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FY 1984 Annual Report

ENERGY EFFICIENT BUILDINGS PROGRAM

September 1985

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

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LBL-18753

APPLIED SCIENCE DIVISION ANNUAL REPORT

ENERGY EFFICIENT BUILDINGS PROGRAM

FY 1984

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Prepared for the U.S. Department of Energy under Contract No. DE-AC03-76SF00098

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ENERGY EFFICIENT BUILDINGS PROGRAM

INTRODUCTION

The importance of buildings in the U.S. economy is shown by the figures in Table 1. In 1983 our buildings sector used $150 billion worth of energy, mainly as electricity. Of the total annual U.S. electricity sales of $130 billion, most ($90 billion) went for operating the equipment and appliances in buildings.

To get a better feeling for the cost of energy in buildings, we note that the United States has 83 million occupied dwellings, with a total floor space of about 110 billion square feet, and another 50 billion square feet of nonresidential ("commercial") space. So every square foot costs about $1/year in energy services, with residential space costing a little less and commercial space a little more.

Since 1973 rising energy prices and awareness have remarkably reduced our energy bills. Our real GNP is up 22%, yet our primary[3] energy use is down 5%. If our energy efficiency were still frozen at 1973 levels, we would today be paying $640 billion annually instead of the $500 billion shown in Table 1; i.e., we are actually saving $140 billion each year, a very significant sum, comparable to our highly publicized national budget deficit.

In buildings the percentage savings are comparable. In the last 10 years, we have built 27% more homes and added 32% to commercial floor space, yet primary energy use in buildings is up only 7%. So energy use per square foot has fallen by 17%, and we are actually saving $30 billion per year.

So much for the past. Now, what of the future? How much more should we save? According to the SERI Solar/Conservation Study,[4] a "least-cost investment" scenario (one that maximizes life-cycle cost effectiveness) would halve our current energy use by the year 2000, and the same factor of one-half also applies to buildings as a sector. So, with optimal investments and design, our annual utility bill for buildings could drop from $150 billion to $75 billion.

Table 1. U.S. energy expenses in 1983 in billions of dollars.[1]

Sector	Fuel ($\$10^9$)	Electricity ($\$10^9$)	Total ($\$10^9$)	Floor space[2] (10^9 ft^2)
Buildings	60	90	150	160
Residential	(40)	(50)	(90)	110
Commercial	(20)	(40)	(60)	50
Industry	110	40	150	
Transport	200	0	200	
Total	370	130	500	

The Energy Efficient Buildings Program at Lawrence Berkeley Laboratory was established to accelerate the capture of this $75 billion potential annual savings. In 1973 we spent about $7.5 million on this research, i.e., about $1 for every $10,000 of potential savings, or the equivalent of advancing the ultimate savings by 1 hour each year. In this chapter (as in earlier editions of the Annual Report), we describe contributions to science and technology leading to advancements measured not in hours, but in months, and in many cases in years.

The Energy Efficient Buildings Program conducts theoretical and experimental research on various aspects of building technology that will permit such gains in energy efficiency without decreasing occupants' comfort or adversely affecting indoor air quality. To accomplish this goal, it has developed five major research groups whose findings and achievements are regularly reported in technical and scientific journals, presented at international conferences, and disseminated as Lawrence Berkeley Laboratory (LBL) reports. We also make available fact sheets on topics of interest to the building energy community, such as indoor air quality testing and blower door manufacturers. A brief overview of the scope and objectives of each group follows.

ENERGY PERFORMANCE OF BUILDINGS (EPB)

The EPB Group studies the flow of energy through all elements of a building. It tests air infiltration rates, studies thermal characteristics of structural elements, and develops models of the behavior of complete buildings. Research is conducted in the laboratory and in the field in single- and multifamily buildings. The potential for savings in this area is great; the heat load associated with natural infiltration is about 2.5 quads per year, costing about $15 billion. It is estimated that it may be economic to reduce this by 25%.

The group developed the LBL infiltration model, which predicts the annual infiltration rate of a building from leakage area and weather data. It is possible, using this model, to predict the annual infiltration rate of a building from a single spot measurement with a blower door. In 1982 the group developed a microcomputer program, CIRA (Computerized Instrumented Residential Audit), which is designed to speed up and improve the accuracy of residential audits of energy consumption. It automatically provides the homeowner with a tailored list of retrofit options, ordered by return on investment, and a corresponding set of energy labels for the house.

The group has also designed and tested a low-cost data acquisition system, the Energy Signature Monitor, a 16-channel, all-solid-state recorder, complete with sensors and user-friendly installation and analysis software, for residential, and possibly commercial, applications.

BUILDING VENTILATION AND INDOOR AIR QUALITY (BVIAQ)

An obvious way to improve the energy efficiency of a building—to lower air exchange rates by reducing air infiltration (whether natural or forced)—may have an undesirable side effect: because the indoor concentrations of air pollutants are reduced by the exchange of air with the outdoors, increasing airtightness may degrade indoor air quality. The goal of the BVIAQ Group is to investigate the factors affecting indoor pollutant concentrations, including pollutant sources, ventilation rates, and removal processes, with particular attention to providing the scientific basis for the development of ventilation standards and system designs that promote energy efficiency while maintaining the comfort and health of building occupants. Activities in support of these goals include (1) development of new methodologies for measuring indoor pollutant concentrations; (2) laboratory studies of the emission and behavior of pollutants arising from building materials, soil, combustion appliances, and household products; and (3) field monitoring of indoor air quality in different types of buildings (primarily residences and office buildings) under a variety of ventilation conditions.

Closely related to this work is the investigation of strategies to control concentrations of indoor air pollutants without sacrificing energy efficiency. To this end, the BVIAQ Group performs laboratory and field tests of various control techniques, including ventilation systems that incorporate heat recuperation, as well as pollutant-specific removal techniques. A recuperation system can provide the necessary level of ventilation while recovering a substantial portion of the energy that would normally be lost in the exhaust air stream. The group has set up a laboratory for testing air-to-air heat exchangers to provide independent data on these devices.

An interesting conclusion that can be drawn from the work of the BVIAQ Group and that of others in the U.S. and around the world is that the strongest influences on indoor concentrations are pollutant emission rates rather than ventilation rates. Indoor concentrations exceeding outdoor levels (and outdoor standards) occur whether buildings have been tightened or not. Throughout the building stock many houses have unacceptably high levels of radioactive radon gas, formaldehyde, and combustion products.

This finding means that substantial attention must be given to indoor air quality, independently of energy conservation measures, to limit the sources of contamination. Such efforts can reduce indoor pollutant concentrations (especially excessive levels), even with a modest reduction in air exchange rates. To help determine the scale of the effort required, the group has developed a number of inexpensive passive samplers for the more common pollutants and tested them in field surveys.

BUILDING ENERGY SIMULATION (BES)

The Building Energy Simulation Group develops techniques to simulate the energy performance of buildings. Starting in 1978, the group developed a family of computer programs, DOE-1 and DOE-2, that performs such simulations. These programs are now widely used by architects and engineers in the design of new buildings and the retrofit of existing ones; DOE-2 is also used extensively by researchers in building science. Each year a new version of DOE-2 and its documentation is produced, incorporating the most recent research results of projects at LBL and elsewhere. During the past few years DOE-2 has become the standard against which other calculation procedures or programs are compared. It has been used to help develop building codes in the U.S., France, and Singapore. DOE-2 is used by many hundreds of groups both in the U.S. and overseas.

The group is developing new techniques to calculate building loads and simulate heating, ventilating, and air-conditioning (HVAC) equipment. New techniques and algorithms have been developed to calculate the envelope element response to convective and radiative heat gains inside and outside of the building and to calculate the effect of using daylight. Calculation procedures for the analysis of passive solar

designs, including direct gain, Trombé walls, and water walls, have been added, as have approaches to model more accurately the interactions between the thermal zones of multizone and multistory buildings. Finally new control and equipment models in the HVAC section of the program simulate nighttime ventilation, plenum heating systems, controls for variable flow systems, and controls for cogeneration equipment.

WINDOWS AND DAYLIGHTING

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. At present the thermal cost of windows is estimated to be about $20 billion per year. The group's investigations are designed to develop the capability of accurately predicting net fenestration performance in residential and commercial buildings. Simulation studies, field measurments in a mobile field test facility, and building monitoring studies help us to understand the complex tradeoffs in fenestration performance. The group develops analytical models and experimental procedures for determining the thermal and solar-optical properties of glazing materials; it also conducts materials-science studies to characterize a new generation of thin-film coatings and other advanced optical technologies that may someday enhance the performance of conventional glazing materials. The first signficant market penetration of windows incorporating high-transmittance low-emittance coatings (R3–R5 windows) occurred in 1984, 8 years after DOE support was initiated in this program. If they capture a large fraction of the market, as expected, they will save consumers $5 billion annually in heating bills.

In nonresidential buildings major reductions in electric energy use and peak electric demand can be achieved if the conflicts and tradeoffs between daylight savings and solar-gain-induced cooling loads can be understood. The DOE-2 building-energy analysis model has been modified to enable daylighting effects to be analyzed and is now being used for extensive parametric studies to determine total building energy use, peak electric demand, and HVAC loads as functions of climate, orientation, and window properties. LBL daylighting studies also employ both 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. Data from outdoor model tests and daylight availability studies are still being collected and analyzed. Computational procedures will be validated with the Mobile Window Thermal Test facility (MoWiTT), now nearing completion. This unique facility combines the accuracy and control of laboratory testing with the realism and complexity of dynamic climatic effects; for the first time controlled measurement of the interaction between fenestration systems and a building HVAC system should be possible.

LIGHTING SYSTEMS

The research of the Lighting Systems Group is divided into four major categories: technical engineering, building applications, visibility impacts, and health impacts.

The technical engineering is concerned primarily with developing new concepts for efficiently 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 concentrate on the design of lighting systems, the effective use of lighting controls, and their interaction with a building's HVAC system.

The visibility impacts focus primarily on basic information needed to establish lighting conditions that enhance productivity in a cost-effective manner. It also seeks to determine any undesirable visual effects, such as excessive fatigue, associated with using modern office equipment in an advanced lighting environment.

The 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 can be measured by sensitive medical instruments.

Facilities for technical engineering are located at LBL; the visibility impacts program is located at the School of Optometry at Berkeley; and the health impacts program is located at the Medical Center on the San Francisco campus of the University of California.

The Lighting Group's successes include advancing the development of high-frequency solid-state "ballasts" for fluorescent lamps and several energy-efficient lamps to replace the familiar incandescent electric 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 lamps yield a factor-of-3 improvement in efficacy and could provide further annual savings of perhaps $5 billion.

BUILDINGS ENERGY DATA (BED)

Without data on how buildings behave once built, even the best-designed energy conservation strategy can go astray. The Buildings Energy Data Group compiles and evaluates data on end uses of energy and on the costs and performance of energy-efficient technical measures. The BECA (Building Energy-Use Compilation and Analysis) data base contains separate elements for each major subset of buildings (efficient new houses, retrofitted buildings, etc.).

From these data BECA prepares estimates of least-cost technical potentials for improving energy efficiency in new and existing homes and commercial buildings, often as a cooperative effort with utilities, state agencies, or industry groups. Individual conservation (or solar) measures are catalogued in order of increasing cost per unit of energy saved. The results are supply curves (marginal cost curves) of saved energy. These are comparable to the supply curves for other market commodities and show the expected levels of production as a function of unit price.

RELATED RESEARCH

Closely related research on energy-efficient buildings and appliances is carried on in other programs of the Applied Science Division and is reported in other chapters of this Annual Report. Specifically the Energy Analysis chapter reviews building energy performance guidelines, appliance energy performance, rating systems for auditors and appraisers, and energy and peak-power modeling. The Solar Energy chapter summarizes the research of the Passive Solar Analysis and Design Group.

FUTURE RESEARCH

We are planning or proposing studies in the following topics:

Duct losses. In the U.S., fossil-fuel heating accounts for about 7 quads of energy annually, worth about $50 billion. As a very rough estimate, about half of this heat travels in warm-air distribution systems, where 10% of it is lost because of leaky ductwork—a loss of about $2 billion. We propose to study distribution losses and to set up a duct laboratory to investigate methods of improving distribution efficiencies and of fixing leaky ducts *in situ.*

Integrated HVAC. As residential construction gets tighter, the need for mechanical ventilation to ensure adequate indoor air quality will increase. This ventilation air represents a heat source (or sink) approaching 1 kW of available power. Integrated HVAC systems that can recover this heat to condition internal air or displace domestic hot water demand could save up to $2 billion annually. Once a ventilation system has been integrated into the HVAC system, it becomes more practical to consider integrating other appliances (dryers, air conditioners, refrigerators, etc.) into a modular system that could save even more energy. We are currently trying to build a consensus of parties interested in this work and begin a unified research program.

Peak power reduction. For a typical summer-peaking utility, electricity for air conditioning systems accounts for at least 25% of the peak demand. This corresponds to the output of about 200 large (1000 MW) power plants. A very cost-effective method of reducing the peak is for commercial buildings to install thermal storage equipment. This allows chillers to be downsized and to be operated during off-peak periods. The cost of thermal storage appears to be about $200 per avoided kW, an attractive proposition compared with the typical cost of $1000 per kW for generation equipment. We have started to survey the use of thermal storage in commercial buildings in the U.S. and would like to carry out studies on the use of various methods of thermal storage such as water, ice, concrete, and phase-change materials to determine the optimal design of storage in commercial and residential buildings.

Responsive meters. At present a utility cannot bill a customer for the instantaneous cost of providing electricity. Thus there is little incentive for consumers to reduce peak usage, since they do not know when it occurs or how much it costs. All consumers see is an average price per kWh. If customers were billed for instantaneous cost, they would have an incentive to adopt cost-effective methods of reducing demand when the cost is highest. Such methods might include the use of thermal storage or the cycling of appliances during hours of high-priced energy. We would like to carry out a pilot study on the use of responsive meters (e.g., the British CALMU system), similar to studies we have already conducted on the use of controls for artificial lighting systems.

NOTES AND REFERENCES

1. The energy costs come from *State Energy Price and Expenditure Report for 1981* (DOE/EIA-0376). Entries are multiplied by 1.1 to account for inflation from 1981 to 1983 and rounded for easy interpretation.
2. The residential floor area comes from Table S2 of the *1982 Residential Energy Consumption Survey (RECS)*, DOE/EIA-0314(82), published August 1984. Table S2 uses exterior dimensions for 84 million heated homes. It gives 122 billion sq ft, and RECS Appendix B estimates inside area is about 10% less. Heated interior area is then about 110 billion sq ft, or about 1300 sq ft per dwelling. Before the RECS surveys, this average area, which includes apartments, was usually quoted as about 1000 sq ft. The commercial floor area (48 billion sq ft in 1980) comes from the *1979 Nonresidential Building Energy Consumption Survey (NBECS)*, DOE/EIA-0318/1, published March 1983. Before this survey, it was usually taken to be 30 billion sq ft.
3. There are two popular ways—"site" or end-use and "primary" or "resource" energy—to account for the energy associated with electricity. We prefer to use "primary" accounting, where 1 kWh sold—3414 Btu at the site—is equated with 11,500 Btu of fuel burned at the power plant. By "reflecting" this primary fuel, we find that 1 Btu of "electricity" and 1 Btu of fuel cost about the same—about $6/MBtu today; thus it is meaningful to add Btu's of primary electricity and Btu's of fuel and call them "primary energy."
4. *A New Prosperity: Building A Sustainable Energy Future. The SERI Solar/Conservation Study,* Brick House Publishing, Andover, MA, 1981. The Buildings section of this comprehensive study was done by an LBL team.

Energy Performance of Buildings*

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The Energy Performance of Buildings Group (EPB) carries out fundamental research into the ways energy is expended to maintain desirable conditions inside buildings. Our results form the basis of design and construction guidelines for new buildings and retrofit strategies for existing buildings. Our primary areas of research are air infiltration and thermal performance. In this article the work carried out in the past year is split into five overlapping sections: building energy retrofit research, air infiltration, diagnostic techniques, air leakage measurements, and moisture in attics. In many of these areas we have designed innovative measurement instruments and developed methods of theoretical analysis. For example we developed a microcomputer program to help in the design and retrofit of buildings, and our requirements for reliable data have lead to the creation of a multipurpose data logger, the Energy Signature Monitor.

BUILDING ENERGY RETROFIT RESEARCH (BERR)

The BERR project involves both experimental and theoretical analysis of the energy savings achievable by upgrading existing buildings. On the theoretical side there is the CIRA project, which has developed a reasonably accurate microprocessor-based energy audit and analysis tool that can be used by all kinds of building energy professionals. The tool, called CIRA (for Computerized Instrumented Residential Audit), differs from existing methods for estimating energy use in buildings. These methods are based on either time-consuming paper-and-pencil procedures at one extreme or large-scale computer simulations that require rigidly formatted input at the other. CIRA, however, uses the recently developed capabilities of microcomputers to allow even the naive user access to sophisticated user-friendly energy analysis programs.

On the experimental side we have been monitoring the energy use of buildings. In FY 1984 we started a new effort in this area—planning for a national retrofit monitoring program. This project, Building Energy Retrofit Research (BERR), a joint effort with Oak Ridge National Laboratory (ORNL) and the Solar Energy Research Institute (SERI), brings together many related projects into one coordinated research effort. The plan identified research areas, addressed user needs, and outlined methods for information transfer. Of the three building sectors included in the plan—single family, multifamily, and commercial—we have concentrated this year on the first two. In single-family housing we have two projects: an evaluation of a new retrofit strategy, the warm-room approach, and a continuation of our energy modeling work with CIRA. In multifamily housing we have focused on federally assisted housing, primarily public housing. This work has involved considerable planning in conjunction with other national laboratories and has laid the groundwork for detailed monitoring to be carried out in the next fiscal year.

Accomplishments During FY 1984

Single-Family Housing

Support and Transfer of CIRA. Development of the CIRA microcomputer program was substantially completed in FY 1983 with an update released in March 1982. In FY 1984 we continued to support the program, and by the end of the fiscal year over 150 copies had been released. A number of commercial firms expressed interest in further developing the program and were awarded licenses to distribute amended versions. One company, which had been working on an International Energy Agency contract to evaluate microcomputer energy use programs, adapted CIRA to run on the IBM Personal Computer and is now distributing this version under license. In the next year other companies are expected to follow suit, adapting CIRA to different segments of the market, thus transferring the research carried out at LBL to the professional community at large.

Warm-Room Retrofit. The warm-room retrofit is a response to a common problem: how to stay warm in a large, poorly insulated house during the coldest parts of winter. A traditional response is for residents to spend most of their time in one heated area of the house—usually the kitchen. In recent years the Institute for Human Development in Philadelphia has pioneered a variation in which the house is divided into warm and cool zones, the occupant controlling the temperature with a portable

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

thermostat. Two cities, Kansas City and Detroit, expressed interest in demonstrating similar retrofits in low-income housing and initiated a program with assistance from LBL. Detroit was unable to obtain funding for the retrofits, but Kansas City was awarded a grant from the Urban Consortium to go ahead with the work. As part of our technical assistance we worked with city officials in selecting potential houses for the project, including controls (Fig. 1). The houses were audited and the residents were informed about the warm-room approach. On the basis of the audits, we selected 5 houses as retrofit candidates and identified another 10 as controls. All residents were enthusiastic about the project, and pre-retrofit monitoring began.

Data were collected on the physical characteristics of the houses, additional gas meters were installed on the furnaces, blower door measurements were performed to determine leakage areas, and air quality measurements were taken to determine indoor levels of radon, nitrogen dioxide, and formaldehyde. In addition residents were asked about their daily activities to identify the most appropriate warm rooms. Residents have been recording their two gas meters every week and have been sending us the readings along with thermographs of their indoor temperatures. We used these data as input into a number of CIRA simulations of energy use in order to calculate the most cost-effective strategies for the retrofit.

Multifamily Housing

The multifamily work for the past year has concentrated entirely on the federally assisted housing sector—both public and federally subsidized private nonprofit housing (HUD Section 202). Initially we surveyed current retrofit activity in public housing and identified potential sites for monitoring. This survey effort continues work started in 1982 with the Housing Authority of Butte County (northern California) and has been funded, in part, through a grant from the University of California's University-wide Energy Research Group. The objectives are to characterize energy use and to evaluate the effects of energy retrofits in public housing.

Figure 1. Kansas City house (center) selected for warm-room retrofit. (CBB 840-9544)

One particular emphasis was to look at the behavioral effects of the target group, the low-income elderly. Our preliminary findings showed large variations in the energy use of the nominally identical apartments chosen for this study, a 60-unit project named Winston Gardens in Oroville, California. We plotted the energy consumption of the individual residents against time, weather, and the average of all residents. To interpret the data, we collected additional behavioral data through interviews of all the residents.

Working with the local housing authority, we proposed testing retrofits on a small sample of units before installing them in the entire project. The first retrofit we selected was a series of small changes to the heat pump, including installation of additional ducts and registers, removing an electric-resistance heat strip, and setting the fan to a lower speed. The initial evaluation showed that the residents were pleased with the changes, and they recommended that the retrofits be carried out on the remaining units. We installed Energy Signature Monitors (ESM) in four units during the summer to look at the effects of the changes to the heat pumps during the air conditioning period and made routine surveys of all units to record open windows, closed drapes, and operation of air conditioners. We will not be able to evaluate the total energy savings, however, until the end of the next heating season.

In parallel with the monitoring of public housing in Oroville, we have worked jointly with the Buildings Energy Data Group and the Energy Analysis Program to evaluate the energy savings resulting from retrofits carried out by the San Francisco Housing Authority over the past 2 years. San Francisco currently has over 7000 public housing units in which such retrofits as low-flow shower heads, attic insulation, and boiler wraps have been installed. More recently the city has entered into a third-party financing arrangement to install active solar systems for domestic hot water needs. We have analyzed the energy savings for five project sites, drawing on weather data from the nearby airport, utility billing records, occupancy information, and additional cost data provided by the housing authority. By using

the analysis technique PRISM (Princeton Scorekeeping Method) to calculate the annual energy use, we showed that four of the five projects showed significant reductions in energy use, primarily in base load (the fifth had such poor quality data as a result of broken meters that no analysis could be made). Data for one San Francisco housing project are shown in Fig. 2.

Planned Activities for FY 1985

We have no plans for CIRA other than seeing it smoothly transferred to the private sector. In the next phase of the warm-room project we will provide technical guidelines to Kansas City for evaluating and selecting proposals for carrying out the retrofits. We will evaluate the installed retrofits and monitor the houses over both a cooling and a heating season. Following the post-retrofit analysis we will assist Kansas City in a workshop for other cities that are interested in carrying out similar programs.

In the multifamily sector we will be working on a multiyear plan to determine the research needed to evaluate energy retrofits for the entire multifamily housing stock. This will require a characterization of the existing buildings, their energy use patterns, knowledge about retrofit performance, and an identification of potential barriers and problems. The goal will be to identify key research areas and the means for transferring the findings to the appropriate parties. In addition we hope to develop monitoring protocols for evaluating the energy retrofits in these buildings.

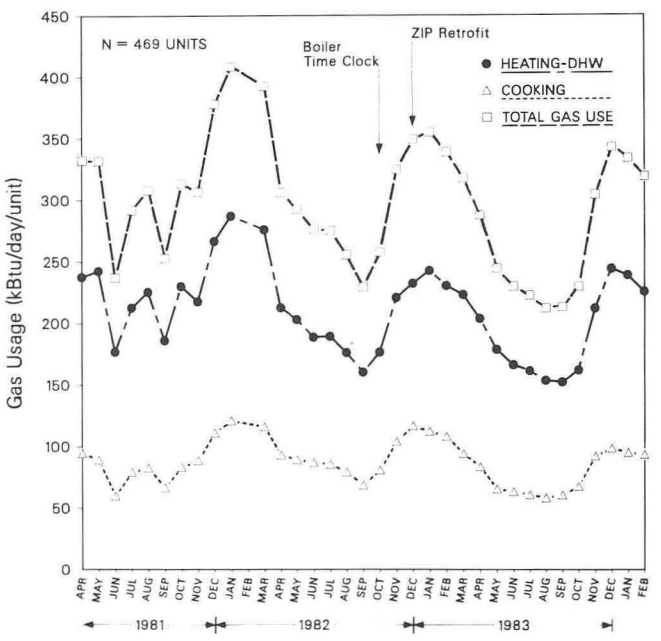

Figure 2. Total and submetered gas use at Potrero Terrace housing project, pre- and post-retrofit, San Francisco, California. (XCG 846-13126)

We are planning a similar effort to characterize the energy retrofit potential in the public housing sector. We plan to continue monitoring and evaluating the energy retrofits at our two public housing sites (Oroville and San Francisco) and also work with other national laboratories planning to monitor public housing. In Oroville we will analyze utility data following the next sequence of retrofits, which will include attic insulation, water-heater wraps, changes in exterior lighting, and, possibly, low-flow showerheads. We will interview residents to further understand their energy-related behavior and may again install ESMs to monitor a sample of units. In San Francisco we plan to monitor the hot water energy use at one project following the installation of an active-solar retrofit. We intend to instrument one of the 10 buildings on the site for detailed monitoring and to survey the residents to understand their patterns of energy use. These initial findings will help us monitor additional matched pairs of buildings to see how accurately we can predict the energy savings of the retrofit. We also intend to analyze data from similar retrofits at housing projects for the elderly in order to characterize the effects of different populations on the performance of the retrofit.

AIR INFILTRATION

With improved insulation of the building shell, heat loss from ventilation—whether controlled or by infiltration—has become an even more important fraction of the building's overall heat loss. Infiltration is the flow of outside air driven by wind pressure and thermal buoyancy into the building. Unlike the equivalent loss for conduction, ventilation heat loss depends on wind speeds as well as the inside-outside temperature difference. We carry out research in three main areas: development of a simplified multichamber model, wind tunnel measurements of wind pressure distributions, and analysis of heat recovery from ventilation air.

Computer programs have been developed that calculate the energy consumption due to infiltration. Those that treat the true complexity of flows in a building, recognizing effects of internal flow resistances, require extensive information about flow characteristics and pressure distribution. Therefore, simplified models have been developed. Most of these, including the LBL model, simulate air infiltration of single-cell structures, such as single-family houses, under given weather conditions. A high percentage of existing buildings, however, have floor

plans that are characterized more accurately as multichamber structures and cannot be treated by single-cell models. Most multicellular models in use are not available to the public or are written as research tools, rather than as tools for engineers and architects. A simplified multicell infiltration model capable of providing the same accuracy as the established single-cell models is therefore being developed at LBL.

Because of the difficulties of measuring infiltration in multichamber structures, few such models have been validated properly, if at all. The possibility of doing piecemeal validations of certain algorithms has been considered. For example, the algorithms for air flow through open doorways and through cracks have been tested separately. Even though infiltration cannot be measured for an entire building at once, measuring a few cells of the whole structure could still provide a severe test for existing models. These data are important not only for validation, but for further understanding of air movement in large multizoned buildings. We need to identify the critical variables in different building types in order to develop more accurate input data and, ultimately, more accurate models.

