was similar to the above study except the intensities chosen were individualized from a calibration procedure, to establish each subjects' scotopic response curve, and referenced to a higher intensity level. The results were consistent with those above in that there was a high correlation between pupil size and subjective report of brightness.

Summary of Computer Development

A Sperry PC computer was installed. Some of the necessary hardware includes Scientific Solutions

LabMaster Board, 16 A/D, 16 D/A, 24 I/O Scientific Solutions DADIO Board, and 24 I/O. Software installed includes: ASYST, Scientific Solutions LAB-PAC, GW BASIC, Turbo PASCAL, and Microsoft C. In-house software developments include: data acquisition, storage, retrieval, reduction, transfer, and blink and block removal programs.

Lighting Ergonomics

Visibility Studies. Cost benefit studies can be a basis for establishing recommended illumination levels. We have studied the present Illuminating Engineering Society recommended levels and written a detailed report. The results suggest that recommended illumination levels for the young population are too high, and that they underestimate the important parameters to be considered, such as the cost of light and the value of visual work.

A comprehensive review of lighting research with respect to lighting quality was completed, and a draft research agenda was prepared and is being critiqued. Components for the luminance mapper have been selected and assembly of the system will begin next fiscal year.

In addition, an educational article appearing in the Journal of Lighting Design and Application titled "To Average or Not To Average" was published.

Glare Studies. The pupil undergoes small, uncontrolled oscillations known as hippus, or generally, pupillary unrest. These oscillations and their associated frequency spectrum could be affected by the presence of glare, especially as the different pupillary pathway is affected by the kind of ocular discomfort associated with glare. In order to examine this issue, studies have been initiated to clarify the nature of pupillary unrest, since existing information is contradictory.

Flicker Studies. A prominent difference between hard copy and the visual display terminal is that the letters on the VDT screen are constantly being refreshed electronically at a rate of 60 Hz. Thus, a VDT viewer is exposed to a flickering light signal that is generally not perceived as flickering because the repetition rate is beyond the critical fusion frequency (CFF). (Exceptions could occur under conditions of reverse video and very high contrast.) Evidence using cortically evoked potentials on higher vertebrates indicates, however, that frequencies even higher than 60 Hz are being processed in the visual pathway. We are presently using the techniques of electroretinography to investigate whether the human retina is responding to the flickering VDT screen synchronous to the refresh rate. Because the signal strengths to be measured are of a quite small fractions of microvolts, we refresh the VDT at frequencies slightly above and below 60 Hz in order to reduce the effect of the ubiquitous 60 Hz environmental background in buildings. Further attention to this problem is necessary as the VDT electrons, upon striking the phosphor, produce a radiating magnetic field that escapes even additional VDT shielding. Preliminary results using extensive data averaging techniques on information from one subject indicate a weak but definite response.

Planned Activities for FY 1988

Direct Effects of Lighting on the Human Autonomic System

Three principal efforts will be undertaken during FY 1988. First, a more detailed study of the factors that influence the variance in the pupillary measurements so we can establish the number of subjects necessary, and the length of times of a subject run for a particular accuracy. Incorporated into this effort is a new study of the effect of spectrum on pupil size, which uses metameric sources, i.e., sources with equal color but designed with different ratios of scotopic to photopic luminance. This study would eliminate any concerns about to color differences that were present as a possible confounding condition in the previous experiment, where incandescent and high-pressure sodium lamps were compared (see Fig. 4).

The second effort will be a comparative examination of effects on visual performance under conditions of equal photopic luminance, but different scotopic luminance, and, therefore, different pupil sizes. Visual performance will be studied by the use of grating contrast sensitivity determination using the computerized spatial frequency testing system previously developed.

The third activity in this area is the completion of the construction of the pupil stimulator to be used in conjunction with the pupilometer system. This instrument is designed to provide the viewer with a slowly varying scotopic luminance under conditions where the photopic luminance is kept constant. The previous pilot studies have shown that scotopically richer sources appear subjectively brighter. Using pupil stimulator we can determine both whether the perception of brightness is correlated with pupil size, and, by studying time-varying scotopic luminances, to what extent perception of brightness is in phase with pupil.