To get accurate results from detailed computer models, the boundary conditions have to be well defined. One critical input parameter that needs further study is the wind pressure coefficient. The pressure distribution around the building can be determined either from measurements on full-scale buildings or on corresponding small-scale models in a boundary layer wind tunnel, our present method.

A new project, stemming from both our infiltration and thermal modeling work, was started in FY 1984. Called Waste Heat Recovery—Integrated Appliances, it addresses the possibilities for energy management in single-family houses. Because the insulation levels of houses are increasing, energy consumption for functions other than space conditioning represents a larger fraction of the total energy consumption. As the energy consumption for water heating, household appliances, and ventilation becomes relatively more important, the need to improve efficiency in these end uses also increases. Although there has been ongoing research for many years on hot water systems, household appliance efficiency, and ventilation systems, there has been very little effort to incorporate the resulting energy flows into an overall energy management strategy. This project is designed to do just that—to examine energy management strategies for residential buildings as integrated systems.

Accomplishments During FY 1984

Multichamber Modeling

To get a summary of existing multicell programs, a literature review was carried out. Twelve of the fifteen programs found used an empirical power-law expression to relate air pressures to air flows. A second common factor was their use of Newton's method of iteration for solving the set of nonlinear equations. However, specific approaches varied from simple one-dimensional methods to more sophisticated two-dimensional methods. The differences were reflected in the necessary storage and the quality of convergence. The programs differed most in their ability to simulate mechanical ventilation systems. Eight could not simulate forced ventilation at all, or at least the literature did not indicate any handling of ventilation systems; two used the simplified method of setting a fixed air-mass flow for unbalanced mechanical ventilation systems, and only five described mechanical ventilation by fan and duct characteristics. Only these last programs were able to simulate the interaction of mechanical and natural ventilation.

A further literature review showed that, as regards air infiltration, a building will fall into one of four broad categories: (a) row house (terrace house), (b) detached house, (c) story-type construction, and (d) shaft-type construction. This subdivision is based on a comparison of the permeability distribution within a building as well as its construction type.

Wind Pressure Studies

To identify air movement into a building as well as its internal flows, we have developed a multigas tracer measurement system. The equipment can use up to four gases to measure four zones in a building. By using freons and sulfur hexafluoride as tracers, many different gases can be detected. Only minor hardware changes are necessary to expand the number of zones covered. The measurement equipment consists of a gas chromatograph with two columns, an electron capture detector (this detects all gases that are electron negative), and a sampling mechanism for the gases of the different zones. A peristaltic pump blows sample gas from the different zones for a 10-minute period into sampling bags; the content of the bags is analyzed, and the sampling cycle continues. In addition to the concentration data for the different zones, weather data are recorded. Our first tracer gas measurements took

place in a 60-unit apartment complex for the elderly in Oroville, California. Scale models of the test house and its surroundings have been built and initial smoke tests conducted to learn about flow characteristics of this housing.

To measure the wind pressure distribution on the surface of building models for different wind directions, a turntable for an existing wind tunnel in the Architecture Department at UC Berkeley was designed and built. A multiport valve connects up to 48 pressure taps on the model surface in a cycle with a single pressure transducer. Software to control the multiport valve and to manage the data has been developed.

Waste Heat Recovery

Our work on waste heat integration will eventually involve all possible sources of heat in a residence. For the first phase we concentrated on recovering the energy used to heat ventilation air. Four types of ventilation strategies for single-family residences were compared: (1) natural infiltration, (2) balanced ventilation with two fans and an air-to-air heat exchanger, (3) an exhaust fan with a heat pump used for space heating, and (4) an exhaust fan with a heat pump connected to the domestic hot water supply. These comparisons, based on an air change rate of 0.5 each, determined the space heating demands as a function of climate and insulation level; we also examined several standard hot water demand schedules. An economic comparison of the four strategies was performed by computing an acceptable first cost based on the energy savings and the time value of money. The results showed that the optimal strategy choice was very sensitive to climate and the insulation level.

Other research in FY 1984 has examined the overall energy efficiency of using a more efficient refrigerator. These computations were again based on climate and insulation level, the important point being that during some fraction of the year, the waste heat from the refrigerator reduces the heating load on the furnace. Compared with the normal housing stock, an efficient refrigerator in a super-insulated house has a smaller absolute effect (but a larger relative effect) on the overall energy consumption.

Planned Activities for FY 1985

An investigation of the average infiltration rate over the heating season for different multistory buildings in a European continental climate showed a strong relation between the wind and stack dependence of a structure and the permeability of the different facades of each zone. Future work will attempt to verify these results. Houses with different floor plans will be simulated by a detailed computer model. This work should also help to find lumped parameters to describe air flow in buildings.

Whereas the hardware development of the multigas tracer system has been concluded, software development for the programs controlling the sampling and data acquisition is still in progress. After the development of the measurement system is finished, measurements in multistory houses are planned. Air transport in vertical shafts and its distribution inside the building will be investigated. Further measurements of air transport in single-family houses will follow.

Pressure measurements in the wind tunnel are planned for models of the Oroville houses. Scale models of all the houses in which we will perform tracer gas measurements must be built. Pressure measurements for these scale models will follow the tracer gas measurements.

The initial work performed in FY 1984 on waste heat integration will form the basis of a general methodology for evaluating energy management strategies. For example, since the "on" time of a hot-water-supply heat pump depends on the demand schedule as well as on changes in indoor temperature (e.g., the temperature drop caused by night setback), the program must consider the hour-by-hour variation in the waste heat supply and in the demand for low-grade heat. The program will consider all sources of heat (e.g., the air conditioner) and include the effects of any thermal storage. This framework can then be used to evaluate the various sources and how they can best be utilized.

DIAGNOSTIC TECHNIQUES

For several years we have worked on two instruments that will help field research into the energy use of buildings. These are the Energy Signature Monitor (ESM) and the Envelope Thermal Test Unit (ETTU). We have also developed low-cost sensors for use with the ESM.

The ESM, our multipurpose data logger, along with its attendant data management software, will make possible the inexpensive collection of large-scale, high-quality data on building energy use. The ESM was developed as an innovative data acquisition system that integrates measurements, data collection, and sorting and is designed to provide low-cost, sophisticated data in a standardized format. Information about the typical number of sensors and accuracy requirements for large monitoring projects

was incorporated into the development of the ESM in order to meet the needs of most researchers without adding unnecessary and expensive features.

The ESM hardware is based on a 6502 microprocessor and includes 10K bytes of EPROM for the assembly language data acquisition program, 16 input channels that accept signals between +4 and -4 volts, two TTL pulse count channels, an RS-232 computer communications interface, and a 24K-byte removable EPROM-based data storage module. The data module includes information on the sensors used and the building and site identity to avoid time-consuming cross-referencing with logbooks and installation reports. Besides hardware, the data acquisition system includes a complete data management software package, written to operate on both CP/M- and MSDOS-based microcomputers. Transformation of the raw data recorded by the ESM into physical units and management of the data from multiple sites will be done automatically by the software on a personal computer at a central data analysis station. Both the data acquisition and data management software are menu-driven to facilitate their use by nontechnical personnel. The ESM can monitor total energy consumption (broken down by end use) as well as related variables as diverse as temperature, lighting levels, indoor pollutant concentrations, office equipment loads, thermostat settings, and door openings.

In addition to the ESM, which measures the overall performance of a building, the group has been developing an instrument to investigate the thermal performance of walls. This effort has had both theoretical and experimental aspects. The theoretical effort lead to the development of Simplified Thermal Parameters, a program to describe the dynamic performance of walls. The experimental work resulted in the Envelope Thermal Test Unit (ETTU), a device that imposes dynamic heat fluxes on a wall and measures the resulting flux on the opposite side of the wall.

Accomplishments During FY 1984

Energy Signature Monitor

The original ESM design, developed in FY 1982, has evolved into its present configuration through 2 years of laboratory and field evaluation of a number of prototype units, all built at LBL. The current design, along with a standard computer terminal, is shown in Fig. 3. The computer terminal, which could be replaced by a much smaller, portable version (such as the Texas Instruments Silent 700 or

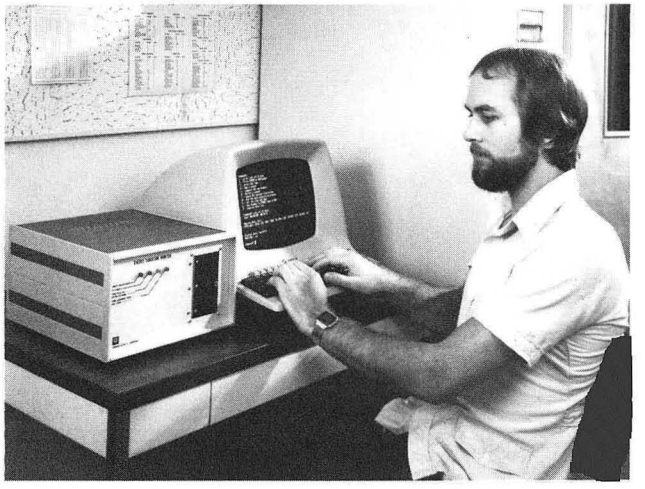

Figure 3. The Energy Signature Monitor (box on left). A computer scientist is setting up data files at the beginning of a field test of the ESM (the terminal is not required for data collection). (CBB 830-8721)

Radio Shack TRS-80 model 100), communicates with the ESM during setup at a test site but is not required during the test itself, thus reducing site equipment requirements. Since the ESM was designed for long-term unattended operation, there is no need for a built-in display (except for the front panel's four status indicator lights), a printer, or a keyboard. A removable data module and three ESM operation control switches are located behind the front panel access door. The rear panel has connectors for the sensors, power supplies, and a standard RS-232 connector for communication with a terminal or another computer.

The ESM has been tested in several field projects: The devices monitored eight single-family residences in Portland, Oregon, during the 1983–1984 heating season; during the summer of 1984, four units were installed in a public housing project in Oroville, California, and three units each were independently evaluated by the Solar Energy Research Institute and the Oak Ridge National Laboratory. Although the basic design has worked well, the field evaluations revealed the need for some modifications that would simplify maintenance and increase versatility. These changes have been incorporated into the current design.

The modifications include both hardware and software. A hardware RS-232 interface chip was added to ensure compatibility with all terminals at high communication rates and to provide selectable baud rates of 300, 1200, and 9600. The RS-232 input circuit was modified to handle nonstandard 0

to +15 volt RS-232 communication as well as the standard -15 to +15 volt RS-232 specification in order to accommodate a popular type of telephone modem. The circuit for a second pulse count channel was added, and both pulse count channels received optical input isolation to make them less susceptible to electronic noise. A larger 24-volt transformer was installed for powering the clamp-on wattmeter circuit. Signal conditioning circuits for the temperature sensors were modified to provide more stable readings. Overvoltage protection provided by back-to-back diodes on all of the analog input channels was removed because of recurring interference with the sensor readings.

The original 8K bytes of EPROM program memory for assembly language data acquisition did not allow any program expansion. Since less than 2K bytes of the 4K bytes of RAM memory were used, an additional 2K bytes of EPROM program memory were added by performing a small hardware change and substituting an EPROM chip for one of the 2K byte RAM chips. The expanded data acquisition program doubled the range of the recorded analog input voltage values (-4.095 to +4.095 V) and improved editing of operator inputs during setup; it also provided additional checks during ESM setup to notify the operator of errors and the ability to review data recorded on the data module without interfering with data acquisition. In addition, the operator can select the data recording interval (between 1 minute and 5.5 days) and have the data recorded as either an average over the recording interval or an instantaneous value at the time of recording.

As part of the LBL-conducted field evaluation, an unoccupied housing unit that was part of an LBL public housing research project was monitored by an ESM. The housing unit was concurrently monitored with a second microprocessor-based data acquisition system to provide a baseline for comparison. The ESM monitored a total of 16 sensors, including inside, outside, and attic dry-bulb and dew-point temperatures; weather conditions; and electric power use.

Installation required approximately 5 hours; had the housing unit been occupied, the installation time would have been a few hours longer because of the need to neatly secure all the wiring where it would not be accidentally disturbed by the occupants.

Comparisons of the data collected by the ESM and the baseline data acquisition system showed essentially identical results. Figure 4 presents ESM and baseline measurements of a living room dry-bulb air temperature that was held constant by the air conditioner thermostat over a 12-day period.

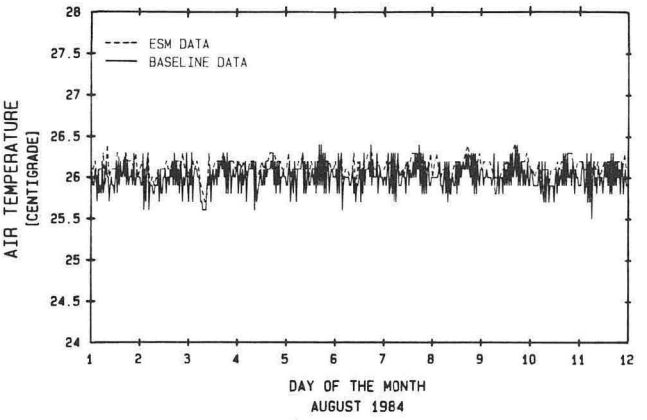

Figure 4. Comparison of ESM and baseline field data: Living room dry-bulb air temperature held at a constant 26°C. (XBL 851-1051)

The ESM recorded hourly averages, whereas the baseline data are in half-hour averages. The temperature comparison is very good, with the ESM recording values averaging 0.2°C higher than the baseline value. Figure 5 shows the variation in the dry-bulb air temperature of an attic over a 2-day period; here the ESM averages 0.5°C higher than the baseline value.

The one problem that has not been suitably solved is provision of a low-cost clamp-on wattmeter that correctly accounts for phase shift and variations in voltage and current wave form. The simple, inexpensive clamp-on wattmeter signal conditioning used in the ESM is not accurate enough for most applications. On the basis of field experience, an improved version has been designed, but unfortunately there has not been enough time to build and test it.

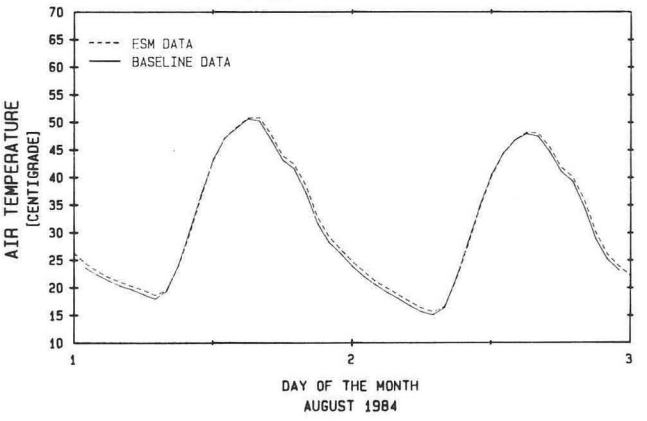

Figure 5. Comparison of ESM and baseline field data: Variation in attic dry-bulb temperature over 2 days. (XBL 851-1052)

The ESM data management and analysis software, to be used on a personal computer at the central data processing station, in conjunction with the data acquisition hardware, forms an integrated system that will allow a user to monitor a large number of sites, perform automatic data management on the recorded values, and process the aggregate data into a usable form with minimum time and expense. The data management program was expanded with the addition of a routine to produce hard-copy plots and refined to provide faster access. The program was also modified to operate with an MSDOS operating system (as on an IBM personal computer) as well as the CP/M operating system used during program development.

Twenty-three ESMs have been built at LBL for design evaluation and for use in two research projects, but there are no plans for LBL to provide ESMs to outside researchers. The process of transferring the technology of the ESM design to a private sector company willing to market a commercial version of the ESM was initiated during FY 1984, and two firms are currently developing a commercial version of the ESM, with the first model scheduled to be introduced by mid-1985. LBL is continuing to provide limited technical design support to these companies so that design modifications developed in the field evaluations may be properly introduced into commercial ESMs.

Thermal Performance of Walls

Efforts in this program in FY 1984 focused on the analysis side of the problem. The decisive distinction between wall measurement strategies is whether they are active or passive, i.e., whether they apply dynamic fluxes on the wall surface, or are merely affected by weather-induced fluxes. To compare these two strategies, data analysis programs based on the Simplified Thermal Parameter (STP) wall model were used to analyze both data taken with the Envelope Thermal Test Unit (ETTU) at LBL (active strategy) and data taken with passive heat flow meters and temperature sensors by the Building Research Association of New Zealand. It was found that even by modifying the STP program to take into account lateral heat flows in the walls, the active data taken with the ETTU in FY 1983 did not provide satisfactory results, and the passive measurements did not contain enough information in the frequency ranges necessary to characterize the walls tested. It was concluded that the best method would be a hybrid, with the imposed active fluxes being close to those caused by the weather. Thus modified, an active system would simply serve to extend the dynamic range of naturally induced fluxes.

Finally the ETTU was transferred to the National Bureau of Standards (NBS), where it will be used on government office buildings. This represents the first use of an active measurement strategy outside LBL, and it will provide field data that can be used to verify our recommendations.

Wood-Stove Monitor

We also completed a small project to develop a single-channel monitor for wood-stove heat output, generalizing the results obtained in FY 1983. A simple heat transfer model was developed that predicts the radiative and convective heat output of a stove from surface temperature measurements, characterizing the stove simply by its surface area.

Planned Activities for FY 1985

No further ESM or ETTU development is anticipated, although ESMs may be used in our other projects. We will continue to provide technical assistance to other groups that are using ESMs and ETTUs.

AIR LEAKAGE MEASUREMENT AND ANALYSIS

Air flow through a building envelope depends on the airtightness of the building and on the pressures driving the flow. Airtightness is a property of the building alone and does not depend on the climate or other external properties. Typically it is quantified by the effective leakage area (ELA), the amount of open area that would permit the same air flow as all of the leaks in a building. The measurement of air flow allows the characterization of building airtightness, comparison of different construction types within the building stock, and estimation of the effectiveness of retrofits on building ventilation.

The research can be divided into three areas: leakage characterization, measurement techniques, and consensus standards. Our characterization effort involves collecting and analyzing measured data (primarily from North America) to determine the aggregate behavior of residential buildings. The standard method for measuring airtightness is fan pressurization. Over the last few years, we have developed a new method for measuring airtightness, AC pressurization. It is hoped that this method, when further developed, will allow a more accurate determination of the effective leakage area. Finally, we are assisting professional societies in the formation of consensus standards concerning the detection of leaks, the

measurement of leakage area, and the specification of appropriate levels of airtightness in buildings.

Accomplishments During FY 1984

Leakage Characterization

For 2 years we have been collecting and analyzing leakage data from fan pressurization measurements with the intent of determining aggregate leakage properties of building envelopes. One result was a compilation of over 500 leakage measurements that included house characterization data. Our first attempt to use these data to characterize the housing stock has yielded several interesting results. For example, the data has demonstrated that the precision of ELA measurements is much higher if both pressurization and depressurization are used (as opposed to using only a single flow direction). Specifically, there is an additional 14% uncertainty associated with using the fan pressurization technique in only one flow direction. The data also bear out the conventional wisdom suggesting a flow exponent of two-thirds. The flow exponent for the entire data set had an average value of 0.67 with a standard deviation of 0.09.

Another interesting result showed the influence of construction type on airtightness. In Fig. 6 the leakage area (normalized by conditioned floor area) is presented for five construction types: (1) houses without an integral vapor barrier, (2) houses with an integral vapor barrier, (3) houses with an integral vapor barrier and external sheathing, (4) double-walled houses, all with vapor barriers, and (5) super-tight houses, in which a blower door was used during construction to ensure airtightness.

Measurement Techniques

We have also continued to develop a device that measures leakage area by the AC pressurization technique. On the basis of extensive laboratory tests with an earlier prototype, the design constraints for a field device were established, and the first field-test prototype was completed. It was determined that the device should operate in the 0.1 to 4 Hz range and that it should provide volume changes large enough to create a pressure response with a root-mean-square value of 4 pascals. The frequency limitations come from the leakage and volume characteristics of houses and from practical limitations on the size of the device. By choosing a 4-Pa signal

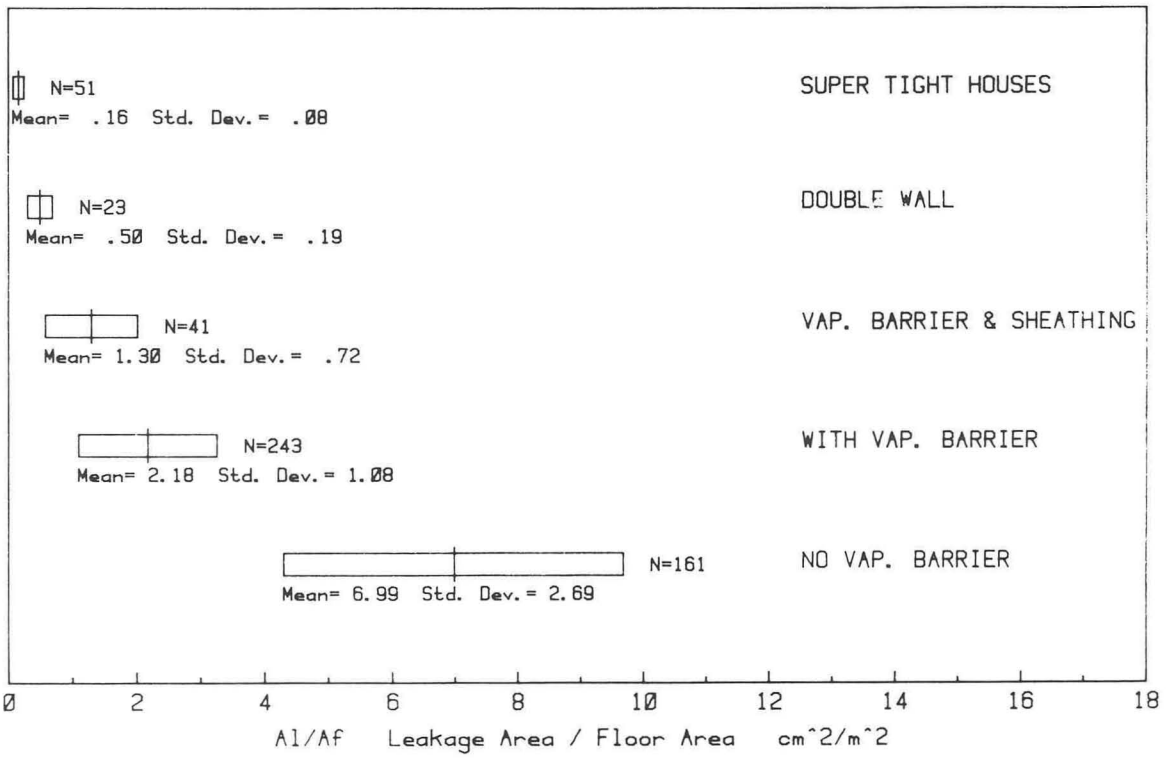

Figure 6. Leakage areas for five house types. (XBL 8312-2536)

there is no need to extrapolate, since the leakage area is defined at that pressure, thereby simplifying the analysis.

The first field prototype consists of a piston and bellows that mounts into the doorway of a house with conventional blower door technology (Fig. 7), and is driven by a variable-speed motor with a scotch-yoke mechanism. This mechanism turns circular motion into pure sinusoidal motion, unlike a crank mechanism, which adds harmonics. In addition, although it uses blower door technology for installation, the piston-bellows apparatus is lighter than LBL-designed fan pressurization equipment.

This prototype was compared with fan pressurization in six houses in the San Francisco area. The tests showed conclusively that AC pressurization did not measure the leakage area of fireplace chimneys (i.e., large, long leaks). They showed reasonable agreement between the two techniques, although fan pressurization measured leakage areas approximately 15% larger than those measured with the AC pressurization prototype, once large leaks had been identified and sealed. The tests also showed that, as the size of a window opening was increased, at some point this incremental increase in leakage area could not be measured. The field tests also tried out a low-cost pressure transducer as a replacement for the expensive low-frequency microphone. The pressure transducer measured the same leakage areas as the microphone, implying that a large reduction in the cost of future devices is possible.

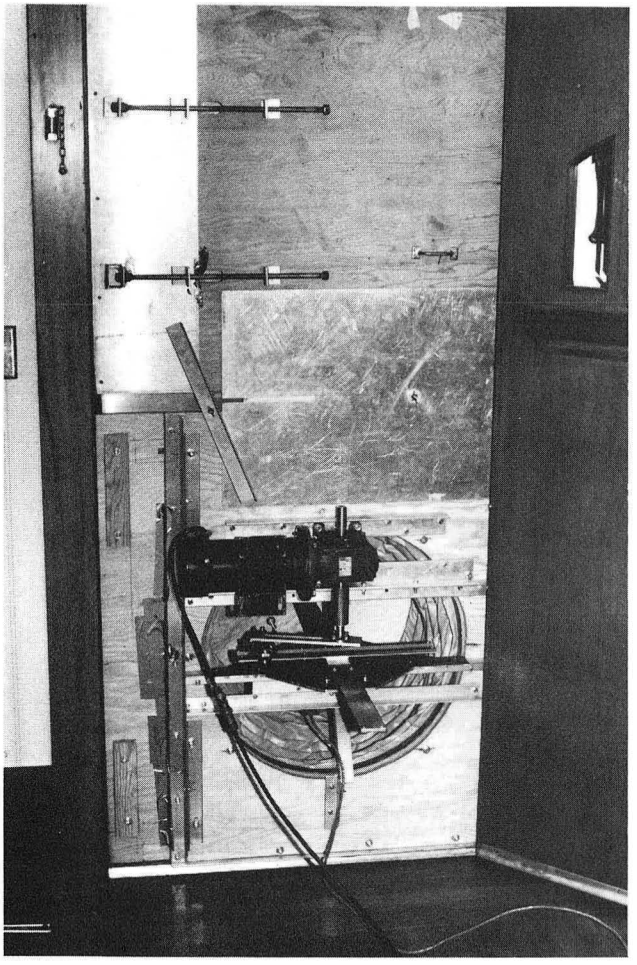

Figure 7. AC pressurization apparatus for measuring leakage areas. (CBB 840-8954)

Standards Development

During FY 1984 we were involved with two standards-writing organizations: the American Society for Testing and Materials (ASTM) and the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). The main activity in ASTM has been the modification of Standard Test Method E-779, "Determining Air Leakage Rate by Fan Pressurization," to correct omissions that have become apparent since its passage in 1981. The biggest single change has been the inclusion of the effective leakage area as part of the standard, including the calculation method. It is anticipated that the revisions, now being reviewed by the society, will be formally approved during FY 1985.

In addition to measurement-related standards such as ASTM E-779, we are working with ASHRAE on energy-related standards. Specifically we are heavily involved with the project on standard 119P, which is intended to promote energy conservation by setting maximum values for air leakage in detached, single-family residential buildings. During FY 1984 the project committee came to agreement on many of the substantial issues involved and produced an internal draft.

Planned Activities for FY 1985

The leakage characterization work will continue and expand. We will also construct a computerized data base that can be used to correlate leakage characteristics with other whole-house characteristics. For example, we will attempt to correlate leakage area with flow exponent and floor area to help simplify the measurement procedure. In late FY 1984 we started a measurement program to examine seasonal changes in leakage area. The program involves measuring the leakage area and flow exponent of a set of houses every month for a year; initial findings should be available during FY 1985.

In the measurement area further field tests will examine the discrepancies between AC pressurization and fan pressurization. Because the size of leak that can be measured depends on the frequency at which the device operates, field tests will be performed with a larger low-frequency bellows to both quantify and reduce the effects of large leaks. The AC pressurization research will concentrate on reducing the cost of a complete apparatus. These efforts include: (1) building dedicated data analysis hardware that eliminates the need for a computer, (2) reducing the cost of the electronic filtering required with the low-cost pressure transducer, and (3) refining the piston-bellows device. Theoretical studies will investigate the potential for measuring multizone leakage areas with AC pressurization.

The standards work will also continue. We expect that in FY 1985 the revised ASTM E-779 will become official and that the ASHRAE standard 119P will be available for public review. Other standards in the formation stage include one on calibration of fan pressurization units and another on methods of leak detection.

MOISTURE IN BUILDINGS

A newer area of research for the EPB Group concerns moisture storage and transfer in building materials. To assist ASHRAE in giving recommendations for ventilation rates in attics, we began in FY 1983 to study the moisture storage properties of wood and the heat/mass balance within attics. At present there are no ASHRAE attic ventilation guidelines, and it is suspected that traditional rules of thumb do not apply to current well-insulated attics. We have developed a model that predicts the attic-air humidity ratio (mass of water per unit mass of dry air) and roof-sheathing (plywood) moisture levels as a function of the roof-sheathing temperature and the outside-air humidity ratio.

Accomplishments During FY 1984

We set up a data collection system at a house in Oroville, in the northern Sacramento Valley. Data were collected to test the moisture storage model developed in FY 1983. A comparison of the predicted and the measured attic air humidity ratio is shown in Fig. 8, and good agreement is seen. It should be noted that during this relatively short period, the wood moisture content remained almost constant.

A second type of test, which we could not complete because of equipment breakdowns, is predicting the annual cycle in the moisture content of wood. Other researchers have shown that wood moisture content tends to peak in midwinter, with the wood drying out in the spring. A continuous record of ventilation rate and outdoor humidity ratio is needed to test this aspect of the model.

Planned Activities for FY 1985

We hope to measure the rate of moisture flow into the roofing members of the attic and test the seasonal model of moisture flow into the structural members of the attic. Once the model has been verified, it will be used to predict optimal ventilation rates. A ventilation rate can be chosen that will keep wood moisture levels below the level at which damage may occur. These activities will depend on the level of funding available.

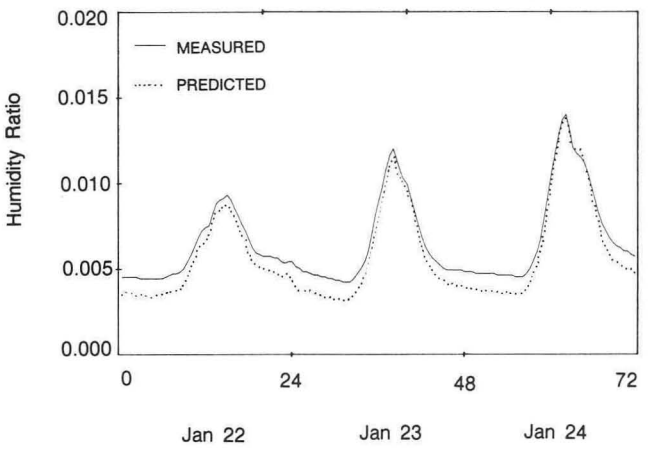

Figure 8. Attic air humidity ratio over 72 hours, as predicted by an LBL model and measured in a house in Oroville, California. (XBL 8411-4918)

Building Ventilation and Indoor Air Quality*

D.T. Grimsrud, A.V. Nero, Jr., S.R. Brown, J. Binenboym, J.F. Dillworth, W.J. Fisk, K.L. Geisling-Sobotka, J.R. Girman, A.T. Hodgson, H. Kaboli, S. Lewis, B.A. Moed, W.W. Nazaroff, A.S. Newton, F.J. Offermann, B.S. Pedersen, K.L. Revzan, R.G. Sextro, G.W. Traynor, B.H. Turk, and R. Young

Lawrence Berkeley Laboratory (LBL) carries out a broad program of work on indoor air quality in the context of its research on energy-efficient buildings and associated environmental effects. Efforts of the Building Ventilation and Indoor Air Quality Program (BVIAQ) include characterizing the emission of various pollutant classes from their respective sources, studying the effectiveness of ventilation in removing pollutants from indoor atmospheres, and examining the nature and importance of chemical and physical reactions that can affect the occurrence and amount of airborne pollutants. The program has groups devoted specifically to three major pollutant classes: combustion products, arising from indoor appliances and other sources; radon and its daughters, arising from materials that contain radium, a naturally occurring radionuclide; and formaldehyde and other organics, arising from a variety of materials and furnishings. In addition, other groups study techniques for controlling airborne concentrations, develop devices for monitoring pollutants in laboratories and buildings, and design or carry out field surveys of indoor air quality. Significant efforts are also devoted to assessing the health effects of indoor pollutant exposures and to establishing a numerical data base of pollutant concentration measurements in buildings.

The core of these efforts consists of research on the behavior of indoor air pollutants, specifically the influence on airborne concentrations of three classes of factors: source strengths or emission rates, ventilation rates or effectiveness, and reaction and transformation mechanisms. The work carried out by each group is primarily experimental, consisting of fundamental—and often quite sophisticated—experiments on pollutant emission, transport, and removal, complemented by significant efforts advancing the theoretical framework within which results may be considered.

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CHARACTERIZING THE SOURCES OF RADON IN BUILDINGS

Radon-222 is produced by the radioactive decay of radium-226, a trace element found naturally in crustal materials. Because it is chemically inert, radon can be transported from the soil into houses via pressure-driven flow through cracks or other penetrations in the house substructure. Soil is thought to be the predominant source of radon in U.S. housing, with building materials and domestic water supplies usually making only small contributions to indoor concentrations.

Indoor radon concentrations are often higher than outdoor concentrations, typically by an order of magnitude or more. These high levels are of concern because, on the basis of lung cancer incidence in uranium miners exposed to radon gas, it has been estimated that they may account for approximately 10% of the lung cancers per year in the United States.[1]

Our research on radon has three goals: (1) to provide a better means of predicting or identifying geographical areas where indoor radon concentrations may be elevated; (2) to improve our understanding of the transport mechanisms involved in the accumulation of radon indoors; and (3) to develop or identify means of controlling excessive radon entry rates.

Our studies on the behavior of radon progeny are described in the succeeding section, "Particles and Radon Progeny."

Accomplishments During FY 1984

Distribution of Radon Concentrations in U.S. Homes[2]

Although a number of investigations have measured indoor radon concentrations in U.S. homes, there has been no uniform appraisal of the extent of the problem. The overall data base on indoor radon concentrations has, however, increased to the point where it now appears possible to obtain a reasonable estimate of the frequency distribution of radon concentrations.

Data from 38 areas in the U.S. were accumulated from the literature or by direct communication with researchers. Although these studies differ in scientific objectives, scope, and measurement methods, we have systematically reviewed their results and have explicitly accounted for their differences in order to form an aggregate distribution of radon concentrations.

The studies vary substantially in size, with eight studies having fewer than 10 homes and another eight having more than 50 homes. Nevertheless, on the basis of measurements in samples with a large number of houses, the data appear to be distributed log-normally, as shown in Fig. 1, where 19 data sets have been aggregated directly from the individual measurements. This log-normal distribution permits the data to be aggregated and provides a framework for the effective parametrization of small data sets. However, questions about the comparability of the data must also be addressed.

The measurements were performed with a variety of techniques and over various time periods. Results reported as radon decay product concentrations were first converted to the equivalent radon concentration, using an equilibrium factor of 0.5. Data taken only for a portion of the year, typically the winter heating season, were renormalized to reflect annual data, as provided by four studies that measured radon concentration both in the heating season and over the entire year. The ratio of annual average to winter measurements yield 0.81 for the geometric mean (GM) and 0.89 for the geometric standard deviation (GSD).

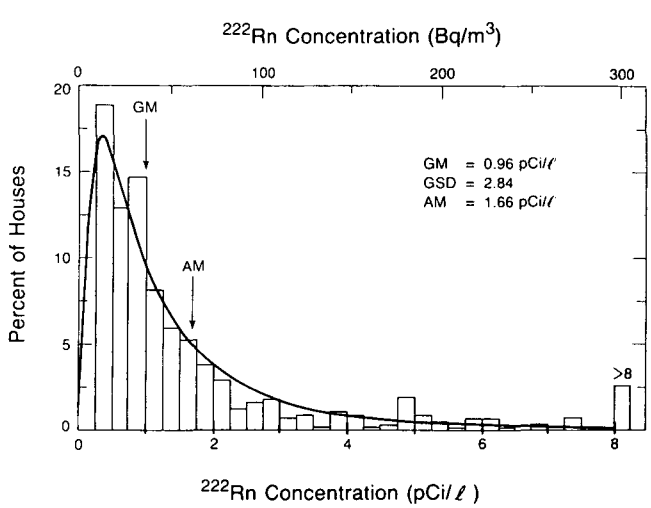

Figure 1. Probability distribution of ^{222}Rn concentrations from direct aggregation of 552 individual data points (19 data sets). The smooth curve is the log-normal function corresponding to the indicated geometric mean (GM) and geometric standard deviation (GSD), calculated directly from the data; AM is the arithmetic mean.
(XBL 8412-6456)

With these various factors taken into account, the data sets were aggregated in several ways, as shown in Table 1. Rather than aggregate directly, the GM and GSD for each data set were combined. Two groups of aggregations were used. The first includes all 38 data sets, totaling 1377 houses; the second comprises 22 of the 38 sets (817 homes). In 16 data sets of the larger group, radon measurements were made because of some prior indication that radon concentrations were likely to be high. These sets are excluded from the smaller aggregation so that it should be free of this bias and therefore be more representative of the U.S. housing stock. Three kinds of weights were applied to the data sets in developing the aggregate values: the number of homes monitored, an equal weighting for each set, and a subjective weighting based on population in the study area, the nature of the study, and whether there were any prior indications of high radon concentrations. A fourth weighting was applied to the normalized 22-set aggregation that uses the population within 50 miles of a localized study area or, for studies using housing with more widely distributed locations, the population of the state.

As seen in Table 1, the resulting distributions have a range in GM of 0.8 to 1.2 pCi L^{-1} and in GSD of 2.6 to 3.1. The 38-set aggregation generally yields higher GMs than the 22-set aggregation, confirming our expectation that the additional 16 data sets have higher radon concentrations. Similarly, the aggregations normalized to correct for seasonal differences have lower GM and GSD values than the unadjusted aggregations. In total, however, the distributions have only a modest dependence on aggregation scheme. If we take the 22-set grouping as more representative of U.S. housing, the resulting overall distribution has a GM of 0.9 $\pm$ 0.1 pCi L^{-1} and a GSD of 2.8 $\pm$ 0.2. The distribution of the GMs from the 22 data sets gives a GSD of 2.0, implying that there is some variability among the regions. This variability, apparently arising from the geographic variability in source strength, is one of the principal motivations for developing a capability to predict areas where high indoor radon concentrations are likely to be found.

The National Council on Radiation Protection and Measurements recently recommended an upper limit of 2 Working Level Months per year as a guideline for radon progeny exposure in the general civilian population.[3] This translates into an approximate average radon concentration of 8 pCi L^{-1}. On the basis of our radon concentration distribution,

Table 1. Radon concentration distributions for various data selections, normalizations, and weights.

Aggregation type[a]	^{222}Rn distribution GM (pCi L^{-1})	GSD	Average[b] (pCi L^{-1})	Fraction of homes exceeding 8 pCi L^{-1} (fraction of U.S. population exposed in these homes)
38 Data Sets:				
Not normalized				
No. of homes	1.22	3.14	2.35	0.051 (0.31)
Equal weight	1.07	3.08	2.01	0.037 (0.25)
Subjective	1.07	3.12	2.04	0.038 (0.26)
Normalized				
No. of homes	1.13	3.09	2.14	0.042 (0.27)
Equal weight	0.98	2.96	1.77	0.026 (0.20)
Subjective	0.97	2.98	1.76	0.027 (0.20)
22 Data Sets:				
Not normalized				
No. of homes	0.97	2.81	1.65	0.021 (0.16)
Equal weight	1.01	3.14	1.94	0.035 (0.25)
Subjective	1.05	3.10	1.99	0.036 (0.25)
Normalized				
No. of homes	0.85	2.64	1.36	0.010 (0.09)
Equal weight	0.88	2.91	1.56	0.020 (0.16)
Subjective	0.92	2.89	1.62	0.021 (0.16)
Population	0.89	2.68	1.45	0.013 (0.11)

[a]Data not normalized have not been corrected for differences between measurements during the heating season and the remainder of the year; normalized data are corrected for this difference (see text).

[b]Average (arithmetic mean) = GM $\times$ exp[0.5 (ln GSD)^2].

approximately 2.1% of U.S. housing, or over 1 million single-family residences, should exceed this concentration. The guideline level of 8 pCi L^{-1} corresponds to an approximate individual lifetime risk of 2% for long-term residents. As indicated in Table 1, the fraction of population exposure in homes above this guideline ranges from 10 to 30%. Thus reduction of exposures in those at high risk reduces both the individual risk and the total population dose.

Migration of Air in Soil into House Basements[4]

Substantial indoor air quality problems can occur when pollutants enter via transport of soil gas through building substructures. One such contaminant is radon. Where housing has been built on or near a waste disposal site, transport of gases such as methane and vinyl chloride through the soil has also been reported.[5] The dominant mechanism of entry appears to be the pressure-driven flow of air through openings in the building substructure. To better understand this process, pressure field and tracer gas measurements were made in and near two houses with basements in Portland, Oregon.

The houses were selected because each had both a higher than average indoor radon concentration and a basement. As shown in Fig. 2 for one house, an array of sampling holes was set up outside the perimeter of the basement wall by inserting an approximately 1-m-long steel pipe into the soil. These pipes served as the pressure sampling points; some were also used for injection or sampling of tracer gas. A blower door maintained a negative pressure differential in the house of 15–30 Pa with

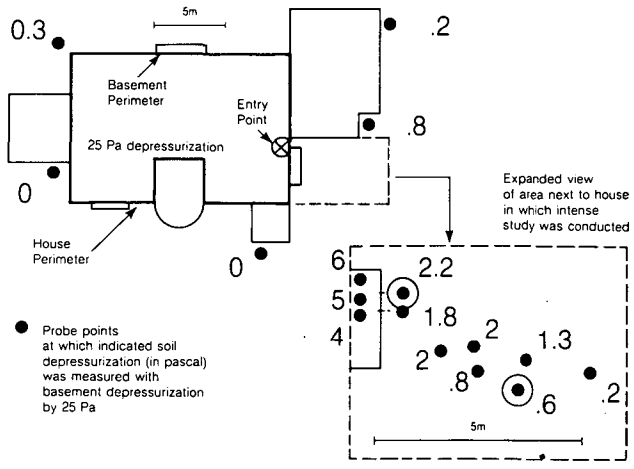

Figure 2. Plan view of house studied for soil-gas flow. Numbers indicate the pressure decrease at the sampling points, in pascals, relative to atmospheric pressure, with the basement depressurized to an average of −25 Pa. Tracer gas was injected at the two circled points (enlarged area). A large hole in the concrete substructure is labeled "Entry Point," as it was thought to be a major site of entry for soil gas. Measurements confirmed this hypothesis.
(XBL 8412-6453)

respect to the atmosphere. Pressure differences between the sampling points in the soil and the atmosphere were then measured at a depth of 0.9 m, and the pressure field in the soil created by the negatively pressurized house basement was mapped.

The results for one set of pressure field measurements are shown in Fig. 2; as can be seen, they are dominated by a major penetration at the intersection of the floor and wall in one area of the basement. The coupling between the house and the surrounding soil influenced soil pressures at distances of up to 5 m from this spot. When the blower door was turned off, the pressure field declined to zero, thus ensuring that the pressures observed were, in fact, due to the depressurization of the house.

A series of experiments were then conducted in which a tracer gas, sulfur hexafluoride (SF_6), was injected into the soil and its concentration monitored over time at points in the soil and in the house. Ten-cm^3 samples of air from the soil were collected in sampling tubes and analyzed for SF_6 concentration using a gas chromatograph with an electron capture detector.

The results are consistent with the observed pressure field coupling between the house and the soil. The tracer gas migrates toward the house under the influence of the depressurization. Tracer gas measurements in the basement were made as a function of time following injection. The net migration velocity of the gas through the soil appears to be greater than 1 m h^{-1}. Further experiments were conducted to determine the influence of the tracer gas entry rate when the basement was depressurized to −25 Pa. Within 15 minutes of injection of SF_6 at a point 1 m from the basement wall, the tracer gas was detected in the basement, and a steady-state indoor concentration was achieved within 1 hour. Injection at a second point 5 m from the basement produced a steady-state concentration after 2.5 hours.

An important implication of these results is that depressurization of a building may enhance the radon entry rate, offsetting the increased air-exchange rate. Radon concentrations in one house were continuously monitored during these experiments. Concentrations increased each time the blower door was operated, supporting the suggestion that structure depressurization comparable to that induced by thermal and wind effects leads to flow of soil gas into the house.

Potable Water as a Source of Indoor Radon in the U.S.[6]

Although the soil adjacent to building substructures appears to be the predominant source of radon in U.S. houses, water can be a significant contributor in certain geographical areas. High levels of radon in water have been measured in several areas, and the effect of radon-bearing water on radon concentrations in indoor air has been investigated (see, for example, Refs. 7 and 8). We have reviewed the state of knowledge regarding domestic water use as a source of indoor airborne radon and have developed a model to estimate the distributional form of the ratio of air to water concentrations.

The transfer of radon dissolved in water into the air depends upon the temperature of the water and the degree of agitation and aeration. Hence the effect on airborne radon levels will depend upon various water uses and use rates. The ratio or transfer factor, f, of the average indoor airborne concentration, C_a, to the concentration in water, C_w, can be determined from

$$f = \frac{C_a}{C_w} = \frac{W\,e}{V\,\lambda}, \qquad (1)$$

where f is the transfer factor between water and air (dimensionless); W is the total water use rate per resident (liters per person per hour); e is the use-weighted average transfer efficiency of radon from water to air (dimensionless); V is the volume per person of the residence (liters per person); and λ is the air exchange rate of the residence (per hour).

Use of this equation assumes that the air in the residence is well-mixed, so that the indoor airborne concentration is uniform spatially. There are two approaches to determining f; the first is to measure the concentrations in air and water directly, and the second is to evaluate W, e, V, and λ on the basis of data in the literature. The first method presents some obvious experimental difficulties, primary among which is the need to separate the radon contribution of the soil from that due to water; thus only houses served with water containing high radon concentrations are likely to give relatively unambiguous results for the transfer factor.

The second approach, on the other hand, may yield more statistically robust data. In reviewing the data for the various parameters just described, we found that the distribution for each variable was reasonably well fit by a log-normal distribution. This means that the resulting variable itself will be log-normally distributed, and the geometric mean (GM) and geometric standard deviation (GSD) for the product can be derived from a straightforward combination of the GM and GSD of the individual parameters. Table 2 summarizes the values for these individual parameters and presents the derived values for the distribution of the transfer factor, f. Using the GM and GSD for f, we find that the resulting arithmetic mean is 1.14×10^{-4}. This agrees with the typical value cited in the literature of 1×10^{-4}.

Radon concentrations have been measured in a variety of water supplies; these concentrations range from a few picocuries per liter or less in surface waters to more than 100,000 pCi L^{-1} in certain private wells in Maine. Since the air-to-water ratio is about 10^{-4}, and since the outdoor radon concentration is 0.1 to 0.4 pCi L^{-1}, radon concentrations in water below 1000 pCi L^{-1} are generally of little concern. Approximately half of the U.S. population is served by surface water supplies, one-third by public groundwater supplies, and the remaining one-sixth by private groundwater. There is currently no evidence that radon concentrations in surface water approach 1000 pCi L^{-1}; thus for half the U.S. population, water is not a significant source of radon.

Table 2. Description of the distributions for the factors used in determining the air-to-water ratio.

Parameter	N	GM	GSD	Units
W: Water-use rate	90	7.9	1.57	L (person-h)$^{-1}$
e: Transfer coeff.[a]	21	0.55	1.12	—
V: House volume	6051	98.7	1.90	m^3 person^{-1}
λ: Air-exchange rate	578	0.68	2.01	h^{-1}
f: Air-to-water ratio		0.65	2.88	—

[a]The overall transfer coefficient is the average of the use-specific transfer coefficients weighted by the water-use rate for each specific end use (see Ref. 7).

A recent survey[8] of public groundwater supplies that serve more than 1000 persons showed a range of concentrations from less than 100 to over 10,000 pCi L^{-1}. The values are log-normally distributed, with a GM of 100 pCi L^{-1} and a GSD of 4.8. At the upper end of this distribution, corresponding to about 0.1% of the samples, the expected contribution from water to indoor airborne radon concentrations is comparable to the overall nationwide average from all sources. No similarly comprehensive survey of radon concentrations in private wells has been conducted. On the basis of the distribution of data for high waterborne concentrations from private wells in Maine and North Carolina, it is possible that 1–2% of the U.S. population is served with water having radon concentrations exceeding 10,000 pCi L^{-1}, and that 0.3% of the population uses water exceeding 100,000 pCi L^{-1}. The extrapolation from this small data base is tenuous, however; there is a need for further data on radon concentrations in private well water.

Planned Activities for FY 1985

Continuing research efforts will help develop a better understanding of radon gas transport into houses. Tracer gas and pressure field measurements will be expanded to include different soil and house substructure types. We will examine the role of key soil parameters, such as permeability, in the development of indoor concentrations of radon and extend our use of existing aerial radiometric data to produce maps of near-surface radium concentrations in soil at larger, more detailed geographical scales.

A methodology for determining the role of soil and various soil characteristics in producing high indoor radon concentrations will be developed. This effort will examine the use of existing data and data bases for derivation of key parameters.

PARTICLES AND RADON PROGENY

Radon progeny, produced by the radioactive decay of ^{222}Rn, are radioactive isotopes of polonium, bismuth, and lead. These elements are also chemically active, unlike their inert radon parent, and can attach to surfaces such as room walls, airborne particles, or lung tissue. Upon inhalation, both attached and unattached radon progeny may be deposited in the lung. The health effects

associated with radon are due mainly to the alpha decay of two of the progeny, ^{218}Po and ^{214}Po. Progeny not attached to particles produce a greater lung dose than attached progeny. Thus particle concentration is important as a determinant of radon progeny behavior and in estimating the associated health risks.

Particles themselves are important indoor pollutants, arising from many sources, such as indoor combustion processes and occupant activities, including smoking, cooking, and use of aerosol sprays. The physical and chemical composition of indoor particles determine their health impacts and are important factors in devising measures to control their concentrations.

Present research efforts are to (1) investigate radon progeny behavior and the role of airborne particles, (2) evaluate techniques for the control of indoor particles and radon progeny concentrations, (3) develop a better theoretical understanding of radon progeny behavior, and (4) characterize the physical and chemical attributes of particles emitted from typical indoor sources.

Accomplishments During FY 1984

Particle Air Cleaning and Radon Progeny Behavior[9,10]

An evaluation of unducted air cleaners was summarized in the FY 1983 Annual Report, and further work has since been done to investigate the effectiveness of air cleaning on particle removal and on airborne radon progeny concentrations. Specifically, several in-duct devices for use with forced-air heating systems were studied.

These experiments were conducted at the Indoor Air Quality Research House and followed procedures described previously (FY 1983 Annual Report). Each device was inserted in the return air duct of a forced-air furnace system installed within the 140-m^3, multiroom test space at the Research House. As in our earlier work, tobacco smoke was the test aerosol, and radon was injected into the test space following ignition of the cigarettes. After a 4-hour period during which uniform mixing of the pollutants occurred and radioactive equilibrium among radon and the radon decay products was established, each device was operated for 3 to 5 hours. Particle concentrations and size distributions were measured throughout the course of the experiments, as were radon and radon progeny concentrations.

Seven devices were evaluated—a bag filter, a high-efficiency particle air (HEPA) filter, two types of panel filter, two types of electrostatic precipitator, and a commercial-grade activated charcoal filter. Results for particle removal are summarized in Fig. 3, where the effective cleaning rate (ECR) is the difference in the observed particle concentration decay rates with and without the air cleaner operating, multiplied by the test space volume. The three devices with the largest ECR values were the bag filter ("ES3" in Fig. 3), the HEPA filter ("ES4"), and one model of the electrostatic precipitators ("EP4"). The effects of the various filters on radon progeny concentrations were similar to those observed for particles. The charcoal filter was evaluated primarily to see if its operation reduced the airborne radon concentration; it did not measurably do so, however.

One important aspect of the use of air cleaners for particle and radon progeny control is shown in Fig. 4. The data (filled circles) are from our earlier studies of unducted air cleaning devices. The total airborne radon progeny concentration—as measured by the ratio of the potential alpha energy concentration (PAEC) to the radon concentration (a ratio referred to as the equilibrium factor, F)—declines with decreasing particle concentration. However, the concentration of unattached progeny increases with decreasing particle concentration until, at low particle concentration, almost all of the equilibrium factor is due to unattached progeny. This effect is indicated in Fig. 4 by the dashed line at the bottom.

The radioactive exposure of lung tissue from unattached progeny decay is 9 to 35 times larger

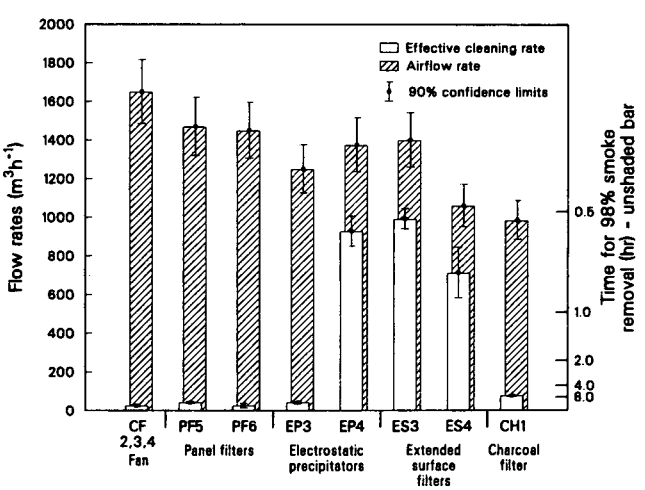

Figure 3. Measured effective cleaning and air-flow rates for several types of ducted air cleaning devices. The right-hand y axis indicates the time required for 98% reduction in particle concentration by each device operated as part of the forced-air system in the 140-m^3 test space.