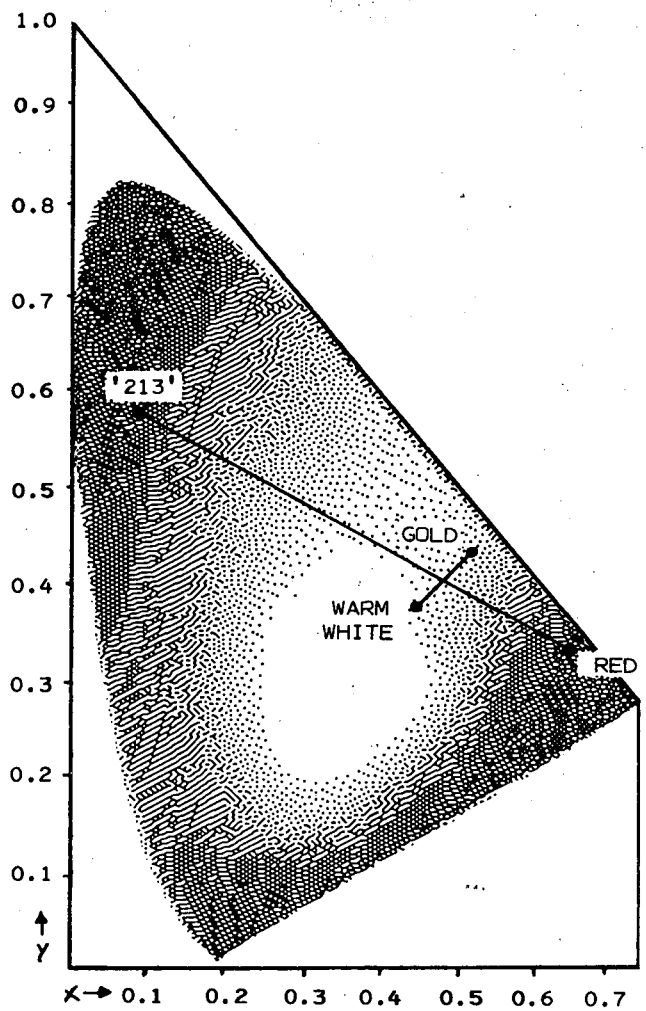

Figure 4. Chromaticity diagram displaying scotopically rich and deficient metameric combinations. (XBL 8712-5381)

Lighting Ergonomics

Visibility Studies. A number of on going efforts in this area are designed to obtain a verifiable, quantitative, and comprehensive methodology for prescribing illumination levels in the workspace. During FY 1988 the focus will be on three principal areas: completing the cost benefit report for publication, constructing an operating luminance mapper, and completing the size methodology analysis as an indicator of visual performance potential. The report on using cost benefit analysis to study the consistency of the lighting recommendations of the Illuminating Engineering Society will be prepared for journal publication. Computer, photographic, and photometric hardware will be assembled as the first configuration of the luminance mapper, and a calibration study will be undertaken. The statistical analysis leading to the universal scaling law resulting from the Bailey data (which uses the ratio of target size to acuity limit as a the metric for visual performance potential) will be completed. This universal scaling is expected to have a radical effect on field procedures for establishing adequacy of workspace illumination. This effort, coupled with the field measurement capability of the luminance mapper, will provide for the first time a very major step in the ability of lighting users to effectively quantify their luminous environments.

Glare Studies. The analysis of the shape of the pupillary unrest (hippus) frequency spectrum will continue. The spectrum under conditions of discomfort glare will be compared to the spectrum in the absence of discomfort glare. The results of the work on the discovery of beat effects on pupillary response, along with a model analysis, will be written for journal publication. The modeling effort makes use of the non-linear logarithmic response of the mean pupil size to changes in light level to compactly describe the connection between the frequency dependent reduction in mean pupil size and the amplitude of the beat response.

Flicker Studies. Work will continue on the electroretinogram response to VDT flicker and several additional subjects will be tested. Should the responses of those additional subjects mimic the results of the previous subject, the combined results will serve to establish a new effect, and these efforts will be written for journal publication.

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