(XCG 8412-13531)

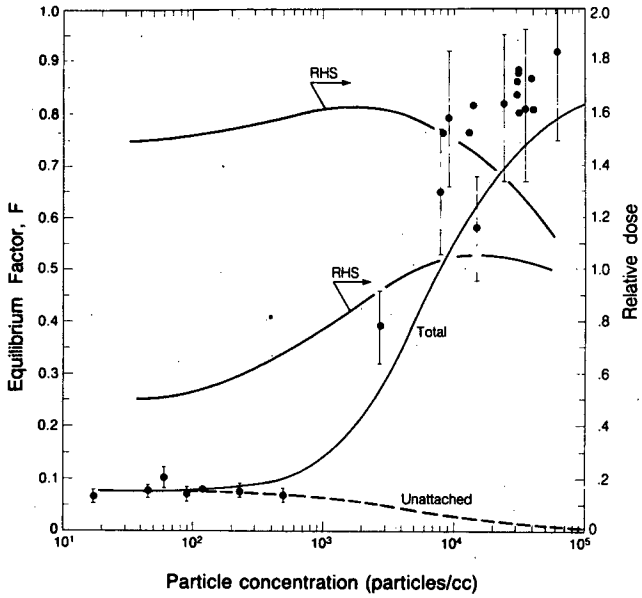

Figure 4. Equilibrium factor F versus particle concentration. The main solid line is based on calculated values for total airborne radon progeny concentrations, while the dashed line at bottom indicates calculated values for unattached progeny. The other two curves refer to the right-hand y axis, showing the relative dose of alpha radiation to lung tissue; the upper curve is based on dosimetric calculations for children engaged in light activity, while the lower curve is for adults at rest. (XBL 8312-6710C)

than that from attached progeny. As the particle concentration decreases, the proportion of unattached to attached radon progeny increases. As illustrated by two of the solid curves in Fig. 4, the relative dose for various particle concentrations has been calculated for two cases: children engaged in light activity (upper RHS curve) and adults at rest (lower RHS curve). On the basis of these results, it appears that the overall health risk may not decline significantly with the reduction of particle concentration.

Numerical Modeling[11]

The complex behavior of radon progeny indoors is influenced by physical and environmental conditions such as the concentration and size distribution of airborne particles and air-flow patterns within the interior space. Existing models can account for the average uniform behavior of radon progeny but not for transport of pollutants or the spatial dependence of deposition processes. A more fundamental, physically based model has been developed that provides a theoretical framework for understanding the behavior and interactions of indoor pollutants. It treats transport and removal processes directly, rather than by the generalized parametrization used in existing mass-balance models. The model was initially developed for the transport and deposition of radon progeny but can be extended to other indoor pollutants.

The mass-transport model is based on a two-dimensional form of the fundamental mass-transport equations, incorporating air motion, diffusional transport, and deposition for both unattached and attached radon progeny. There are a number of factors that contribute to air motion in a building, including natural convection caused by the temperature differences within a space. In addition to these enclosure flows, simple boundary layer flows were also simulated for free and forced convection. Deposition is also incorporated in the model, based solely on diffusion through the boundary layer to the surface. The model assumes that there is perfect adherence of the airborne species upon contact with the surface; thus, airborne concentration at the wall surface is zero, and there is no reentrainment of the pollutant. Coupled nonlinear transport equations are solved numerically to provide both temporal and spatial concentration profiles, which can then be used to predict deposition velocities for the radon decay products.

Parametric sensitivity studies of variations in diffusivity, attachment rate (particle concentration), and flow condition were performed. Diffusivity has a strong influence on radon progeny deposition rates. The diffusion rate, in turn, depends on the physical and chemical nature of the specific progeny atom. Free progeny (unattached to airborne particles) appear to exist in various forms, ranging from free atoms to small molecular clusters. The parametric model runs examine values of diffusivity between 0.01 and 0.1 $cm^2\ s^{-1}$, the range encompassing most experimentally determined values.

The effect of particle concentration was investigated by varying the attachment rate between 0 and 250 h^{-1}; these values correspond to concentrations of 0 to 60,000 particles cm^{-3} (using a mean attachment rate coefficient of $4.3 \times 10^{-3}\ h^{-1}$ [particles $cm^{-3}]^{-1}$). Air flow, as noted earlier, was modeled using both buoyancy-driven enclosure flows and free and forced convective boundary-layer flows. As it turns out, the boundary-layer flows adequately represented the transport effects of the enclosure flows and were simpler (and cheaper) to model.

The variation in concentration gradient for the first radon progeny, ^{218}Po, as a function of diffusion rate and air-flow rate is illustrated in Fig. 5. As shown, the boundary-layer thickness (a characteristic distance in which the activity, A, differs substantially

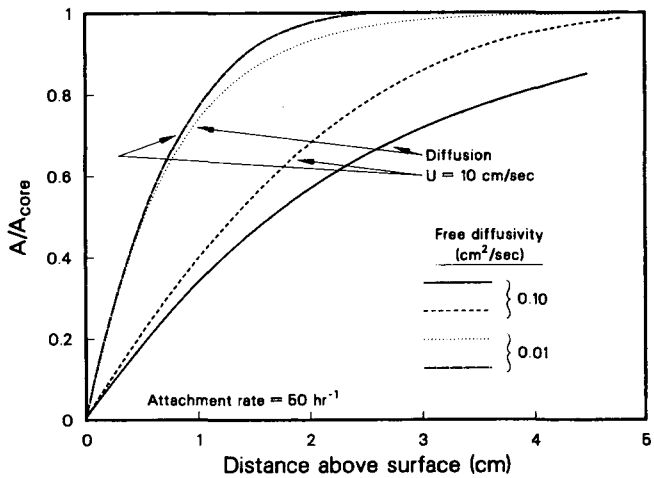

Figure 5. Free progeny activity concentration profiles for ^{218}Po, illustrating the relative influence of diffusivity and air motion. The strong sensitivity of the profiles to choice of diffusivity diminishes slightly when there is convective flow contributing to pollutant transport. The ratio A/A_{core} is the activity A (pCi m^{-3}), of ^{218}Po measured above the surface in this one-dimensional situation divided by the activity, A_{core}, of the air in the core or body of the room. (XCG 849-13313)

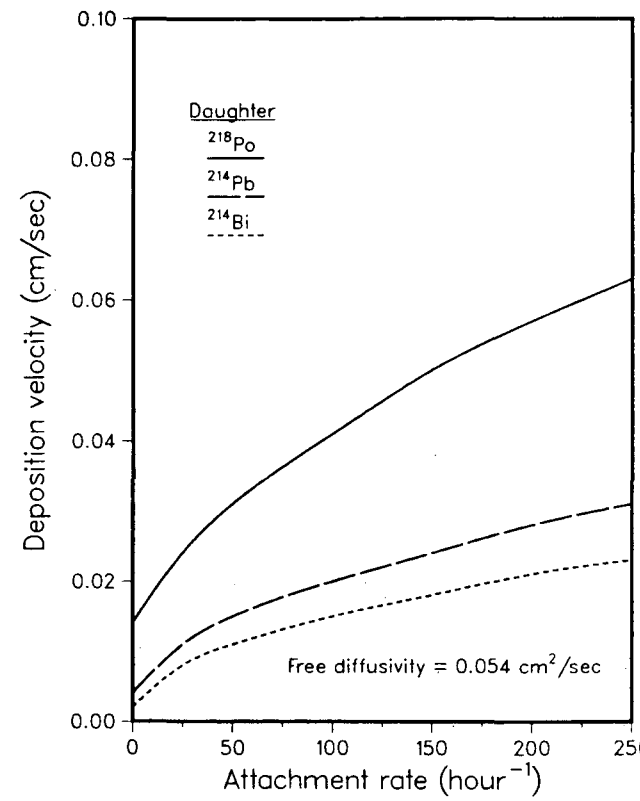

Figure 6. Variation of free progeny deposition velocity with attachment rate (particle concentration), based on one-dimensional diffusion. Because each progeny is generated from a nonuniform source, the change in the resulting concentration profile is seen as a decrease in deposition velocity for each successive decay product. (XCG 848-13217)

from the core activity, A_{core}) diminishes with decreasing diffusion rate and, in the case of low diffusion rates, decreases somewhat with increasing airflow rate. These calculations were done with an attachment rate of 50 h^{-1}, equivalent to a particle concentration of around 12,000 particles cm^{-3}, which is in the range of values commonly found indoors (in the absence of cigarette smoking).

In interpreting experimental results, most researchers assume that the three radon progeny of interest, ^{218}Po, ^{214}Pb, and ^{214}Bi, behave similarly. However, the deposition rates are influenced not only by diffusion rate but by the concentration gradient at the wall. Since the progeny are formed by sequential radioactive decays, the sources for these nuclides are not necessarily uniform spatially. This effect is illustrated in Fig. 6, where the variation in deposition velocity is shown for each progeny as a function of particle concentration.

The use of a mass-transport model has provided insight into the effects of key parameters on radon progeny behavior. The dependence of progeny deposition on environmental conditions and differences among the progeny themselves provide an important guide to the interpretation of experimental results.

Physical and Chemical Characteristics of Indoor Particles[12]

The indoor environment appears to be a major pathway for exposure to air pollutants for much of the U.S. population. Among these pollutants are particle and volatile organic emissions from indoor sources. In collaboration with researchers from the California Department of Health Services Air and Industrial Hygiene Laboratory, we have investigated the physical and chemical characteristics of particle and organic emissions from a natural-gas-fired stove and from tobacco combustion.

The experiments were conducted in a 36-m^3 room in the Indoor Air Quality Research House. Measurements in an adjoining room obtained data on the background pollutant levels. Particle size and concentration were measured in near-real time, using an electrostatic classifier and an optical particle counter for particle sizing and a condensation

nucleus counter for total particle concentration. These instruments were operated under a computer control that also recorded the data on magnetic tape for later off-line processing. Samples for the chemical analyses were collected simultaneously on various media. The chemical analyses of the particles included determination of polycyclic aromatic hydrocarbon (PAH) composition; organic, elemental, and total carbon content; morphology and elemental composition of individual particles; and mutagenicity. In addition, samples of volatile organic compounds (VOC) were collected and analyzed.

To obtain sufficient material for the chemical analyses, the gas range was operated for 15 minutes every half hour for 4 to 6 hours. The average particle concentrations remained above 50,000 particles cm^{-3}. The tobacco smoke was generated by a cigarette-smoking machine, which operated at a rate of two 35-cm^3 puffs per minute. Both mainstream and sidestream smoke were emitted in the test space. A typical 6-minute burn consumed ~600 mg of tobacco and produced a peak concentration of 100,000 to 200,000 particles cm^{-3}.

The results of these experiments are summarized in Table 3 for selected chemical species. The table shows values only for species that had measured concentrations greater in the test chamber than in the outer room. Overall, particle emissions from natural gas combustion contribute relatively little to indoor levels of these constituents, while tobacco combustion, as expected, is a significant source of particles, chemicals associated with particles, and volatile organic compounds.

As shown in Table 3, most of the carbon associated with cigarette smoke is organic carbon, while natural gas combustion produces no excess levels of particle-phase carbon. The Ames test for mutagenicity was performed using the TA98 strain of *Salmonella typhimurium*. A positive response without the addition of rat liver extract (−S9 in the table) represents the effects of direct-acting mutagens; the addition of rat liver extract (+S9) tests for compounds whose metabolites are mutagenic (indirect-acting mutagens). Gas stove particle emissions are slightly mutagenic in the direct-acting Ames analysis, while cigarette smoke is highly mutagenic with respect to indirect-acting mutagens.

Because tobacco smoke is composed primarily of liquid aerosols, adequate samples of smoke particles could not be collected, and elemental analysis thus could not show elevated levels of any constituents of cigarette smoke. For gas stove emissions, the elemental analysis showed increased levels of sulfur associated with the particles, while levels of the other elements listed in Table 3 were not above background. These results are not surprising because sulfur compounds are a constituent of natural gas. For the particle-phase PAH analysis, no individual PAH species had elevated levels from gas stove emissions. For cigarette smoke, however, all five PAH compounds in Table 3 had elevated levels. Finally, volatile organic compounds showed slightly elevated levels from natural gas combustion, while only formaldehyde is produced in elevated quantities by tobacco combustion.

Table 3. Initial analysis of emissions from two common sources of indoor particles.

Parameter	Gas stove	Cigarette smoke
Carbon content		
Organic	—	>150 $\mu g\ m^{-3}$
Elemental	—	—
Total	—	>150 $\mu g\ m^{-3}$
Particle mutagenicity		
−S9	>30 rev m^3	—
+S9	—	>1500 rev m^{-3}
Elemental composition		
S	>5%	—
Others (Na, Mg, Al, Si, K, Cd)	—	—
Selected PAHs		
Fluorene	—	>200 ng m^{-3}
Fluoranthene	—	>100 ng m^{-3}
Benzo(a)anthracene	—	>20 ng m^{-3}
Benzo(a)pyrene	—	>20 ng m^{-3}
Chrysene	—	>60 ng m^{-3}
Selected VOCs		
Benzene	<10 ppb	—
Formaldehyde	—	<10 ppb
Acetaldehyde	<10 ppb	—
Acetone	<10 ppb	—
Particle size distribution		
Geometric mean	~0.1 μm	~0.2 μm
Geometric stnd. deviation	2.0	2.5

These data, along with data to be collected on other particle sources such as kerosene heaters, aerosol spray cans, or cooking will be used to develop signatures for individual indoor sources. It appears possible to use such data in conjunction with a simple indoor source apportionment model to help identify the sources of pollutants from a real-world mixture of indoor pollutant species.

Planned Activities for FY 1985

Investigations of radon progeny behavior will continue, and additional studies will examine the

effects of environmental conditions and different particle sources. Improvements in the methods for direct measurement of unattached progeny will be made, and unattached progeny concentrations will be measured as a function of particle concentration and environmental conditions. In addition, studies of the activity-weighted size distribution of radon progeny will continue, again under a variety of particle and environmental conditions.

The predicted behavior of progeny, especially ^{218}Po, the first radon decay product, will be compared with experimental results. This comparison will be used to validate and improve the existing theoretical understanding of radon progeny behavior and will help guide additional experimental efforts.

ORGANIC EMISSIONS

Because heating and cooling outdoor air as it enters a building consumes a significant amount of energy, recent office construction practices have minimized the use of outdoor air for ventilation. These practices, along with the increased use of synthetic building materials and furnishings, have resulted in many nonspecific health complaints by office workers that may be related to poor indoor air quality. The underlying causes of these complaints are unknown. Few studies of organic contaminants in indoor air in nonindustrial buildings have been made, but fragmentary evidence suggests that such contaminants can be major contributors to poor indoor air quality.[13,14] In the industrial indoor environment, elevated levels of organic contaminants have been shown to induce a variety of toxic, carcinogenic, and teratogenic effects. The possibility that chronic exposure to these same compounds may occur in nonindustrial environments makes it imperative that these contaminants be identified and their levels and sources characterized.

In FY 1984 our research efforts were directed toward (1) modeling and extending the results of emission testing of adhesives in small chambers, (2) expanding and improving instrumentation and facilities for the analysis of volatile organic compounds (VOCs), (3) characterizing the performance of a solid sorbent air sampling system exposed to a variety of compounds, and (4) initiating a study of personal exposures to a common toxic chemical, methylene chloride, from consumer products such as aerosol sprays and paint removers.

Accomplishments During FY 1984

Organic Emissions from Building Materials

The emission rates of VOCs from five adhesives with indoor applications had been determined previously in a study of 15 structural and interior finish materials and 15 adhesives.[15] The five adhesives were those that still emitted significant quantities of organics 9 or more days after application. To assess the potential impacts of adhesives on indoor air quality, the emission rates of VOCs were used in a single-equation mass-balance ventilation model. The model was applied to a hypothetical office space, under the following assumptions: (1) exfiltrating and indoor air have the same average pollutant concentration; (2) ventilation is the only important removal process; (3) the emission rate is independent of pollutant concentration; (4) there are 7 workers per 100 m^2; (5) the adhesive is applied to an area equal to the area of the floor at the manufacturer's recommended rate of coverage; and (6) the system is at steady state.

Indoor concentrations of organics produced were modeled for three solvent-based adhesives (labeled S-1, S-2, and S-3) and two water-based adhesives (W-1, W-2) at two ventilation rates. For the solvent-based adhesives, only concentrations of toluene, the major compound emitted, were modeled; for the water-based adhesives, because of the complexity of the compound mixture emitted, concentrations of total alkanes were modeled.

The results, shown in Table 4, demonstrate that the two water-based adhesives can produce high concentrations of VOC, particularly in spaces with low ventilation. The low ventilation rate is the ASHRAE recommended minimum rate in spaces without occupant smoking. Threshold limit values (TLVs) are also listed in Table 4 for toluene and for representative alkanes for comparison with the modeled concentration. However, the model results must be interpreted with caution because the adhesives would be overlaid with carpet or other coverings that would undoubtedly reduce emission rates, while perhaps extending the duration of the emissions.[16]

Instrumentation and Facilities Development

We have constructed a 20-m^3 environmental chamber with a unique, flexible design to facilitate its use in a wide variety of indoor air quality studies.

Table 4. Calculated steady-state concentrations of toluene and total alkanes emitted by building adhesives at two ventilation rates.[a]

Adhesive[b]	Ventilation rate per occupant ($m^3\ h^{-1}$) 34	8.4	Threshold limit values ($mg\ m^{-3}$)
	Toluene concentration ($mg\ m^{-3}$)		
S-1	0.06	0.25	375
S-3	2.8	11	
S-7	0.25	1.0	
	Total alkane concentration ($mg\ m^{-3}$)		
W-1	76	310	1050–1600[c]
W-2	67	270	

[a]The calculations assume that the adhesives were applied to an area equal to the floor area in a hypothetical office space having an occupant density of 7 workers per 100 m^2.

[b]"S-" adhesives are solvent-based; "W-" adhesives are water-based.

[c]Range of threshold limit values for *n*-heptane through *n*-nonane.

The wall, ceiling, and floor panels are constructed with a rigid fiber-glass frame and are insulated with 10 cm of high-density polyurethane foam. All interior surfaces are stainless steel; the door and interior seams are sealed with silicone gasket material. Electrical and plumbing feedthroughs are also sealed. The materials for the chamber were selected, in part, for their low emissions of volatile organics as determined by our building materials emission testing. The chamber, which has a natural infiltration rate of 0.03 to 0.08 air changes per hour (ach), is equipped with an interim single-pass ventilation system in which inlet air is drawn from the laboratory through a coarse filter by a variable-speed blower. The volumetric flow rate is monitored by both orifice plate and turbine flowmeters located in the air inlet downstream of the blower. Air is exhausted outdoors. We have fabricated an interface for continuous monitoring of the turbine flowmeter and have checked its performance with tracer gas decays over a range of ventilation rates (0.5 to 3.0 ach). We have also obtained and begun programming a multichannel data logger and controller for the wide array of instrumentation that will be used with the environmental chamber.

We have extended our ability to sample and analyze air for volatile organics by acquiring a solid-sorbent sample concentration/thermal desorption unit, a dual-channel gas chromatograph (GC) data system, and a bench-top capillary gas chromatograph–mass spectrometer (GC-MS). The sample concentration/thermal desorption unit is interfaced to a capillary GC. The output of the flame ionization and electron capture detectors of the GC are read by the dual-channel data system. Considerable effort has been expended on validating the performance of this system (see below). The GC-MS is operational and will be interfaced with the sample concentration/thermal desorption unit. Two members of our group have been factory-trained in the use of the GC-MS.

Validation of a Multisorbent, Thermally Desorbed Sampler

A pressing problem in research on VOCs in indoor air is the development and validation of a sampling and analytical method applicable to the broad array of compounds likely to be encountered. While a thermally desorbable solid sorbent for organics offers an attractive solution, no single sorbent has a satisfactory performance record for all or most compounds. An obvious solution is to use several complementary sorbents in one sampler. One such sampler, containing glass beads, Tenax GC, Ambersorb XE-340, and activated carbon, is commercially available from Environchem, Inc. for use in their sample concentrator/thermal desorption unit. We are presently conducting a detailed evaluation of this system. This evaluation has several goals: (1) to determine maximum sample volumes at standardized conditions for 17 highly volatile compounds representative of a variety of chemical classes (Table 5); (2) to determine the effect of sample flow rate, humidity, analyte concentration, and competing compounds on maximum sample volumes; (3) to determine sample storage life; and (4) to estimate maximum sample volumes for untested compounds.

Results to date for both the multisorbent sampler and the sample concentrator/desorption unit have been good. Calibration standards for 14 compounds have been prepared with a static dilution bottle technique that has high linearity and accuracy.[17] Operating parameters for the system have been optimized, and the system blank has been improved. To achieve satisfactory separation of the lowest-boiling compounds, an on-column cryofocusing device was developed and incorporated into the system. Retention times with precisions of 0.5% or better have been obtained for the 14 compounds,

Table 5. Selected test compounds for multisorbent performance characterization.

Hydrocarbons	*Aldehydes and Ketones*
n-Pentane	Acetaldehyde
n-Hexane	Acetone
Benzene	Methyl ethyl ketone
Alcohols	*Amines*
Methanol	Ethyl amine
Ethanol	Propyl amine
Esters	*Chlorinated Hydrocarbons*
Methyl acetate	Dichloromethane
Ethyl acetate	Carbon tetrachloride
Methyl acrylate	1,1,1–Trichloroethane
	Vinylidene chloride

and multiple-point calibrations of these compounds were all highly linear ($r^2 \geqslant 0.99$).

Consumer Products with Methylene Chloride

Preliminary tests and protocol development have been completed for a study of methylene chloride–containing consumer products to be conducted in the 20-m^3 environmental chamber. In this study, emission rates will be determined while simulating typical consumer usage patterns for paint strippers and aerosol paints at different ventilation rates. The average area concentrations of methylene chloride and other major solvents in the chamber will be measured and compared to the personal exposure of the user of the products. An infrared analyzer will measure methylene chloride concentrations, and gas chromatography will measure the major solvents and the methylene chloride. The data will be analyzed within the context of a predictive ventilation model for describing the concentrations of airborne pollutants in residential indoor air.

Planned Activities for FY 1985

The characterization of the performance of the multisorbent sampler and the sample concentrator/thermal desorption unit will be completed. Both laboratory measurements of building material emissions and field measurements of the concentrations of VOCs in office buildings will then be made, using the validated analytical system. A more sophisticated air handling system for the environmental chamber will be fabricated and its performance checked. We will continue our studies of VOCs from building materials by measuring emissions of materials in the 20-m^3 environmental chamber and will determine the effects of aging, temperature, and ventilation on the emissions. The first phase of the study of methylene chloride emissions from consumer products will be completed and a second phase begun. The scope of the second phase is as yet unspecified but may include testing of additional product types, determining the effect of temperature on emissions, or measuring stratification of concentrations during product application.

POLLUTANT EMISSIONS FROM COMBUSTION APPLIANCES

Previous work with combustion appliances has indicated that kerosene heaters are a major indoor air pollution source,[18] and other research has indicated that wood-burning stoves may also be a source.[19] In FY 1984 we completed an analysis of controlled field studies designed to evaluate (1) the indoor air pollution and interroom pollutant transport due to unvented kerosene-fired space heaters and (2) the impact of wood-burning stoves on indoor air pollution levels.

Both studies are part of our efforts to characterize pollutant emission rates and concentrations from combustion appliances, assess the health implications of such exposures, and explore techniques to reduce pollutant concentrations while maintaining energy-efficient residences.

Accomplishments During FY 1984

Data on air pollution from kerosene-fired space heaters and wood-burning stoves were analyzed in detail to evaluate emission rates, pollutant concentrations, and interroom transport rates. The studies were conducted in the same unoccupied residence leased especially for these projects. The house, located in Truckee, California (elevation: 1800 m) is a single-floor ranch-type house with a total volume of 236 m^3. All tests were conducted during the winter months (average outdoor temperature was $-0.2°C \pm 3.3°C$).

Kerosene Heater Tests

We investigated the effect of unvented radiant and convective kerosene-fired space heaters on indoor air quality in an unoccupied house under several realistic use conditions. The experiments were conducted with the heaters running in the master bedroom or in the living room. The goals of the experiments were to (1) test the impact of window and internal door openings on the room's pollutant concentrations; (2) measure the interroom pollutant

transport rate; and (3) measure the emission rate profile over time of two types of heaters.

The convective and radiant heaters were operated in the bedroom until its air temperature increased at least 8°C. This procedure was followed under four operating conditions: (1) while the bedroom door and window were closed; (2) while the door was open 2.5 cm and the window closed; (3) while the door was fully open (74 cm) and the window closed; (4) while the door was closed and the window open 2.5 cm.

The bedroom door is 204 cm high and the window 101 cm high. Except for doors to closets and bathrooms, all other interior doors were kept open during the tests, and exterior doors and windows were closed. Heater tests conducted in the living room lasted several hours because the 8°C temperature rise was not reached. The average full consumption rates were 7300 ± 1200 kJ h^{-1} for the convective heater and 6400 ± 300 kJ h^{-1} for the radiant heater.

Interroom pollutant transport rates were calculated for tests with the bedroom window closed, using carbon dioxide concentration data and a two-compartment mass-balance model with several simplifying assumptions. The bedroom was treated as one compartment with a volume of 31 m^3 and the rest of the house as a second compartment having a volume of 205 m^3. House and room volumes were measured by injection of a tracer gas under well-mixed conditions. The volumes were confirmed by direct measurement. The primary simplifying assumption used to calculate interroom transport rates was that the indoor-outdoor flows for each compartment were equal in both directions. This was plausible because the large indoor/outdoor temperature differences, the low local wind speeds, and the wind-protected location of the house allowed us to assume that the stack effect, as opposed to the wind effect, was the primary driving force for infiltration in this house. In addition, the flows through the building shell were generally small compared to the interroom flows. Thus we were able to assign a portion of the total house infiltration air-flow rate, measured by CO_2 decay, to the bedroom and to the rest of the house, using the length of wall exposed to the outside.

Increases in average bedroom CO_2 concentrations ranged from 2440 to 5440 ppm. Peak bedroom CO_2 concentrations ranged from 2870 to 5970 ppm. These numbers can be compared to the short-term (8-hour average) U.S. occupational CO_2 standard of 5000 ppm.[20]

As expected, carbon monoxide concentrations were highest when the radiant heater was used, and NO_x ($NO + NO_2$) concentrations were highest when the convective heater was used. However, NO_2 concentrations, although varying widely, were similar for both the convective and radiant heaters. This was surprising because earlier work showed NO_2 emissions for convective heaters were higher than for radiant heaters.[18,21] The range of increase in NO_2 concentrations was from 0.12 to 0.60 ppm for the convective heater tests and from 0.12 to 0.52 ppm for the radiant heater tests. These numbers can be compared to the short-term (1-hour average) California outdoor NO_2 standard of 0.25 ppm.[22] The CO concentrations ranged from 0.5 to 2.7 ppm for the convective heater tests and from 8.9 to 18 ppm for the radiant heater tests.

An important observation is that moderate increases in ventilation rates (from opening a window or door 2.5 cm) did not reduce the peak pollutant concentrations because the heater operated longer to achieve the same temperature rise. The peak CO_2 concentration (less indoor background) averaged 4080 ± 870 ppm when the window and door were closed, 4370 ± 700 ppm when the door was open 2.5 cm, and 3830 ± 1100 ppm when the window was open 2.5 cm. However, fully opening the bedroom door diluted the pollutants, lowering the peak CO_2 concentration to 2560 ± 160 ppm above background.

Semicontinuous emission rates were determined for CO, NO_2, and N(of NO_x). The CO emission rate from the convective heater fell rapidly during the first hour of operation; thereafter, its CO emissions were insignificant (less than 2 μg kJ^{-1}). The CO emission rates from the radiant heater compare well with the same heater near sea level, which ranged from 60 to 140 μg kJ^{-1}.[18] The N(of NO_x) emission rate in this study was slightly below those of the near-sea-level tests of the same heater.[18] The near-sea-level N(of NO_x) emission rates ranged from 15 to 16 μg kJ^{-1} for the convective heater and from 1.7 to 2.2 μg kJ^{-1} for the radiant heater. However, the NO_2 emission rate for the convective heater was dramatically lower in these high-elevation tests than in the earlier low-elevation tests. The latter showed an NO_2 emission rate that ranged from 12 to 25 μg kJ^{-1}, whereas the high-elevation tests showed long-term rates between approximately 2 and 6 μg kJ^{-1}. The low-elevation tests were conducted for only 1 hour, and NO_2 emission rates are higher during the initial burn period, but these facts do not explain the entire difference observed.

Interroom pollutant transport rates were calculated for all tests with the bedroom window closed. When the bedroom door was also closed, the interroom flow rate averaged 6 ± 3 m^3 h^{-1}. This corresponds to an interroom air exchange rate (relative to the bedroom volume) of 0.2 h^{-1}, compared with the values of 0.35 to 0.5 h^{-1} that represent the total flow of air out of the bedroom for these tests. The interroom temperature difference peaked at approximately 8°C. Pollutants continued to be transported from the bedroom to the rest of the house for several hours after the heater was shut off. The average interroom temperature differences over the measurement period were in the range of 3° to 5°C.

When the bedroom door was open 2.5 cm, the interroom flow rates ranged from 16 to 53 m^3 h^{-1}, corresponding to an interroom air exchange rate range of 0.5 to 1.7 h^{-1}. Interroom temperature differences and interroom pollutant transport rates are shown in Fig. 7.

When the bedroom door was wide open, interroom flow rates were so high that they could be calculated only while the heater was operating and a pollution gradient existed. Figure 8 shows the time-dependent interroom flow rates and temperature differences for the convective and radiant heater tests. These rates are considerably higher than those with the door closed or slightly open (2.5 cm). At the end of the convective heater test, the bedroom CO_2 concentration was almost identical to the living room and kitchen values. We hypothesize that the

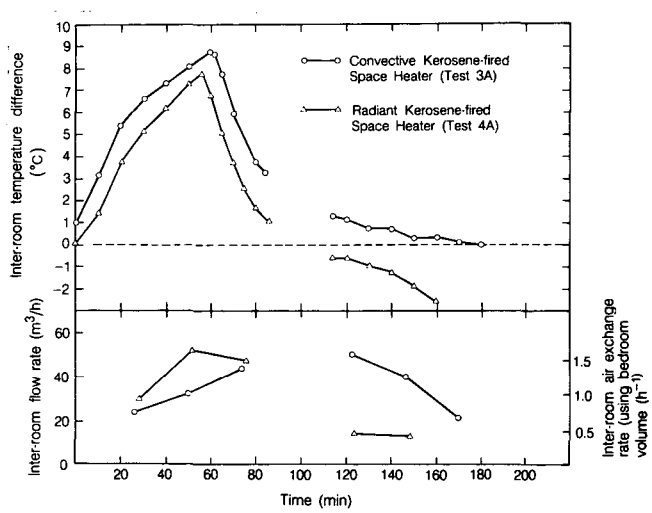

Figure 7. Interroom temperature differences and air-flow rates during operation of a kerosene-fired space heater in a bedroom with the door open 2.5 cm. Flow rates were calculated using a two-compartment mass-balance model in which flow is between the master bedroom (31 m^3) and the rest of the house (205 m^3). (XBL 848-3401)

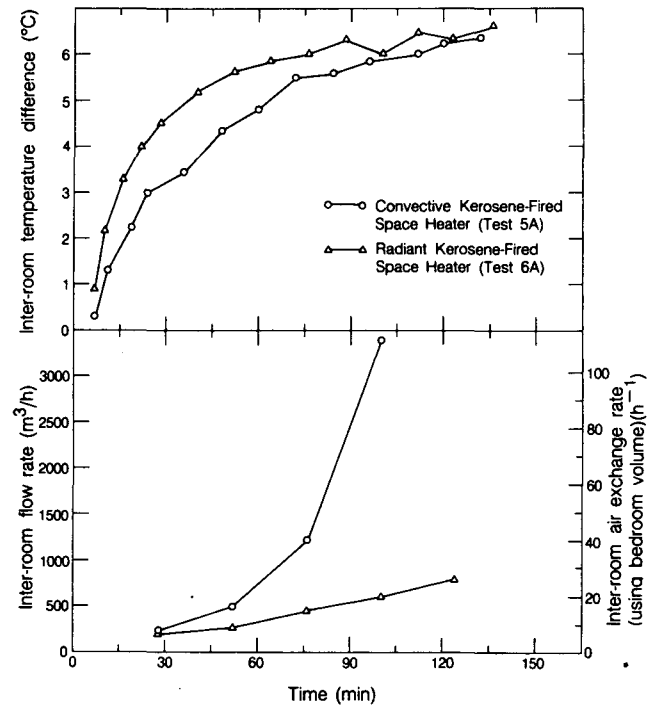

Figure 8. Interroom temperature differences and air-flow rates during operation of a kerosene-fired space heater in a bedroom with the door fully open (74 cm). Flow rates were calculated using the two-compartment mass-balance model. (XBL 842-9420)

larger interroom pollutant transport rate in this test may be due to the greater heat output of the convective heater and/or to the larger vertical temperature gradient in the bedroom. The latter explanation is plausible since virtually all of the heat from the convective heater is contained in its plume, while the radiant heater's output has both convective and radiant components.

Wood-Burning Stoves

Four types of wood-burning stoves were tested to determine their contribution to indoor air pollution. Three models (stoves A, B, and C) were considered airtight, while one (stove D) was not. The flue vent system was 20 cm (8 inches) in diameter and included a damper. Stoves A, C, and D were designed for 20-cm flues. Stove B was designed for a 15-cm flue, so an adaptive collar was added.

The protocol for all tests was to simulate actual use conditions. The stoves were lighted with kindling and stoked with both pine and oak logs. Fuel consumption was determined by weighing the wood before combustion and subtracting the mass of the charred remains. The stoves were operated so as to

keep the average indoor air temperature between 20° and 25°C. (Average outdoor temperatures ranged from −2°C to 3°C.) The heaters were operated for a minimum of 5 hours during each test. Tests for suspended particles were conducted for 2 days without using any wood-burning stove.

A summary of air exchange rate, carbon monoxide (CO), and submicron particulate data is shown in Table 6. Table 7 summarizes the total suspended particulate (TSP) and benzo(a)pyrene (BaP) results. In general, the three airtight stoves (A, B, and C) did not emit significant amounts of pollutants indoors, while the nonairtight stove emitted high amounts of carbon monoxide and suspended particles containing polycyclic aromatic hydrocarbons (PAH).

Table 6. Summary of CO, submicron particle, and house air exchange rate data from operating a wood-burning stove.

Test number	House air exchange rate (h^{-1})[a]	Δ CO (ppm)[b]		Δ Submicron particles ($\mu g\ m^{-3}$)[c]	
		Avg.	Peak	Avg.	Peak
Airtight					
A-1	0.48	0.5	2.6	24	140
A-2[d]	0.88	0.1	0.2	3	27
B-1	0.42	0.5	0.9	1	10
B-2	0.44	1.0	1.3	8	130
C-1	0.46	0.1	0.5	1	17
C-2	0.40	0.3	0.7	13	270
C-3	0.36	1.0	2.7	22	110
Nonairtight					
D-1	0.67	2.1	7.5	490	1,890
D-2	0.56	8.6	35.0	—	—
D-3	0.58	7.2	42.0	750	9,980
D-4	0.66	0.8	2.8	100	1,880
No stove	0.3[e]	—	—	4	8
No stove	0.3[e]	—	—	8	19

[a]Calculated from decay of sulfur hexaflouride.

[b]Average increase in concentrations over background are averaged over rooms and time, while peak change in concentrations over background are averaged over rooms.

[c]Only living room monitored. Concentrations are increases over background. Particles <0.6 μm, assumptions include spherical shape and 2.0 g cm^{-3} density.

[d]Used as a fireplace.

[e]Based on data during other days.

Table 7. Summary of indoor and outdoor TSP and PAH concentrations with operation of a wood-burning stove.

Test number	TSP ($\mu g\ m^{-3}$)		BaP ($ng\ m^{-3}$)		Sum PAH/TSP[a] ($ng\ \mu g^{-1}$)	
	In	Out	In	Out	In	Out
Airtight						
A-1	71	12	0.88	0.47	0.65	0.30
A-2[b]	28	12	3.5	0.51	0.69	0.25
B-1	38	19	0.94	1.9	0.14	0.47
B-2	49	31	0.48	0.83	0.084	0.15
C-1	24	10	0.34	0.55	0.085	0.36
C-2	34	18	0.42	1.1	0.11	0.33
C-3	39	7.2	0.71	1.2	0.11	0.86
Nonairtight						
D-1[c]	650	14	76	0.61	0.63	0.31
	470		41		0.75	
D-2[c]	320	11	29	0.74	0.40	0.34
	380		66		0.74	
D-3[c]	430	15	19	1.7	0.21	0.70
	820		490		2.8	
D-4[c]	210	27	37	3.1	0.82	0.62
	28		2.0		0.38	
No stove	24	16	0.16	0.68	0.47	0.18
No stove	19	17	0.044	0.18	0.018	0.049

[a]Sum of 5 PAHs measured; sum PAH = BbF + BkF + BaP + BghiP + IcdP.

[b]Stove used as a fireplace.

[c]Two measurements taken at different times during test.

The airtight stoves all caused at least one short-term peak increase in CO and submicron particulate levels. Although peaks were observed during stoking and reloading, the short-term peak concentrations were highest when starting the stove. These peaks raised average CO levels above outdoor levels, but except for two tests, they did not elevate indoor PAH concentrations above corresponding outdoor concentrations. The two exceptions were with stove A.

TSP concentrations were greater indoors than outdoors for all tests, including two control tests in which no stove was used. Since we would expect the TSP concentration to be lower indoors than outdoors in the absence of an indoor source, the data suggest that another source of particles must exist. Because the house has no other combustion appliance or other obvious source of suspended particles, we con-

clude that dust was suspended or resuspended by the researchers in the house or by some other, unknown mechanism. The differences between the indoor and outdoor TSP concentrations for the airtight stove tests ranged from 14 to 59 $\mu g\ m^{-3}$. Some of this difference is undoubtedly due to the stove; however, we cannot consider all of it to be stove-generated because of the control test results.

The nonairtight stove D was a serious pollution source, and the very high levels of indoor TSP that were found can be attributed to it. Stove D was a 30-inch Franklin type and had visible gaps in its construction. During one test, indoor TSP levels reached 820 $\mu g\ m^{-3}$, BaP levels 490 ng m^{-3}, and CO levels 43 ppm. For reference, the U.S. Environmental Protection Agency's outdoor 24-hour TSP standard is 260 $\mu g\ m^{-3}$, the 8-hour CO standard is 9 ppm, and the 1-hour average CO standard is 35 ppm.[23] It should be noted that the indoor environment was not a consideration in the development of these particulate standards.

Indoor and outdoor NO_2 and NO concentrations were very low in all tests—below 0.02 ppm on the average. Formaldehyde (HCHO) concentrations were also low in general. Only stove D increased HCHO concentrations above the house's normal variation. These increases ranged from 10 to 49 ppb.

Planned Activities for FY 1985

We plan to conduct an in-depth review of the state of research on indoor air pollution from combustion appliances. As part of this review, we will develop an indoor air pollution exposure model (for homes with combustion appliances), identify information gaps, and design strategies to fill them.

Further laboratory research will also be conducted in FY 1985. Organic emissions from kerosene-fired space heaters will be quantified, and catalysts for controlling kerosene heater pollutants will be evaluated.

INDOOR AIR QUALITY CONTROL TECHNIQUES

There are three basic techniques for controlling concentrations of indoor air pollutants: source control, removal by ventilation, and removal by other means than ventilation.

The first technique, source control, excludes or removes pollutant sources or modifies them to reduce the rate of emission or entry. It is often possible to greatly reduce pollutant source strengths, sometimes by factors of 5 to 10, reducing pollutant concentrations correspondingly. In addition, many source control measures do not require maintenance or increase the building's energy requirements.

Ventilation is the second general control technique. Its major advantages are that it can effectively reduce the concentration of several pollutants at once and that the equipment for it is readily available. Increased ventilation, however, does increase building energy demands. In addition, when source strengths are very high, the extra ventilation required to achieve acceptable pollutant concentrations may be impractical because of the additional energy requirements, noise, and equipment costs.

The third general control technique, pollutant removal by other means than ventilation, requires active air cleaners, such as those that force air through a filter or adsorbent, or an increase in the rate of such "natural" removal processes as deposition on (or reaction with) interior surfaces.

During FY 1984 the Control Techniques Project conducted research on several techniques of pollutant control; its major research accomplishments and future plans are described below.

Accomplishments During FY 1984

Formaldehyde Transfer in Enthalpy Exchangers

An increasingly common technique of ventilating residences is to mechanically supply and exhaust approximately equal amounts of air and to transfer heat between the incoming and outgoing airstreams in an air-to-air heat exchanger. Some heat exchangers in these ventilation systems, often called enthalpy exchangers, are designed so that water vapor as well as heat is transferred. In summer, when the outdoor air is humid, the transfer of moisture from the incoming to the outgoing airstream reduces the latent load on air-conditioning equipment; in winter, moisture transfer is reversed—from the outgoing to the incoming airstream—to reduce humidification requirements.

A potential problem with enthalpy exchangers is that some indoor-generated pollutants may be transferred from the outgoing to the incoming airstream, reducing the ventilation system's effectiveness in controlling these pollutants. Transfer of pollutants between airstreams can occur by air leakage, even in exchangers not designed for moisture transfer; however, enthalpy exchangers may have additional mechanisms for pollutant transfer. Significant transfer would appear most likely for pollutants that are chemically similar to water or soluble in water.

Manufacturers' product literature,[24] results from a previous field study,[25] and an examination of the

physical and chemical properties of the formaldehyde (HCHO) molecule indicate that significant transfer of HCHO, which is highly soluble in water, may occur in some enthalpy exchangers. A laboratory study[26] was therefore conducted to determine the transfer rates of HCHO and two tracer gases (propane and sulfur hexafluoride) between airstreams passing through the cores of two enthalpy exchangers of different design. In the core of the first exchanger (Heat Exchanger No. 1), gases such as water vapor are transferred directly through paper sheets that separate the two airstreams; the sheets are impregnated with substances identified only as a "hydrophilic resin" and a "hygroscopic agent."[27] Possible transfer mechanisms are ordinary molecular diffusion through pores, Knudsen diffusion, and activated diffusion or permeation. In the rotating, counterflow heat-wheel core of the second exchanger (Heat Exchanger No. 2), gases such as water vapor are absorbed within a lithium chloride coating on the surfaces of the core and then desorb when these surfaces become exposed to the other airstream. In both cores, the transfer is from the airstream containing an initially higher concentration of the gas to the airstream that initially contains a lower concentration.

An example of the results obtained from experiments that simulated wintertime operation of the heat exchangers is given in Fig. 9. This figure shows

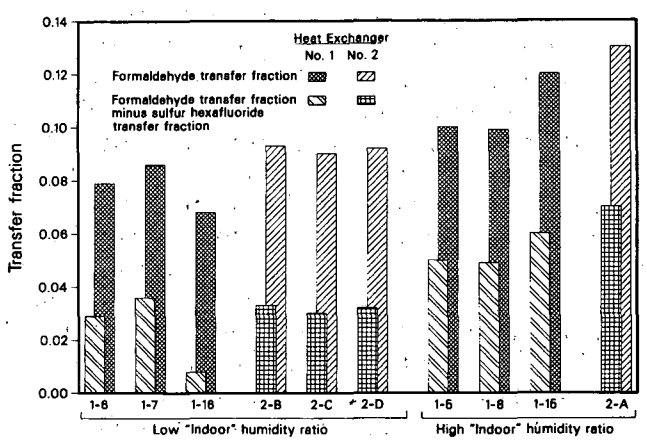

Figure 9. Formaldehyde transfer fractions measured during winter tests. The results are grouped into tests where the indoor humidity ratio was low (0.0037–0.0066) or high (0.0075–0.0091). The estimated uncertainty in the formaldehyde transfer fraction is less than 12% of the measured value. Also shown is the difference between the formaldehyde and sulfur hexafluoride transfer fraction. Test numbers are listed below the bars; the initial "1-" and "2-" denote Heat Exchangers No. 1 and No. 2.

(XCG 847-13166)

that only 8% to 13% of the HCHO in the exhaust airstream (upstream of the core) was transferred to the supply airstream (i.e., the formaldehyde transfer fraction was 0.08 to 0.13). Moreover, the transfer fraction of HCHO was only 0.01 to 0.07 greater than the transfer fraction of sulfur hexafluoride (SF_6), and the primary transfer mechanism for SF_6 was thought to be leakage between airstreams. The transfer fractions of HCHO and tracer gases were slightly greater during experiments that simulated summertime operation, but the HCHO transfer fraction never exceeded that of SF_6 by more than 0.09.

Our major conclusion was, therefore, that transfer of HCHO by processes other than air leakage is not a substantial problem in these heat exchangers. Because the transfer fractions were small and only slightly affected by operating conditions, the nature of the transfer mechanisms remains speculative, although probable mechanisms are identified in the full report.[26]

The transfer of water vapor between airstreams in enthalpy exchangers may still substantially affect indoor HCHO concentrations, however, because HCHO emissions from many sources will increase along with indoor humidity. When the outdoor air has a lower humidity ratio than the indoor air, ventilation provided through an enthalpy exchanger will not reduce the indoor humidity or HCHO concentration as substantially as ventilation without moisture transfer. The magnitude of the increase in indoor HCHO concentration caused by the moisture transfer will depend on ventilation rates, the indoor moisture generation rate, the outdoor humidity ratio, the efficiency of moisture transfer, and the relationship between HCHO emission rate and indoor humidity. Calculations indicate that moisture transfer under typical conditions could lead to 4% to 28% higher indoor HCHO concentrations. Thus, in these exchangers, transfer of moisture between airstreams will generally have a larger detrimental effect on the indoor HCHO concentration than the transfer of HCHO between airstreams.

Impact of Ventilation on Indoor Pollutant Concentrations

It is frequently assumed that indoor pollutant concentrations are inversely proportional to the ventilation rate when the predominant source is indoors. However, many factors can change this relationship. Pollutant removal by nonventilation processes such as active air cleaning or deposition on surfaces may reduce the sensitivity to ventilation. In some cases, the indoor radon or formaldehyde source strength is positively coupled to the ventilation rate. Finally,

the source strength for radon progeny, which is directly proportional to the radon concentration, generally decreases when ventilation is increased, a relationship that causes indoor progeny concentrations to vary more rapidly than in a simple inverse dependence.

All these factors make it necessary to use mathematical models to relate concentrations and ventilation rates.[28] Figure 10 illustrates some results obtained from relatively simple mass-balance models; the curves indicate how indoor pollutant concentrations are predicted to change when the ventilation rate is increased or decreased from a typical value of 0.5 ach. The sensitivity varies, but all of the curves in the figure indicate that indoor concentrations rise rapidly as the ventilation rate becomes unusually low, thus showing the importance of avoiding these rates. The analysis also indicates that models must account both for the couplings between pollutant source strengths and ventilation rates and for pollutant removal processes other than ventilation when estimating the impact of a change in ventilation rate on indoor pollutant concentrations.

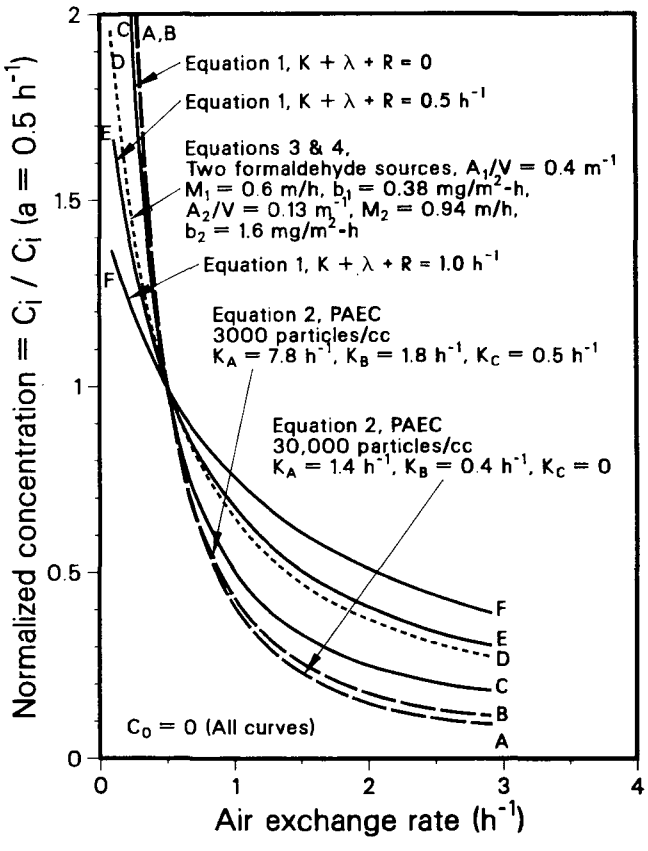

Figure 10. Predicted effects on indoor concentration of changing the air exchange rate from a typical value of 0.5 ach. Curve C shows the frequently assumed relationship in which concentration is inversely proportional to the air exchange rate. *K* is the deposition constant; λ, the radioactive decay constant; and *R*, the air cleaning constant. *A* is the surface area of a formaldehyde source, *V* is the house volume. *M* and *b* characterize the emission rate of formaldehyde. PAEC is the potential alpha energy concentration. The equations are from Ref. 28. (XCG 8410-13399)

Review and Analysis of Control Techniques

Another effort in FY 1984 was to complete an extensive and critical review of literature on indoor air quality control techniques. The outcome is a report[29] that describes the working principles of various control techniques, discusses the effectiveness, advantages, and disadvantages of different methods of ventilation, and evaluates, to the degree possible, pollutant-specific measures based on air cleaning or source control. To our knowledge, the report constitutes the only comprehensive review in this area.

Tracer Gas Studies of the Ventilation of Large Buildings

Controlling pollutant concentrations in large buildings is accomplished primarily by providing mechanical ventilation. The systems in such buildings generally supply and exhaust air at many points and are controlled automatically in response to thermal loads and outdoor temperature. Often, several ventilation systems, each drawing air from outside, are present within a building.

During FY 1985 a research effort was initiated that focuses on using multiple tracer gases to evaluate ventilation rates, the degree of short-circuiting of air from supply to exhaust, and the distribution of outside air in large nonindustrial buildings. The information gained will be of value for at least two reasons. First, when ventilation performance is characterized as part of more comprehensive studies that include air quality measurements and health-related surveys, the result should be a greatly increased understanding of the causes of problems in "sick" buildings and of factors that affect their pollutant concentrations. Second, we will be better able to characterize how ventilation system performance depends on various design and control features and on other building characteristics.

During FY 1984 a gas chromatograph with an electron capture detector was procured for simultaneous measurement of the concentrations of several tracer gases, and an evaluation of its performance with several tracers was initiated. A prototype of a programmable tracer gas injection system that initiates, terminates, and controls the rate of injection

into a building's ventilation system was also designed and fabricated. Finally, work started on the design of a programmable sampler that will automatically collect small air/tracer gas samples in containers that can be mailed to the laboratory for analysis.

Planned Activities for FY 1985

Our research on the use of tracer gases to study ventilation in large buildings will continue in FY 1985. The major objective will be to complete the development and evaluation of the experimental equipment and techniques so that monitoring of buildings can commence in FY 1986. Another research effort will be directed toward exhaust ventilation of residential buildings with heat recovery by using a heat pump to transfer heat from the exhaust airstream to the domestic hot water and/or to the indoor air. A computer model will be developed to evaluate various operational strategies in a range of climates. If sufficient support is received, laboratory and/or field studies of the technology will also be initiated.

PASSIVE SAMPLERS

Field studies of indoor air quality and of the effects on it of reduced ventilation have been limited, in part, by the high cost of using continuous monitors. Passive samplers capable of measuring daily or weekly integrated contaminant concentrations could greatly reduce these costs because they do not require power supplies, accessories such as pumps and chart recorders, or the attendance of technicians. With such samplers, large-scale audits could be conducted to ensure that building energy conservation programs are implemented without adverse effects on occupant health and safety. They would also make possible large-scale studies of the indoor air quality of existing buildings and facilitate epidemiological studies, which have typically relied on exposures derived from distant, fixed-site monitors. Because passive samplers are inexpensive, unobtrusive, and do not require a power supply, they are ideal both as area monitors in buildings and as personal monitoring devices for direct measurement of exposures. The development and validation of passive samplers to meet these needs is the focus of this project.

Accomplishments During FY 1984

Water Vapor Passive Sampler

We have continued tests of the performance of the water vapor passive sampler (Fig. 11). Previous tests had shown that the acrylic diffusion tubes in the original design adsorbed water nonreproducibly so that stable blanks and adequate shelf life could not be obtained. More recently, samplers with aluminum diffusion tubes have shown both stable blanks and good storage stability, gaining only an insignificant 0.2 ± 1.2 mg after 27 days of storage. Even after more than 90 days, exposed and blank samplers had equal weight gains of less than 6 mg.

We extended the field validation by exposing 75 water vapor passive samplers to the highly variable humidity of a bathroom with mildew problems in an occupied residence. Fifteen samplers were capped and collected after exposure intervals of 1, 3, 5, 7, and 9 days. The output of a LiCl hygrometer was logged to obtain exposure data for comparison. The temperature ranged from 14° to 34°C, and the relative humidity ranged from below 10% to 100%. The sampler response with respect to the absolute humidity exposure was linear, with accuracy comparable to previous tests.[30] Precision was also good, ranging from 0.4% to 2.3% for the individual exposure intervals.

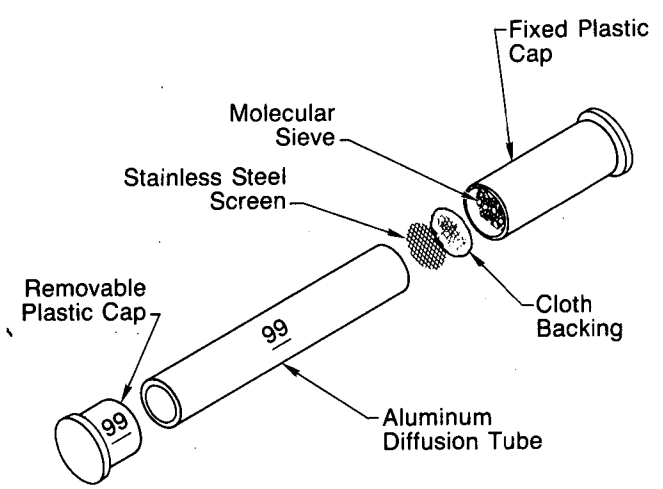

Figure 11. Exploded schematic of the water vapor passive sampler. Note that cap and tube are numbered to maintain a matched set. (XBL 8312-7408)

Carbon Monoxide Passive Sampler

The carbon monoxide passive sampler under development is based upon the reaction of a palladium compound with CO. Sampler performance was improved by optimizing both the concentration of the palladium compound in the preparatory solution and the pH of the solution. Because the palladium compounds also require water vapor as a reactant, a major difficulty has been stabilizing the sampler's response to varying humidity. Improvements in stabilization were made by using a dynamic humidifying atmosphere to condition the samplers during preparation.

Correction for Sampler Starvation

An important source of error inherent in diffusive sampling is depletion of the analyte in the region around the open end of the sampler, often referred to as sampler starvation. Error due to depletion occurs when external mass-transfer resistance is significant compared with the sampler's internal mass-transfer resistance. A simple method to correct for this error has been developed. When multiple diffusive samplers of different lengths are simultaneously exposed, a plot of the calculated concentration of the analyte at the open end of the sampler versus diffusive flux can be made and extrapolated to a sampler of infinite length, yielding an estimate of concentration in the bulk atmosphere. The utility of this method was demonstrated by using water vapor passive samplers of different lengths to compare extrapolated concentrations of water vapor with concentrations measured by a dew-point hygrometer. The results of these experiments are illustrated in Fig. 12 and support the use of multiple diffusive samplers of different lengths in circumstances where sampler starvation is likely to be a significant source of error. A more detailed explanation of the experiments and results can be found in a recent report.[31]

Planned Activities for FY 1985

We will continue the development of the CO passive sampler and, if progress is satisfactory, will begin field validation, comparing its performance with that of a continuous analyzer in a variety of residential environments. In addition, a critical assessment of analytical techniques for carbon dioxide determinations is planned so as to evaluate the feasibility of developing a CO_2 passive sampler.

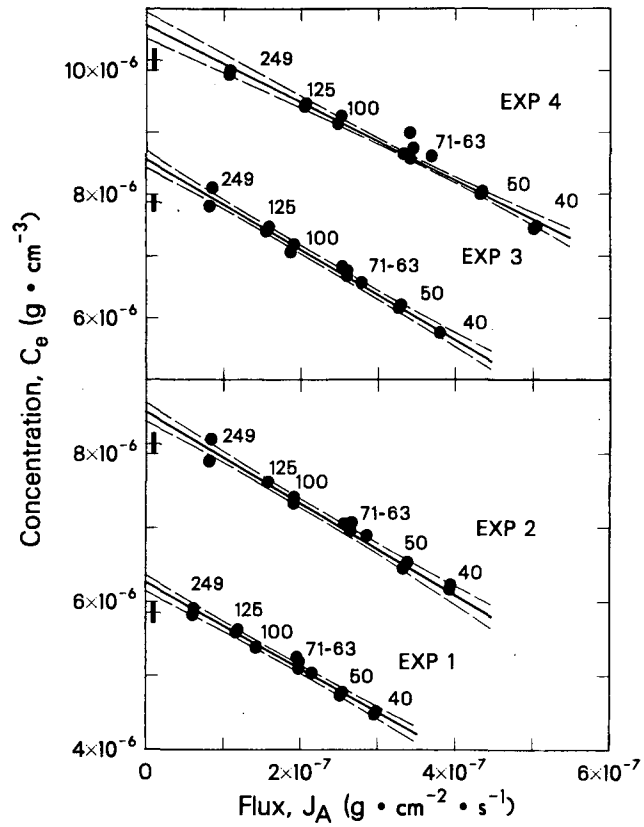

Figure 12. Extrapolation of concentration of analyte (water vapor) at open end of tube and flux data for 15 water vapor samplers of various lengths. Data are for four exposures. Dashed lines show 95% confidence limits of the slopes. Heavy bars on left axis are measured values of the concentration of water vapor in the bulk atmosphere. Sampler lengths in millimeters are shown near data points. (XCG 849-13259)

CONCENTRATION OF INDOOR POLLUTANTS DATA BASE

In the last decade, as many countries throughout the world have begun to pay serious attention to their energy policies, the importance of conserving energy in occupied buildings, both residential and commercial, has been increasingly acknowledged. But as various energy-conserving measures have been implemented (particularly those that reduce ventilation), there has also been a growing awareness that such measures, combined with the presence of pollutant sources, can adversely change air quality in buildings, causing health and comfort problems for the occupants. To identify the sources of these problems and develop solutions, much research has been

carried out, mainly in Europe and North America, to monitor pollutant concentrations and other relevant parameters in a wide variety of building types and geographic locations.

Some research has been published in journals or conference proceedings, some in internal reports; some, because of personnel shifts or program changes, has been neither formally collected nor published. The diversity of research sources and inaccessibility of some results, combined with the rapid growth in the amount of research, has made it apparent that a centralized collection of these results in an easily accessible form would facilitate their exchange, evaluation, and analysis.

The goal of this project, therefore, is to create a computerized data base of field studies devoted to monitoring indoor air quality in occupied buildings in the United States and Canada. (The term "data base" as used here means a collection of data files and command procedures that together comprise a data resource.) The Concentration of Indoor Pollutants (CIP) Data Base will contain research results, bibliographic references, and information describing the experimental environment, research procedures, and validity of the data.

Accomplishments During FY 1984

The CIP data base system is being implemented in a microcomputer environment using a commercially available data base management system. We are using an IBM PC microcomputer running dBase II from Ashton-Tate, which is currently the most widely implemented data base management system for microcomputers that is powerful enough for this application. Any microcomputer running dBase II would be able to access the data base.

Choosing a microcomputer environment for the data base entailed acquiring a computer system for use at LBL but offered significant long-term savings by eliminating time-sharing costs. In addition, the system is dedicated to this project, ensuring rapid, consistent response. Finally, dBase II is both powerful and flexible, allowing the data base to be implemented, modified, and updated easily and quickly.

The microcomputer system provides capability for designing, developing, and archiving the CIP data base and for remote access over telephone lines. The system configuration is a local-area network with the following major components:

Hardware:

- Three IBM PC's and one Compaq PC for staff use, network serving, and remote access.
- A 35-megabyte Winchester hard-disk subsystem with an integral 45-megabyte cartridge-tape backup device.
- A high-speed continuous-duty matrix printer capable of near letter-quality output at medium speed.
- Network hardware from 3-Com Corporation.

Software:

- Data base management system: "dBase II" from Ashton-Tate.
- Word processor: "Wordstar" from Micropro.
- Macro assembler: "8086-88 Macro Assembler" from Seattle Computing.
- Host emulation: "Remote" from Microstuf.
- Network software: "Etherseries" from 3-Com Corporation.

This system offers considerable flexibility and potential for extension as the CIP data base system evolves and expands. It is also in the mainstream of advanced microcomputer development and will remain so for at least several years, thus ensuring upward mobility in terms of new hardware and software. We believe it will be a valuable model for developing other, similar systems.

Users will be able to interact with the data base in two ways. The major mode will be via distributed and updated libraries of floppy disks containing the CIP data base. The other mode will be via remote access to the system at LBL over telephone lines. Together, these modes will provide considerable flexibility and broad access.

Menu-driven routines are being written to simplify search and retrieval of data and to provide online help facilities. In addition, the user will have access to the full capabilities of the powerful dBase II language. Because individual users will have their own copy of the CIP data base, they will be able to analyze the data at any level of detail they wish, either via dBase II or via various statistical, graphics, and other packages available commercially.

Since the project goal is to provide an evolving and growing resource to a broad community of users throughout the country, it is important to maintain contact with that community to attract new users and update the resource. A newsletter was therefore initiated to address user needs, respond to questions, and generally provide a communications medium for users. Updates, changes, and enhancements to the CIP data base system will be announced in the newsletter. In addition, remote access to the system provides the potential for an electronic bulletin board for users. The first edition of the newsletter was distributed in May 1984.

There are three funding sources for the project: the U.S. Department of Energy, the Gas Research Institute, and the Electric Power Research Institute. To facilitate their input and guidance, a technical advisory committee was formed to meet twice a year and review all aspects of the project and its progress. The committee is composed of one representative from each funding agency and two members chosen from the user community in consultation with the three agency representatives. The first meeting of this committee was convened at LBL and was successful in defining and resolving a number of issues concerning design and implementation of the data base.

The data base is divided into four distinct categories: bibliographic, numeric, site-description, and methodology. The last three categories are grouped together as summary data.

The bibliographic portion of the CIP data base is a resource in itself as well as an integral part of the overall system. Bibliographic searches will sometimes be all a user wants; at other times they represent the first step in retrieving more complete information on an experiment or class of experiments.

The bibliography contains citations of field studies monitoring pollutants in buildings. It does not include citations of articles describing data obtained solely in chamber studies. The references have been taken from journals, government reports, and conference proceedings, as well as unpublished communications and review articles. The articles themselves have been acquired as a necessary resource in building the data base and as a potential user resource.

Each entry contains the following discrete items of information:

- Title
- Authors
- Reference
- Remarks (associations, special features, etc.)
- Keywords
- Pollutant(s) measured
- Date of publication
- Country
- State/province
- Geographic region
- Type of building measured
- Format of the data

Bibliographic resources typically include the title, authors, reference, and date of publication as standard items. The other information has been included so that a user will have a better idea of the content of an article. Currently, only citations relating to four building types have been included in the data base: residences (single and multiple dwellings, apartments, mobile homes, etc.), schools, office buildings, and other public buildings. Factories, hotels, and restaurants are examples of building types not included. The citations have been restricted to studies conducted in the United States and Canada. To enable a user to be specific about the geographic area, the location has been divided into three parts: country, geographic region (e.g., northeast or southwest), and state or province.

Abstracts have not been included in the bibliographic data base, but often will be included in the summary data base.

At this time, the bibliographic data base supports the following functions via customized menu-driven procedures:

- Enter new references
- Edit existing references
- Print out references
- Search the data base

The first two functions are used principally by the project staff. New references are added with the "enter" function, and errors or omissions are corrected with the "edit" function. Customized hard-copy printouts or displays on a video monitor are obtained with the "print" function.

From the user's perspective, the heart of the data base is the search facility. Currently a user can search the bibliography using any of the following parameters: authors, date of publication, pollutant type, country, state, building type, and keywords. A search request can be either very broad or very specific and may contain any number or combination of search parameters. Repeats are allowed, such as multiple authors, pollutants, states, etc. As in all computerized search operations, the rules of entry are very specific and must be observed. The burden of memorizing these rules is much reduced, however, by having relevant help messages displayed at all times during the search and retrieval processes.

During FY 1984 approximately 180 bibliographic references were entered into the data base. This represents perhaps 70% of the suspected total number of published articles that meet project criteria for subject and location. In addition, the source articles for these references were collected, scanned for keywords, and catalogued.

Numerical, site, and methodological data (summary data) presented a novel and complex design problem. Several approaches were tested before settling on one solution. The entry of summary data is

significantly more time-consuming than the entry of bibliographic data. The software is still being developed, and little information has actually been entered. The current design will support two types of summary data, textual and tabular. Abstracts, conclusions, and other textual content of included works will be entered verbatim into the data base, either entirely or in part. Numerical and graphical data will be entered and displayed in a tabular format. This allows output to virtually any printer or console without additional or specialized software or hardware. There will also be a capability of searching through the summary data for parameters not included in the bibliographic entry, such as pollutant ranges, building materials, and instrument techniques.

The summary data base is intended to provide specific information on the techniques and equipment used in a particular experiment or series of experiments, as well as some indication of the quality of the data. Because no standard format can cover all possibilities, the format and content of this data base will vary from experiment to experiment.

The planned assessments of data quality and their inclusion in the data base present difficulties, both technical and practical. Experience and the counsel of the advisory committee will be valuable in establishing techniques and criteria for making these assessments.

Planned Activities for FY 1985

The initial focus will be on completing the data base design and implementation. There will then be a period of testing by a select user group for debugging and to receive comments and suggestions for modifications and enhancements. When this testing cycle is complete, there will be a more general distribution of the data base to interested persons. Access will be supported through distribution of floppy disks containing the data base system and remotely through phone lines to the computer system at LBL.

At the time of initial distribution, it is expected that the bibliographic facility will be virtually complete and current. The summary data facility will be relatively complete as far as support software and design is concerned, but it will contain the data from no more than 15 to 30 experiments. Once the data base is a functioning resource, the major project activities will be entering summary data from the remaining experiments, maintaining the bibliography, updating and maintaining the data base software, maintaining the computer system at LBL, and generally serving the user community through the newsletter and other modes of contact.

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Windows and Daylighting*

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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 heat gain through windows. In other words 5% of our national energy consumption—3.5 quads annually, or the equivalent of 1.7 million barrels of oil per day—is tied to the energy-related 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 energy performance of windows and skylights, including both thermal and daylighting aspects. This capability will be used to generate guidelines for optimal design and retrofit strategies in residential and commercial buildings and to assist in exploratory development of new high-performance materials and designs.

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 at one extreme and perform field tests and *in-situ* experiments in large buildings at the other. We have developed, validated, and now use a unique and powerful set of interrelated computational tools and experimental facilities that enable us to address the major research issues in this field. A multidisciplinary team of scientists, engineers, and architects conducts these studies, in collaboration with researchers in industry and academia.

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

Our work is organized into four major research areas:

- Optical materials studies
- Fenestration components and systems
  - —Thermal analysis
  - —Daylighting analysis
- Fenestration performance in buildings
  - —Simulation studies
  - —Field measurement facility
  - —Building monitoring
- Fenestration impact studies

Each of these areas is reviewed in the following sections.

OPTICAL MATERIALS STUDIES

Significant reductions in energy consumed by the building sector will come not only from better building design strategies but also from the development and introduction of new glazing materials. Since the inception of our program in 1976, identification, characterization, and exploratory development of promising new fenestration materials have been major activities. Research on new optical materials and on modifications of existing glazing materials is intended to create a technology base to assist industry with developing the next generation of advanced fenestration systems.

In addition to the research projects described below, the overall Optical Materials effort at LBL includes development of a multiyear research plan and scientific coordination of related DOE-funded research projects at universities, private sector firms, and other national laboratories.

Results of the DOE-supported program are made available to interested parties in the private sector. For example, an annual technical conference and industry forum is held each year in August in conjunction with a meeting of the International Society for Optical Engineering (SPIE). This meeting serves as a forum to review and discuss the direction of the overall DOE program as well as to report on recent technical progress. A joint international effort on glazing optical materials under the auspices of the International Energy Agency is being developed with our participation.

In 1976, when our program began, we identified the development of low-emittance ("low-E") coatings as a major program objective. DOE-supported research activities have helped the fenestration

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industry to accelerate market introduction of new high-performance window systems incorporating these coatings. Several small firms began offering commercial products in 1982, and in 1984 many of the largest glass and window manufacturers introduced "low-E" products. In the near term 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 offers the potential to produce transparent windows having heat transfer values as low as those of insulating walls. On an annual basis such windows should outperform the best-insulated wall, even for a north orientation in a cold climate, since diffuse solar gain will offset some conductive losses. We initiated planning in late 1984 for a Low-E Window Roundtable, to be co-sponsored with the National Fenestration Council. We believe that the positive impact of this DOE-supported effort can serve as a model for the transfer and development of research findings in other optical materials areas.

GLASS AND PLASTIC SUBSTRATES

Accomplishments During FY 1984

To predict the optical properties of complex window systems incorporating thin-film coatings, the optical properties of the glass and plastic substrates must be accurately known. These properties have not been available in a complete and self-consistent form even for the most common varieties of glass used in windows, hence the need for this measurement effort. This year we completed work on standard clear glasses, glasses having absorbing additives, and high-purity glasses. Our results are 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 provide some spectrally and directionally averaged bulk properties for calculating solar and thermal radiative heat transfer through windows. Figure 1 shows the real and imaginary components of the complex index of refraction for a clear glass as determined by Kramers-Kronig analysis of reflection measured with a Fourier-transform spectrometer over the near-infrared and infrared spectrum.

Future measurements will be greatly simplified with our new spectrometer, which covers the ultraviolet to the near infrared. In addition to having optics that are far superior to those of our previous

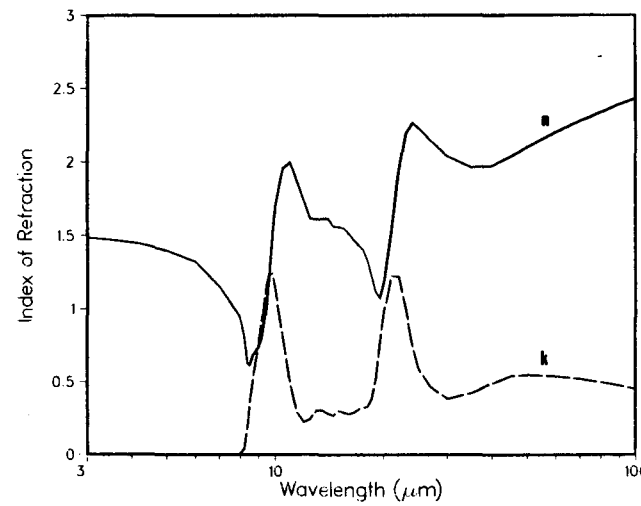


Figure 1. Real (n) and imaginary (k) parts of the complex index of refraction for soda-lime silica glass.
(XBL 8412-5271)

instrument, this system features completely automated operation and data collection. The instrument is installed and operating, although not all functions have been tested.

Planned Activities for FY 1985

We will collect, organize, and catalogue our low-emissivity samples. These samples will be completely characterized as part of our participation in the Low-E Window Roundtable in August 1985. Our spectrometer will be fully functioning.

LOW-CONDUCTANCE, HIGH-TRANSMITTANCE GLAZINGS

An ideal glazing material for residences in cold climates would have good optical clarity, high solar transmittance to admit sunlight in winter, and low thermal conductance to reduce heating costs. Such windows would perform better than insulated walls on an annual basis, even in northern orientations in cold climates. Simulation results for a north-facing window in Madison, Wisconsin are shown in Fig. 2. Windows must have U-value and shading coefficient combinations that place them to the right of the "0" net heat transfer line if they are to provide net energy benefits. Two promising research activities are under way to develop the technical basis for such advanced windows.

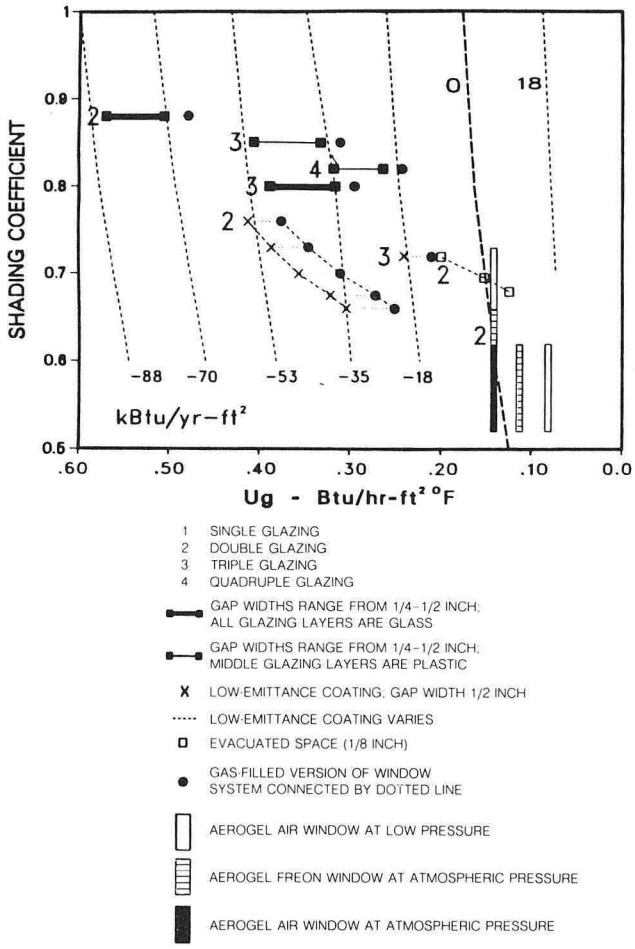


Figure 2. Simulation results for north-zone window, Madison, Wisconsin, showing net annual useful flux (primary window area = 66 ft^2). (XBL 856-2870)

Low-Emittance, Gradient-Index Coatings

Accomplishments During FY 1984

Since 1976 we have contributed to the development of window coatings that transmit sunlight but reflect in the thermal infrared, thus suppressing radiative heat transfer. Commercially available coatings based on metal-dielectric multilayer films have satisfactory optical properties but are not sufficiently durable to be used in nonsealed glazings. By producing a film having a continuously varying index of refraction to reduce reflection in the solar spectrum, we could use materials that are inherently more durable but less transparent than the metal films. Our analytical studies suggest that a gradient-index coating could improve solar transmittance by 25% without reducing emittance or durability.

We have begun by studying the titanium oxynitride (TiN_xO_y) system, producing these gradient-index coatings by plasma-assisted chemical vapor deposition (CVD). Better compositional control and durability have been achieved in a limited number of samples deposited by magnetron sputtering. We installed a new sputtering system and completed the first tests for homogeneous coatings. The coatings are being characterized by electron microscopy, Auger electron spectroscopy (AES), and Rutherford backscattering (RBS), in addition to complete optical characterization. RBS has proved particularly valuable in our efforts to remove impurities from the coatings. Figure 3 shows the small amount of chlorine remaining in the coating after adding H_2 to scavenge the bulk of the unwanted Cl in our CVD films.

Planned Activities for FY 1985

We will add reactive gas-handling capabilities to our sputtering system to produce TiN_xO_y films. The process parameters will be varied in an attempt to achieve the optimum optical properties predicted by our analytical models.

Aerogels

An unusual material, silica aerogel, is being developed at LBL for application as a transparent insulating window.[2,3] Aerogel is a microporous silica material containing a high fraction of voids (up to 97% by volume). It is transparent rather than translucent because the pore size is much smaller than the wavelength of light; it therefore transmits rather than scatters light (Fig. 4). Aerogel is an

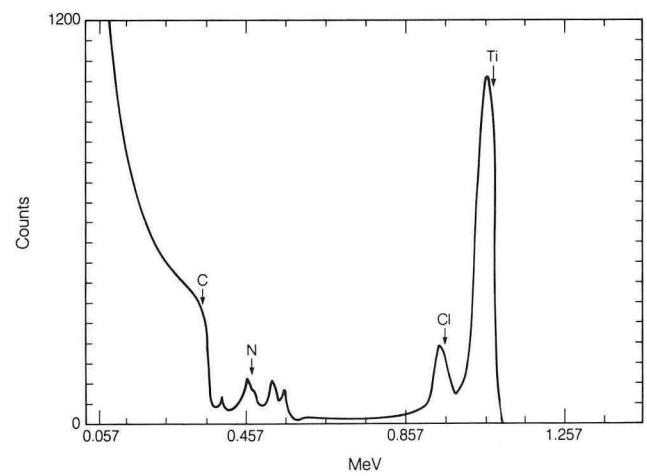


Figure 3. Rutherford backscattering spectrum for titanium oxynitride coating on glossy carbon substrate. (XBL 854-9799)

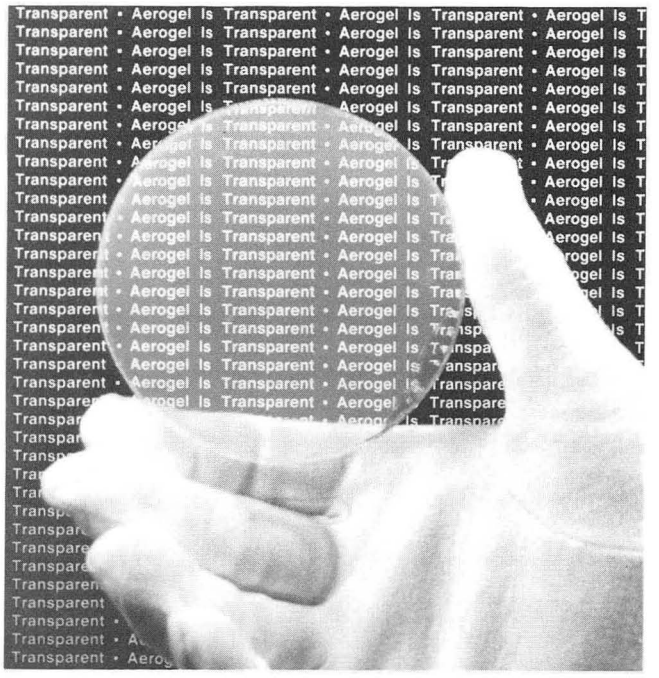


Figure 4. Photograph of a disc of aerogel, illustrating its transparency and image-preserving optical qualities.
(CBB 8410-7760)

excellent thermal insulator because of its low density and extremely small pore size. A nonevacuated 1-inch-thick aerogel window would have an R value of about 7, which would climb to nearly R-20 upon removing 90% of the air. The goals of the project are to improve the optical and thermal properties of aerogel, develop methods to protect it from the environment, and discover less expensive synthesis methods to accelerate its introduction into the commercial window market.

Accomplishments During FY 1984

Preparation of Aerogel. Aerogel production has two stages: (1) preparation of an alcogel by hydrolysis and condensation of silicon-alkoxides and (2) drying of the alcogel to achieve the aerogel. The first step mixes alkoxide, water, and solvent to produce very fine particles in solution that link together to form an alcogel, a semisolid consisting of a silica matrix containing mainly alcohol. In the second step the alcohol is removed to leave an open-pore silica matrix. We improved both steps to make the process simpler and more economical.

We prepared aerogels from two silicon-alkoxide starting compounds: $Si\text{-}(OCH_3)_4$ (tetramethyl orthosilicate—TMOS) and $Si\text{-}(OC_2H_5)_4$ (tetraethyl orthosilicate—TEOS). Good-quality transparent aerogels were made from base-catalyzed TMOS. Although TMOS is quite toxic, the final aerogel product is completely safe. To produce aerogels on a commercial scale, however, it would be desirable to use the much less toxic TEOS. Only acid-catalyzed TEOS had been used successfully to produce aerogel, but it displayed greater shrinkage and light scattering than did TMOS. A base-catalyzed process using TEOS was needed, and this we succeeded in developing. We then carried out experiments to optimize the process, using the factorial design technique. Concentrations of alkoxide, water, alcohol, and catalyst and the process temperature were changed simultaneously, and properties including light-scattering, optical spectra, pH, rheology of the sols, shrinkage, and surface area were measured. These studies have helped us better understand the process chemistry and evaluate the significant parameters in preparing TEOS aerogels having the desired qualities.

Supercritical Drying of Alcogel. More than 90% of the alcogel volume consists of fine pores containing alcohol. This alcohol must be removed to produce aerogel. Air drying causes the alcogel to collapse because of the extremely high interfacial forces at the gas/liquid interface. To prevent this damage, the alcohol is removed from the pores under supercritical conditions that minimize the interfacial forces. For alcohols supercritical conditions are 270°C and ~1700 psi pressure. Such high temperature and pressure makes the process expensive and time-consuming (2 to 3 days for each batch). In a major breakthrough we simplified the drying process by substituting liquid CO_2 for alcohol and supercritically drying at 40°C and $\leqslant$ 1200 psi. The drying time for each batch was reduced to 8 to 10 hours, and the equipment is simpler and less expensive than for high-temperature, high-pressure supercritical drying. This new drying method is a significant step in bringing the process closer to commercial viability.

Thermal Analysis of Aerogel. The thermal conductivity of aerogel is important both for determining the insulating value of an aerogel window and for helping us understand and improve its thermal performance. This year we tested various methods for measuring these properties. The laser pulse technique enables us to rapidly measure small samples in a small evacuated chamber. Its accuracy, however, is questionable. Supplemental measurements by conventional hot-plate techniques are also inconclusive because of the difficulty in preparing large, flat samples. Preliminary results were sufficient for us to develop suitable analytical models to apply to future results.

Planned Activities for FY 1985

Experiments to optimize the preparation of TEOS will continue. Alternative methods of preparation will be explored. The initial experiments in supercritical drying will be extended by performing detailed measurements to compare the properties resulting from the two drying methods. Methods of comparison will include spectroscopy, light scattering, and electron microscopy.

We will prepare new aerogel samples of optimum dimensions and with appropriate coatings for thermal conductivity tests. We will determine the magnitude of radiative heat transfer independently to evaluate the potential for using absorbing additives to reduce the conductivity of aerogel. The properties of evacuated and gas-filled aerogel windows will be determined and compared to other window designs.

OPTICAL SWITCHING PROCESSES AND MATERIALS

Optical switching materials or devices can be used for energy-efficient windows and other passive solar applications. An optical shutter provides a large change in optical properties under the influence of light, heat, an electric field, or their combination. The change can occur as a transformation from a material that is highly solar transmitting to one that reflects over part or all of the solar spectrum (Fig. 5). A less desirable alternative would be a material that switches from highly transmitting to highly absorbing since some of the absorbed energy would enter the building. An optical shutter coating would control the flow of visible light and/or solar heat gain through a building window, thus performing an energy management function. Depending upon design, such a coating could control glare, modulate daylight admittance, and limit solar heat gain to reduce cooling loads, prevent overheating, and improve thermal comfort. Initial results from energy simulation studies of office buildings suggest that the dynamic control attainable with optical shutter coatings provides substantial economic benefits by minimizing cooling and lighting energy use, reducing peak electricity demand, and potentially reducing the HVAC system size.

We consider materials that possess variable or reversible optical properties as potential candidates for an optical shutter. There are three classes of phenomena that may prove useful:

(1) Chromogenic materials, including electrochromic, photochromic, and thermochromic types.

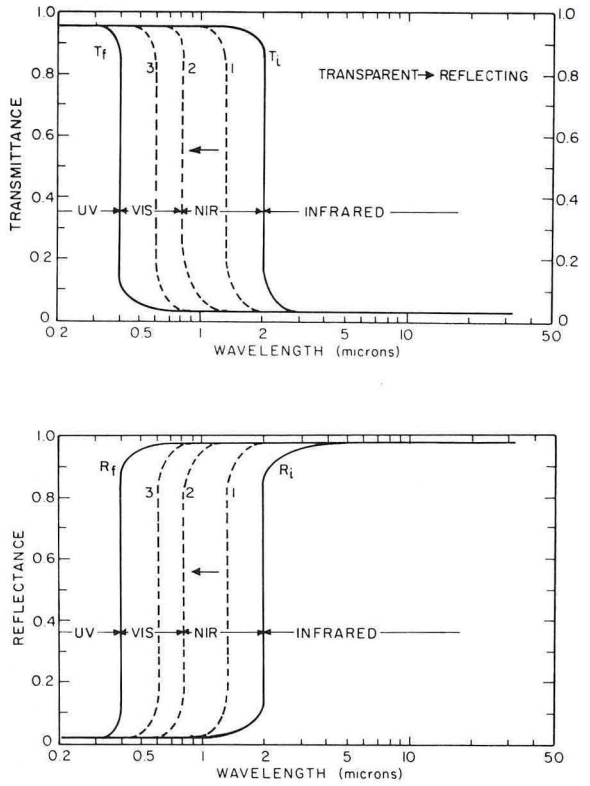


Figure 5. Idealized broadband spectral response for a solar optical shutter. This example ignores the effect of absorption and shows a highly transparent film transforming into a highly reflecting one. Such a shutter can control certain portions of the solar spectrum to provide or restrict both solar heating and lighting. (XBL 828-6452)

(2) Physio-optic media, including mesogenic molecules or liquid crystals, and magneto-optic, electro-optic, and mechano-optic or deformable media.

(3) Electrodeposition, including reversible electrodeposition and electrophoresis.

Our research program focuses on electrochromic coatings because they offer the potential for active control (by an applied voltage) in response to building operating requirements and environmental conditions and because there is sufficient experience with optical displays and related applications to suggest that they would be the best candidates for glazing applications. The active control capability will allow the greatest range of potential benefits in terms of reducing cooling loads, providing daylighting savings, controlling peak electricity demand, and reducing HVAC size.

Electrochromic Devices

Electrochromism is exhibited by many inorganic and organic materials.[4] An electrochromic material undergoes an intense color change when a colored compound is formed from an ion-insertion reaction induced by an instantaneous applied electric field. The reaction might follow:

$$MO_x + yA^+ + ye \rightleftarrows A_yMO_x \quad .$$

There are three categories of electrochromic materials: transition metal oxides, organic compounds, and intercalated materials. The materials that have attracted the most research interest are WO_3, MoO_3, and NiO_x films. With organic electrochromics, coloration of a liquid is achieved by an oxidation-reduction reaction, which may be coupled with a chemical reaction. Intercalated electrochromics are based on graphite and so are not useful for window applications.

A solid-state electrochromic device containing the elements shown in Fig. 6 can be fabricated: a transparent conductor, an electrochromic layer, an electrolyte or fast-ion conductor, a counter electrode, and a second transparent conductor. Many variations on this configuration are possible, although several of the approaches used for small electronic displays cannot be scaled up successfully to the dimensions required for windows.

Accomplishments During FY 1984

Prior to 1984 a technical review of electrochromism revealed many possible materials that could be incorporated into solar glazings.[4] During 1984 our research focused on electrochromism in nickel oxide, which can be switched from transparent to bronze or dark gray, depending on impurities. We performed experiments on oxidized metal films and chemically deposited oxides on indium-tin-oxide coated glass. We obtained a normally transmitting film with solar transmittance (T_s) and visible transmittance (T_v) as follows: T_s (off) = 0.73, T_s (on) = 0.37, T_v (off) = 0.75, and T_v (on) = 0.24. The spectral response is shown in Fig. 7. In an electrochemical cell 1 volt is required to switch the film. Besides spectrophotometry, voltammetry and Auger electron spectroscopy were performed on this film. These studies will help determine the active species in the electrochromic coloration reaction.

LBL continues to serve as scientific coordinator for the overall DOE-supported switching films program. Associated research was continued in 1984 by EIC Laboratories[5] and the Department of Electrical Engineering at Tufts University.[6] Electrochromic near-infrared reflectance modulation was demonstrated in polycrystalline WO_3 material.[7] Devices based on the configuration in Fig. 6 and with complementary electrochromic electrodes were made. Research by the Solar Energy Research Institute (SERI) has concentrated on devices based on amorphous WO_3 in the configuration: transparent conductor/WO_3/ion conductor/Au or indium-tin-oxide.[8]

Planned Activities for FY 1985

We will complete optical, chemical, and structural studies of electrochromic nickel oxide. We will

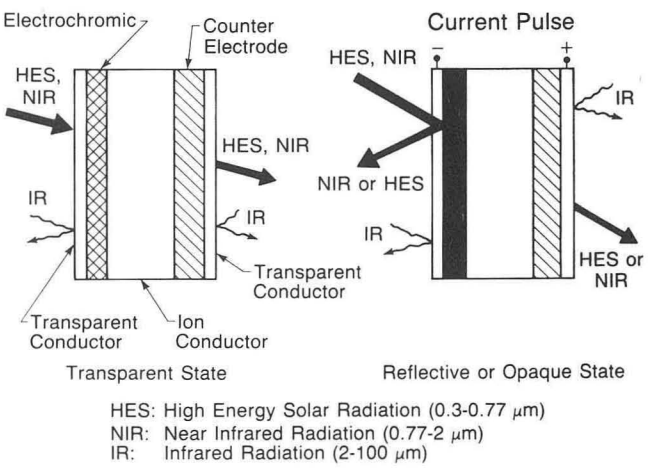


Figure 6. Schematic of an electrochromic optical switch shown in each of two states, transparent and colored. A current pulse causes an ion-based chemical reaction to take place in the electrochromic material. (XBL 842-10105)

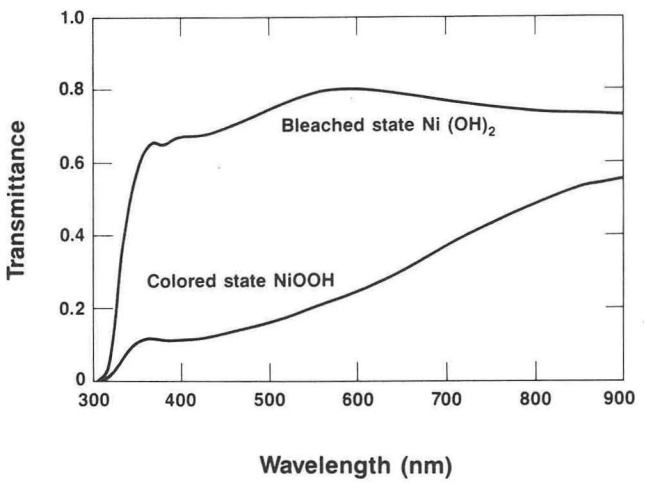


Figure 7. Transmission (near-normal) spectrum for nickel hydroxide in bleached and colored state. Conditions are IM-KOH electrolyte with 1 V applied potential. (XBL 852-6955)

compare the electrochromic response of sputter-prepared nickel oxide materials to the electrochemically prepared coatings. With our new reactive magnetron sputtering system, we will begin to survey and characterize electrochromism in other candidate materials such as titanium oxide. The objective is to identify and characterize electrochromic materials with performance characteristics that are better than the commonly used WO_3 films.

Other Switching Film Mechanisms

A number of other materials systems were reviewed to determine their suitability as optical switching materials. We continue to follow development of photochromic and thermochromic materials to determine if any may prove suitable to building applications. We also examined various physio-optic processes (i.e., liquid crystals, magneto-optic and electro-optic materials) as well as processes based on reversible electrodeposition and electrophoresis. Each approach has at least one attractive feature, but in general they appear less promising than the alternatives described above.

Accomplishments During FY 1984

An example of a device studied in FY 1984 is the dynamically light-scattering liquid crystal cell. It transforms from transparent to opaque white under applied potential; no polarizers are required. Its optical properties are T_s (off) = 0.82, T_s (on) = 0.77, T_v (off) = 0.83, T_v (on) = 0.20. Although the response of this device (Fig. 8) is promising as a broadband optical shutter, it suffers from excessive power requirements and lack of uniformity over large areas.

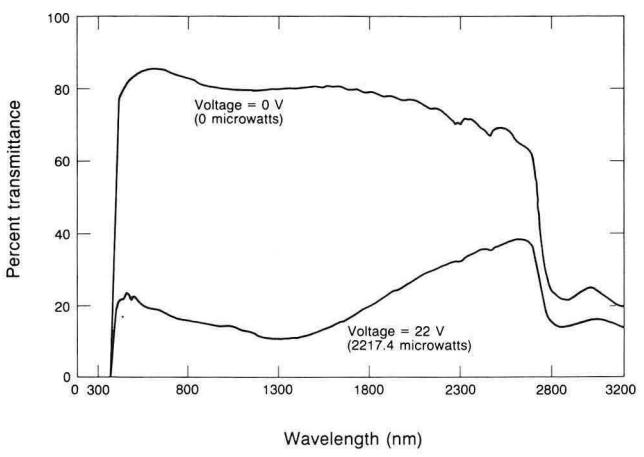


Figure 8. Spectral transmittance (near normal) for a dynamically scattering liquid crystal device. Response includes two glass cover plates and two transparent conductor electrode films. (XBL 852-7033)

Planned Activities for FY 1985

We will continue to follow these novel approaches for optical switching mechanisms to determine if results in other fields have relevance to aperture requirements. We expect to obtain samples of photochromic plastics to determine their suitability for building applications.

MATERIALS FOR IMPROVED USE OF DAYLIGHT

The intensity and spatial distribution of daylight transmitted through windows and skylights must be controlled in order to reduce electric lighting requirements while maintaining occupant comfort. Conventional solutions rely on architectural elements and interior or exterior devices to control daylight admission and distribution. 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.

In earlier studies we evaluated the performance of a variety of devices for daylight acceptance and control on the basis of their reflective and refractive optics. In 1982 we turned our attention to innovative optical materials and devices that showed the potential for replacing more complex mechanical systems. We reviewed the feasibility of approaches such as fiber-optics systems, hollow light guides, holographic coatings, selective-reflectance materials, and various scattering media. One promising approach that uses fluorescent concentrators to collect and redirect daylight is the subject of a patent disclosure.

Light Guides

Accomplishments During FY 1984

In 1984, on the basis of the preceding year's review of potential systems for light guides, we focused on two promising areas. We predicted improved performance for hollow reflecting light pipes because of the availability of new low-cost materials of high reflectivity (more than 95%). Figure 9 shows the calculated transmission efficiency of this type of light guide as a function of aspect ratio (length/diameter) for R = 95%. Even for aspect ratios of 50 (e.g., L = 15 m, D = 0.3 m) the transmis-

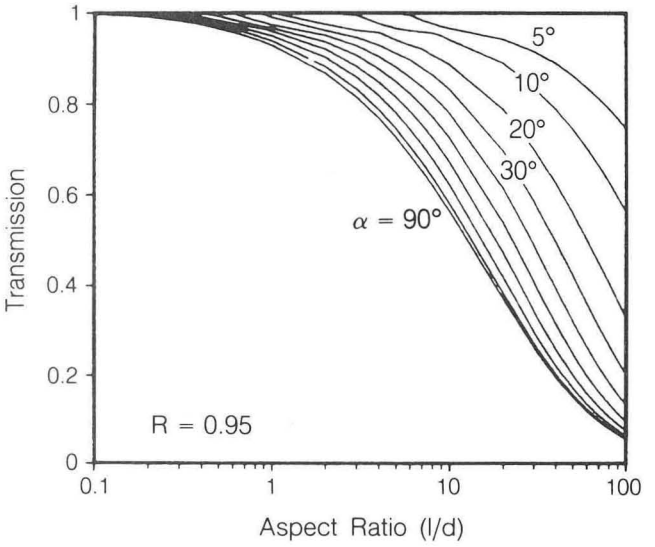


Figure 9. Transmission efficiency of a tubular light guide vs. aspect ratio (length/diameter). The parameter α is the half-angle of the concentrated sunlight. The inner surface reflectivity R is 0.95. (XBL 854-9798)

sion has acceptable values at moderate concentration angles. We also investigated the performance of plastic optical fibers and the potential for improvement through further purification of the base polymer.

Planned Activities for FY 1985

We will continue our investigation of hollow reflecting light guides. Available reflecting materials will be completely characterized and the results used in improved analytical models. We will compare these model results with the actual performance of hollow prismatic light guides. Scale models of light guide elements will be tested in our sky simulator.

FENESTRATION COMPONENTS AND SYSTEMS

Research activities in this area are intended to develop and refine experimental techniques and analytical models for accurately determining the heat transfer and solar optical properties of fenestration components and systems. 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 new simulation capabilities 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 overall plan for developing and implementing these new analysis capabilities in energy simulation models is shown schematically in Fig. 10.

THERMAL ANALYSIS

Accomplishments During FY 1984

We completed revisions to the fenestration chapter of the 1985 *ASHRAE Handbook of Fundamentals.* These include new tables on the properties of windows with (1) low-emittance coatings, (2) low-conductance gas-filled spaces, and (3) various convective and temperature-dependent boundary conditions. We also continued our participation in an International Energy Agency (IEA) task group (Annex XII) on windows and fenestration. We will jointly calculate the thermal properties and annual performance of several window systems and compare results from researchers in nine countries. One major objective is to better understand the accuracy and limitations of each calculation procedure and test method. We also participated in an International Standards Organization (ISO) work group on the thermal performance of fenestration.

Planned Activities for FY 1985

We will continue to participate in the IEA and ISO fenestration tasks. We will work with the ASHRAE Fenestration Committee to define the technical requirements for the next ASHRAE Handbook chapter update and will again work cooperatively with others to provide the required data. We will use our thermal analysis model, THERM, and experimental results to further investigate the effects of sealed glass edges and window sash and frame elements on overall conductance. We will also participate in DOE-cosponsored workshops on window U-value measurements and on low-emittance window systems.

SOLAR OPTICAL MODELS

Accomplishments During FY 1984

The solar optical properties of windows change with the sun's angle of incidence. For geometrically complex shading systems such as venetian blinds or egg-crate louvers, no adequate models exist to predict solar heat gain as a function of incidence angle. In addition, solar gain from ground-reflected sunlight and diffuse light from the sky cannot readily be calculated for complex shading systems. We are developing a new technique for determining solar heat gain through complex fenestration systems, a technique based on a standard series of laboratory

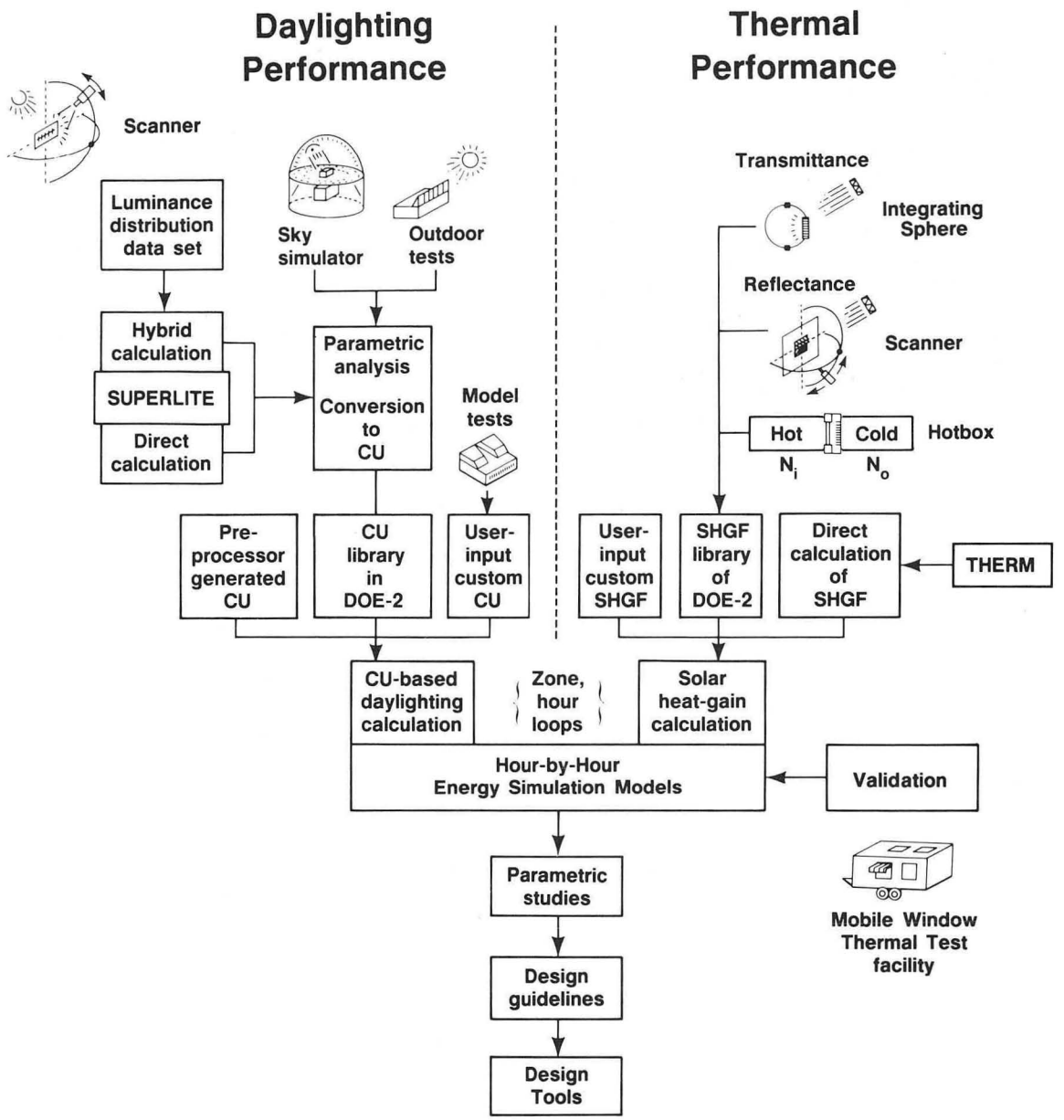


Figure 10. Schematic diagram of DOE-2.1 fenestration modeling capabilities under development. The new solar heat-gain model is shown on the right, the new illuminance model on the left.

(XBL 8212-4972A)

measurements of the fenestration system's optical properties. Transmittance will be measured using a large integrating sphere with the window system mounted in a port and illuminated either with an electric light source or solar radiation.

In 1984 construction was completed on this 2-m-diameter sphere (Fig. 11). Preliminary results were obtained for shading devices, and comparisons with data from other sources were made. Sample results for several window-blind systems are shown in Fig. 12. For each sun position, total reflectance will be calculated by integrating measurements of bidirectional reflectance obtained from a radiance/luminance scanner. The design of this apparatus was completed in FY 1984, and major functional elements were assembled (Fig. 13) and tested.

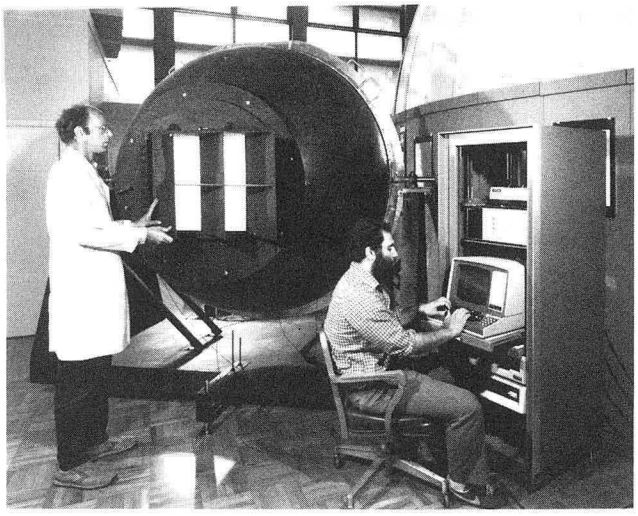


Figure 11. The integrating sphere for measuring hemispherical transmittance of glazing materials and fenestration systems. (CBB 837-6399)

Planned Activities for FY 1985

The major effort will be to complete initial development and testing of the radiance/luminance scanner to the point where we can begin to collect performance data. The integrating sphere and the scanner will then be used to determine the optical properties of shading systems. We will also complete initial development of the analysis procedures for determining the angle-dependent solar optical properties of multilayer fenestration systems based on the measured optical properties of each layer.

FENESTRATION LABORATORY

In 1977 we established the Fenestration Laboratory in the College of Environmental Design at the University of California, Berkeley, to support our research and development activities and to provide independent testing and evaluation of fenestration materials and devices. This facility enables us to evaluate both experimental prototypes and new devices being introduced to the market. In addition to the new integrating sphere and scanning radiometer described above, testing facilities include a calibrated hotbox for measuring window conductance and an air-leakage tester for measuring air flow across a window for a range of positive and negative pressure differentials. We have also developed capabilities for measuring the optical properties of glazing materials and coatings to fully characterize their performance. In FY 1984 the Fenestration Laboratory prepared sensors and instrumentation for the Mobile Window Thermal Test Facility and calibrated its heat-flow sensors, both described later in this article.

DAYLIGHTING ANALYSIS

To predict the energy consequences of daylighting strategies, one must be able to predict the day-

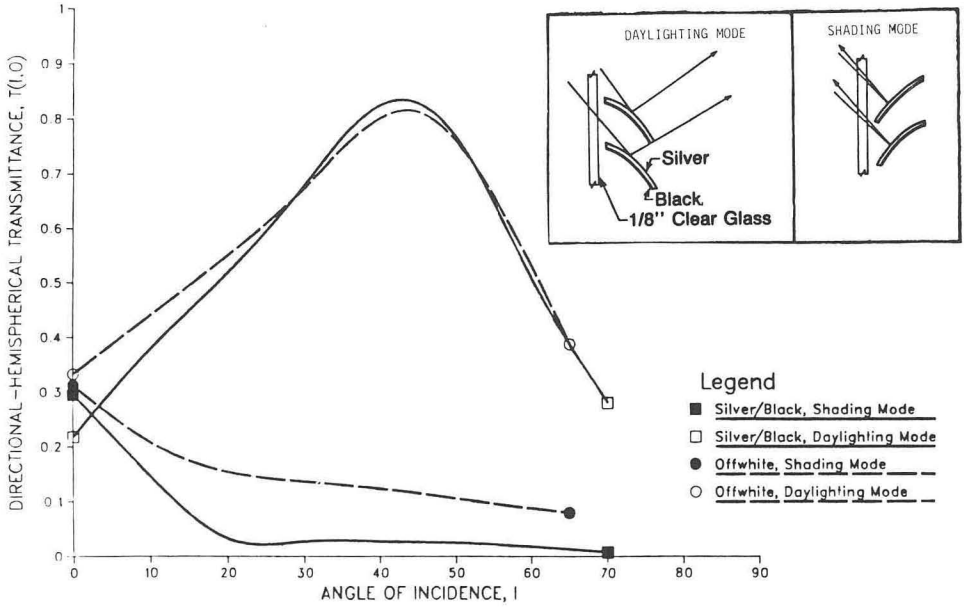


Figure 12. Measured transmittance of two venetian blinds with different surface treatments as a function of position and angle of incident light. (XBL 848-3341)

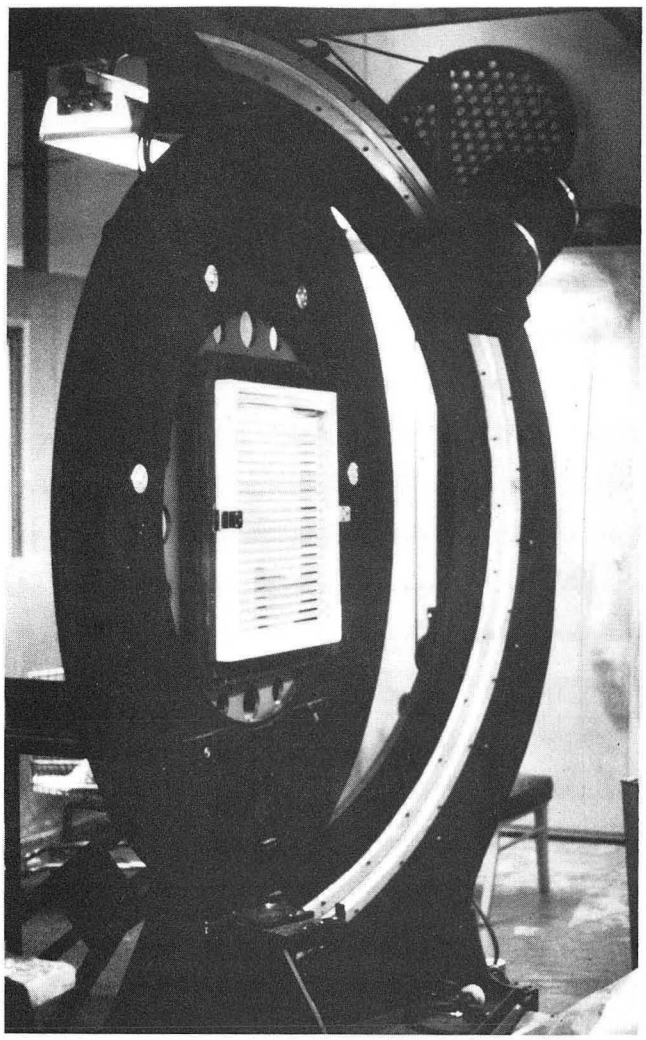


Figure 13. Scanning radiometer under construction. (XBB 852-5442)

light illuminance distribution pattern in a building from any window or skylight under all sun and sky conditions. Since no single approach provides the best solution, we use a variety of techniques to assess various aspects of daylighting performance.

The types and capabilities of the analysis and design tools required to evaluate the daylight performance of a building differ, depending on (1) the complexities of room and window geometries, (2) daylight utilization strategies in conjunction with electric lighting and building HVAC systems, and (3) the level of analytical accuracy required at a specific stage of design.

In previous years we developed several simplified daylighting design tools (e.g., the QUICKLITE program) that are now widely used in the architectural and lighting design communities. Last year we further developed our more advanced computational models (e.g., the SUPERLITE program) to expand the range of modeling capabilities and to improve computational accuracy. We also extended our analysis of daylight availability measurements and the photometric measurement capabilities of our Daylighting Laboratory.

Accomplishments During FY 1984

We continued to test and evaluate the SUPERLITE program, concentrating on the ability to model complex shading systems. Our approach is to define the daylight transmittance properties of the window and shading system as a candlepower distribution function that varies with the incidence angle of sunlight. Since we had only a limited data base of measured candlepower distributions, we used theoretical distributions that could be compared to results generated by other computational techniques. This comparison showed good agreement.

We tested a version of SUPERLITE with an electric lighting modeling capability and compared results with those from other computational models. The agreement was generally good. This new capability will allow us to study the combined effects of daylight and electric light in a room.

We developed an input processor that enables users to create an input file interactively by answering questions that appear on their terminal screens. This will be linked to a library of input room designs and a data base of photometric results. We also continued work on a user's manual for SUPERLITE that should facilitate its use by a wider audience.

Planned Activities for FY 1985

We will continue testing and validation of SUPERLITE's modeling of shading devices, using candlepower data sets measured by the luminance scanner.

We will release the SUPERLITE 1.0 program to users after completing the users' manual and continue further testing and modification of the program's capacity to analyze electric lighting systems.

We will then use SUPERLITE to produce the initial entries for a daylighting performance data base for various building and fenestration designs. The input and output processors will be extended so that parametric simulations can be routinely completed and results automatically entered into our performance data base.

COEFFICIENT-OF-UTILIZATION MODEL

Building energy analysis computer models must be able to properly predict the daylighting performance of complex design strategies commonly used by innovative architects. The models should either internally calculate the daylight illumination or be supplied with data precalculated by other illumination models or measured in scale models. The first approach, internal calculation of daylight illumination, is generally not practical 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) 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 1984

Our approach is to derive the CU model from regression analysis of a parametric series of daylighting analyses using SUPERLITE. We modified SUPERLITE to generate these parametric series and also modified the output to report the indoor illuminance level due to each external light source—the sun, sky, or ground.

We use a statistical computer software package to generate test regression equations for the sun, sky, and ground components with a limited number of generalized variables (e.g., location of window, window dimensions). Initial results suggest that good fits can be obtained with relatively simple regression expressions.

Planned Activities for FY 1985

We will expand the analytical effort to develop new CU models that can handle greater variation in room geometry and surface reflectance. After generating all equations, they will be thoroughly tested and validated. The final model will be documented as part of our efforts to formally publish results in FY 1986.

DAYLIGHTING MODELS FOR ENERGY SIMULATION PROGRAMS

As a result of collaborative efforts with the Building Energy Simulation (BES) Group over the past several years, we completed development and testing of an operational daylighting model in the DOE-2.1B program. This model enables us to determine the direct effects of daylighting on lighting electrical consumption, associated thermal loads, peak electric demand, and HVAC-system size requirements. The model can simulate, on an hourly basis, the use of simple operable shading systems by altering a window's solar optical properties in response to occupant requirements for thermal and visual comfort. Its output reports not only indicate average hourly and monthly savings for each zone but also provide several types of statistical summaries and frequency plots that enable us to examine the details of annual energy performance.

Accomplishments During FY 1984

We continued to test and use the new features in DOE-2.1B and enhancements in DOE-2.1C for fenestration studies. The 2.1C version of the program has the capability to replace a constant value (e.g., light transmittance) with a function that can be dependent on many other factors. For example, the light transmittance could be a variable function of solar intensity and temperature. These user-generated "functional values" can be used to model complex designs with functions generated from scale model tests, or to assess the performance of new materials or designs with user-defined performance characteristics.

Planned Activities for FY 1985

Work will continue on the daylighting model for DOE-2.1D in conjunction with the BES group; it will be able to simulate more complicated sun-shading devices and more sophisticated daylighting solutions such as light shelves. These improvements will be based on the new coefficient-of-utilization model derived from SUPERLITE calculations or model tests. The new daylighting model should enable the program to simulate, without additional revisions, the performance of building designs of arbitrary complexity. A schematic of the planned procedure for calculating daylight illuminance and solar gain is shown in Fig. 10.

DAYLIGHT AVAILABILITY STUDIES

Accurate daylight availability models are necessary for many design and energy analysis simulations. In 1978 we began an availability measurement project to fill this need, as data were lacking for most U.S. locations. However, a generalized model of availability that is widely accepted has yet to be developed.

Accomplishments During FY 1984

We published three papers analyzing daylight availability data for San Francisco.[9–11] Analysis focused on the relationship of measured illuminance and irradiance to atmospheric parameters such as turbidity. A new functional relationship was developed to determine an illuminance turbidity for visible radiation analogous to the conventional turbidity terms used with solar radiation. We also developed new functional relationships for zenith luminance as a function of turbidity and found that our clear-sky luminance distribution data agree well with data from currently accepted European models. These results were published in the Technical Proceedings of the International Daylighting Conference.[12] (Sample results are shown in Fig. 14.)

To better coordinate research efforts on daylight availability, we have worked with the Florida Solar Energy Center (FSEC) to host review meetings attended by experts representing all the major groups undertaking daylight measurements in the United States and Canada. Topics included defining daylight measurement requirements, analysis procedures, sensor selection and calibration, and a standard format for presentation of data throughout the United States and Canada. We also initiated a three-way collaboration between LBL, FSEC, and Pacific Northwest Laboratories (PNL) to characterize luminance distributions under partly cloudy skies. For this study we will shift our availability measurement station from San Francisco to Berkeley and add new measurement techniques and instrumentation, including a scanning sky luminance mapper developed by PNL. Analysis of the data will be jointly undertaken by PNL, FSEC, and LBL.

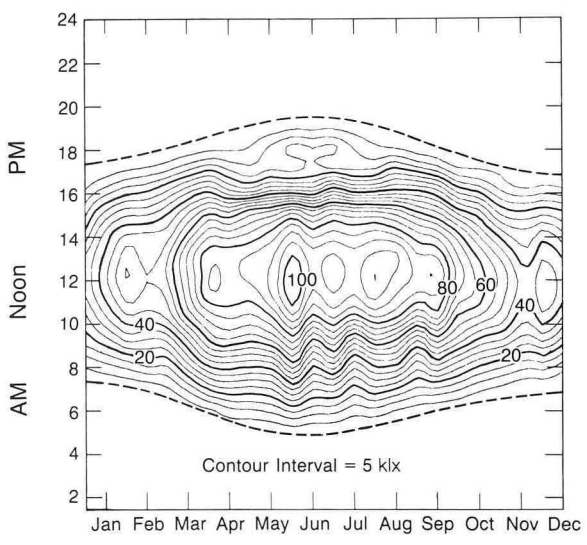


Figure 14. Isolux contours of global horizontal illuminance, based on four years of data measured in San Francisco. (XBL 845-10362)

Planned Activities in FY 1985

We will continue analysis of our existing data base and complete a study of the luminous efficacy of daylight and sunlight. The sky luminance scanner will be installed and become operational. Our new measurement capabilities should enable us to better understand topics requiring detailed measurements and to develop data for more standardized daylight availability models for designers in U.S. climates. The practical importance of errors in availability models on energy predictions is not well understood. An effort will be continued in FY 1985 to quantify these errors.

DAYLIGHT PHOTOMETRIC LABORATORY

The Sky Simulator

A 24-ft-diameter hemispherical sky simulator (Fig. 15) 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

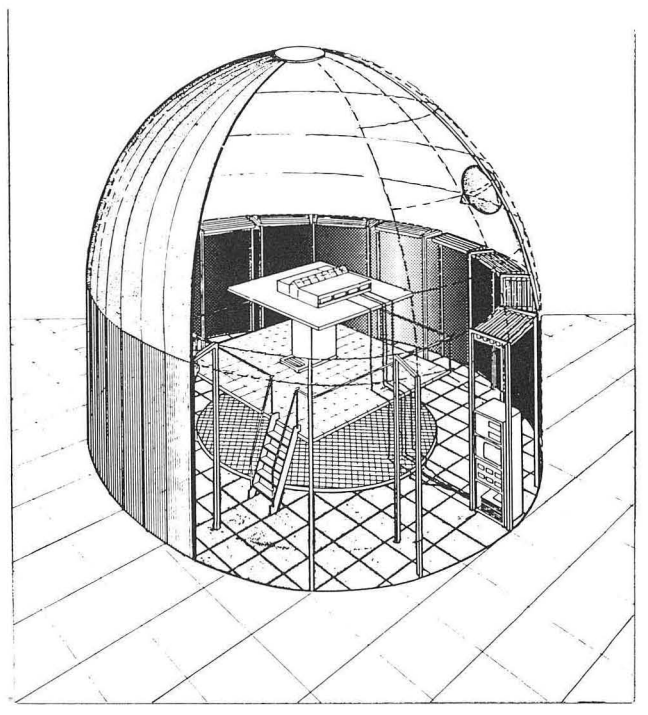


Figure 15. Schematic of 24-ft^2 diameter sky simulator with model on platform. (XBL 8412-5328)

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 studies, for educational purposes, and on a limited basis by architects working on innovative daylighting designs.

Accomplishments During FY 1984

The sky-and-sun simulator were used to collect scale-model data on the daylighting performance of fenestration systems. In one study these data were compared with computer-model predictions for the identical room and fenestration designs. We also used the facility to study the daylighting performance of atria. These large glazed spaces are increasingly popular in office and retail buildings, but little information is available on their daylighting performance. A photograph of our reconfigurable atrium scale model is shown in Fig. 16. Our initial studies suggest that many common assumptions about the usable daylight in deep atria are overly optimistic and may lead to disappointing results.

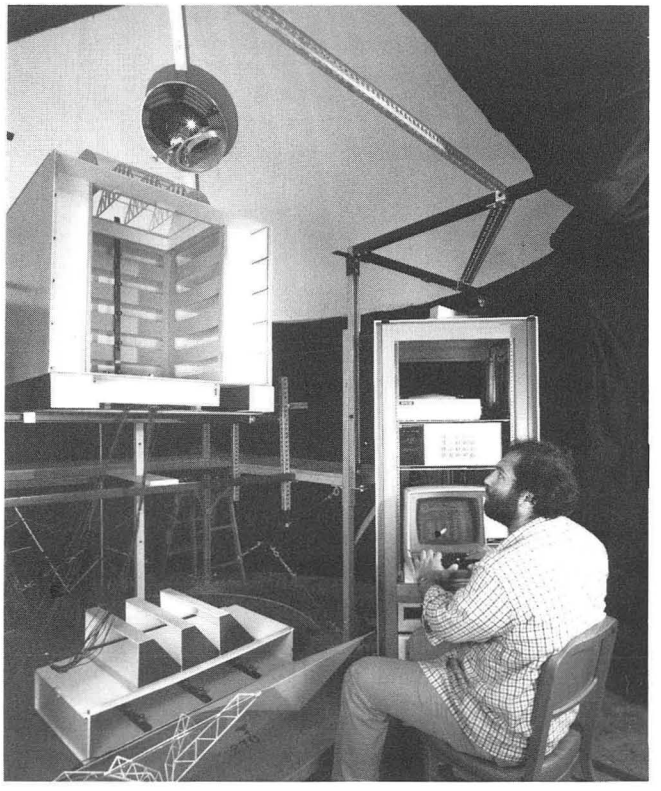


Figure 16. Interior of sky simulator showing reconfigurable scale model of a five-story atrium (with one side removed). (CBB 848-5926)

Planned Activities for FY 1985

As part of our continuous upgrading of this facility, the sun simulator will be modified to provide a beam of more uniform cross section. The entire facility will be relamped and recalibrated so that the full dynamic range of possible sky luminance distributions can be precisely defined, in conjunction with the automated control-system software. We will also upgrade the illumination control system to provide more accurate luminance distributions. New amplifiers will be fabricated and installed to increase the precision of our photosensors in the upper light-level range and extend the lower range to measure illuminance as low as 0.1 lux. These efforts should significantly extend the efficiency and performance of the facility as a research and design tool.

Outdoor Scale-Model Testing

In 1983 a 3000-ft^2 deck was constructed on the roof of Building 90 at LBL for model testing under outdoor sky conditions. We designed and built four platforms on this deck for scale models. The platforms can be oriented in different directions for simultaneous scale-model studies of the same design. We also installed a computerized data-acquisition system with 60 photometric sensors and appropriate data-collection software.

These facilities will be used to collect test data in parallel with our indoor model studies. Differences between the two sets of studies will help us understand how closely results from the standardized sky distributions in the simulator will predict results under real sky conditions. In FY 1984 there was little activity with the outdoor test facility, but in FY 1985 outdoor model tests will be carried out in conjunction with sky luminance measurements. The intent is to better understand the illuminance variability in interior spaces as a function of sky luminance distribution and the time-dependent variability under partly cloudy conditions.

Hemispherical and Bidirectional Visible Transmittance Testing

Accomplishments During FY 1984

The integrating sphere described in a preceding section (see Fig. 11) can also measure hemispherical visible transmittance of materials, devices, and building facades with an appropriate photometric

sensor. Initial photometric measurements on a number of shading devices were made in conjunction with the thermal analysis testing described earlier. The sphere was also used to characterize the transmittance of 14 roof-glazing systems for atrium spaces.

The design and construction of the basic mechanical system of the luminance/radiance scanner was completed. The system will accept a 2 ft × 2 ft sample and scan at a maximum radius of about 6 ft. The system is driven by a series of stepper motors that at present are manually controlled.

Planned Activities for FY 1985

We expect to extend the calibration for the integrating sphere to include reflectance measurements and an improved assessment of measurement error. An improved collimated light source will also be designed and built.

Further research on the luminance scanner will center on development of the automated control system that will govern all aspects of the scanner operation and data acquisition. By the end of the year we expect to have the hardware installed and sufficient software operational so that limited data can be collected and analyzed.

DESIGN TOOLS

There is a continuing need to introduce improved daylighting design tools to potential users. In previous years the technical development of specific tools was undertaken by LBL staff and subcontractors. In FY 1984 increased emphasis was placed on documenting specific tools and distributing them to building industry professionals.

Accomplishments During FY 1984

New design tools for daylighting are beginning to be marketed by private-sector software firms, but it is difficult for a potential user to evaluate them. There is thus a need for photometric data and evaluation procedures to compare these tools. Initial steps were taken to develop the general procedure for comparisons and to establish a photometric data base derived from sky simulator measurements and SUPERLITE simulations.

To develop additional avenues of transferring daylighting research results to professionals, we contracted with Donald Prowler at the University of Pennsylvania to help initiate a daylighting research network of universities.

The plan for this network was reviewed by a group of practitioners and educators and was formalized as the Daylighting Network of North America (DNNA). An application process was initiated for two levels of network membership, Instructional Centers and Regional Centers. Regional Centers are intended to become nodes of daylighting research and dissemination activity for faculty and practitioner alike. The centers will make a concerted effort to plan and implement professional, educational, and design assistance programs.

The technical development of several daylighting design tools was completed during FY 1983. In FY 1984 the following design tools received additional testing, graphic development, packaging, and dissemination:

- *Clear Sky Protractors.* Developed with Harvey Bryan at the Massachusetts Institute of Technology (MIT), the protractors consist of a series of transparent overlays that are placed over architectural plans and elevations to determine a window's daylight contribution at any point in a room.
- *MICROLITE 1.0.* This microcomputer-based program, a successor to QUICKLITE 1.0, can be used for daylighting analysis. A user-friendly version with color graphics for a microcomputer and a preliminary user's guide were completed by Harvey Bryan at MIT. The Designer's Software Exchange is distributing this package to educators and professionals.
- *SUPERLITE 1.0.* An extensive effort was launched to develop a graphically enhanced user's manual for this state-of-the-art mainframe computer model. Two draft versions of the manual were completed and reviewed. Final professional market evaluation is planned.
- *Daylighting Nomographs.* The completed manual and set of nomographs to estimate potential energy and peak-load savings in commercial buildings received additional professional distribution during FY 1984. More than 250 copies were selectively disseminated at engineering and architectural conferences and design tool workshops.
- *Advanced Envelope Design Tool.* As private firms have begun to develop and market simple microcomputer tools, we have turned our attention to the development of the next generation of more

sophisticated tools based on advances in both hardware and software. We envision a tool that relies heavily on (1) imaging technologies to capture, store, manipulate, and present simulated environments as they are conceived and developed throughout the design process; (2) expert-systems software and design process studies to support the iterative and complex nature of building design; and (3) an array of information outputs to better communicate information between design team members and between the design team and the client. In 1984 we initiated a series of exploratory studies to better understand the requirements for such a tool. We also developed a working prototype of one useful element of this system, a self-calibrating photographic luminance camera that is described in the last part of this article.

Planned Activities for FY 1985

Additional technology transfer activities and specific dissemination pathways for daylighting research will be developed. A major emphasis will be placed on the further organizational development of the Daylighting Network as a focus for implementing daylighting research and information dissemination at a regional university-center level.

Final evaluation and dissemination of the SUPERLITE 1.0 User's Manual and program tape will be conducted during FY 1985.

Exploratory development of the Advanced Envelope Design Tool and several of its constituent elements will continue. The luminance camera will be tested and evaluated in a range of daylighted environments.

FENESTRATION PERFORMANCE IN BUILDINGS

Thermal and radiant energy flows through windows and skylights, unlike the flow through most other building-envelope components, can be managed so that these architectural elements provide net energy benefits to the building. Although heat loss and solar-gain-induced cooling loads must be minimized, solar gains in winter and useful daylight throughout the year reduce conventional energy requirements. Optimizing fenestration systems thus involves complex tradeoffs between competing requirements. Furthermore, since net energy use is a function of the interaction of the time-varying heat transfer through fenestration with the thermal and operational properties of the building, fenestration performance must be analyzed in the context of overall building performance if accurate conclusions are to be drawn. The optimum solutions do not depend on fenestration properties alone but may also be a sensitive function of climate, building type, orientation, and operating parameters. We examine fenestration performance in buildings from three complementary perspectives.

First, our *computer simulation studies* are designed to provide a better understanding of all aspects of optimizing fenestration design for energy performance and will lead to guidelines and analysis tools to assist the fenestration industry and the building design community. Our work originally focused on thermal performance in residential buildings but has shifted during the past 6 years to an emphasis on nonresidential buildings, including daylighting, peak-load management, and HVAC sizing issues.

As our second approach we have designed and built a heavily instrumented *Mobile Window Thermal Test (MoWiTT) Facility* to accurately measure the time-dependent HVAC load induced by fenestration under outdoor climate conditions. This facility tests the interaction of all climate parameters with a fenestration system installed in a room-like chamber, while eliminating or reducing many of the uncontrolled parameters one finds in complete buildings.

Some important performance issues, nevertheless, can be understood only by examining them in occupied buildings, so our third approach is direct measurement of fenestration performance as part of a *building monitoring program.* These three approaches, taken together, allow us to understand in detail the critical parameters that influence net fenestration performance in buildings.

SIMULATION STUDIES: NONRESIDENTIAL BUILDINGS

Most building simulation studies have focused on minimizing total energy consumption. Commercial and industrial customers, however, are generally billed for electricity on the basis of both energy consumption and peak electrical demand. A complete study of the cost effectiveness of fenestration systems, particularly daylighting strategies, must include their impact on peak electrical loads as well as on energy savings. Although the energy impact of daylighting has been under study by our group and others, there have been no prior detailed investigations of the impact of daylighting on peak loads.

Accomplishments During FY 1984

Over the past 2 years the energy performance of a five-zone prototypical office building has been simulated with DOE-2.1B for a wide range of glazing properties, window sizes, lighting loads, orientations, and climates. Both skylights and vertical fenestration were included. Initially we examined the impact of fenestration properties, including the effects of daylighting strategies, on office building energy performance and peak electrical demand. Lighting energy savings due to 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 the primary fenestration properties (U-value, shading coefficient, visible transmittance) as well as glazing area, orientation, climate, and operating strategy.

We conclude that, in almost all instances, it is possible to find a fenestration design strategy that outperforms a solid insulating wall or roof and that daylighting is almost always an essential component of the potential energy savings. If the installed electric lighting power density is high, the energy savings potential is large. However, if the electric lighting system is efficient and has low lighting power density, daylighting benefits will be smaller and may be negated by cooling loads from solar gain. We conclude that the net benefits of fenestration are highly dependent on the tradeoffs between daylighting savings and cooling loads resulting from solar gains. Visible transmittance properties, improved shading design, and window management will thus assume increasing importance for maximizing energy benefits from daylight.

A significant element of our studies has been a first attempt to quantify the impact of window-management strategies for controlling thermal comfort and glare from windows. Our studies in 1984 helped to identify three major technical factors that influence the daylighting/cooling balance. These are (1) the distribution of daylight in an interior space, relative to the lighting control sensor; (2) the luminous efficacy of transmitted daylight; and (3) the time-dependent variability in sunlight intensity based on climate conditions as well as hourly and seasonal patterns. Sample results from our simulation studies are shown in Figs. 17 and 18.

We continued our general studies on the peak-shaving potential of daylighting and completed a specific new analysis for West Coast climates as part of a study sponsored by Southern California Edison and Pacific Gas and Electric. Results show that—despite solar gains—daylighting can significantly

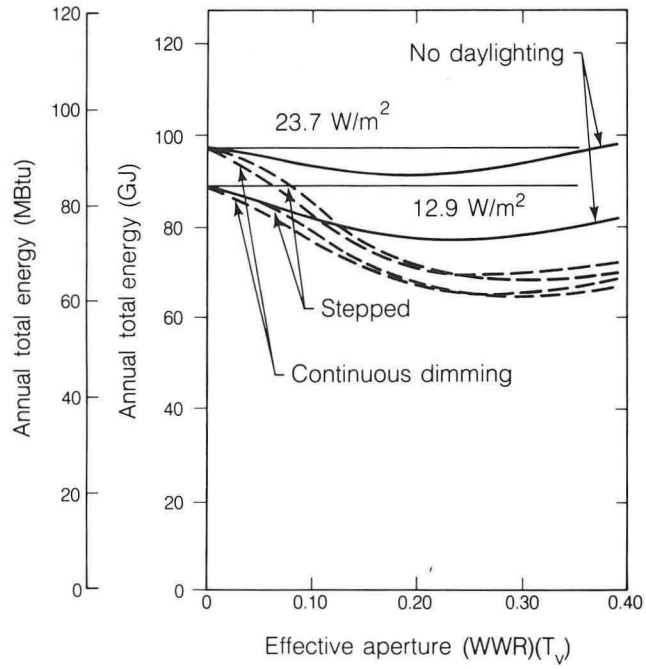


Figure 17. Energy consumption on the south zone of an office building in Madison, Wisconsin. The variation in annual energy use with window area and transmittance at two lighting power densities is shown for (1) an opaque exterior wall (thin horizontal lines), (2) a nondaylighted case, and (3) a daylighted case with two types of lighting controls. (XBL 847-9811)

reduce peak electrical demand during summer months. Parametric studies indicate that peak demand is a nonlinear function of glazing properties and window size for the daylighting case, but the relationship is almost linear in the nondaylighting case. The critical tradeoffs—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. A breakdown of this load for a sample office building on the date of maximum demand is shown in Fig. 19 for both daylighted and nondaylighted cases. The economic implications of these results will depend on local utility rate structures. Figure 20 shows, as a function of installed lighting power density, conditions under which daylighted offices with small or large windows may produce higher or lower peak demand than a nondaylighted space.

Energy effects with skylights follow similar patterns, with some noticeable differences. Daylighting benefits are maximized with relatively small ratios of skylight to roof areas (0.01–0.04). Because skylights provide more uniform daylight distribution, the

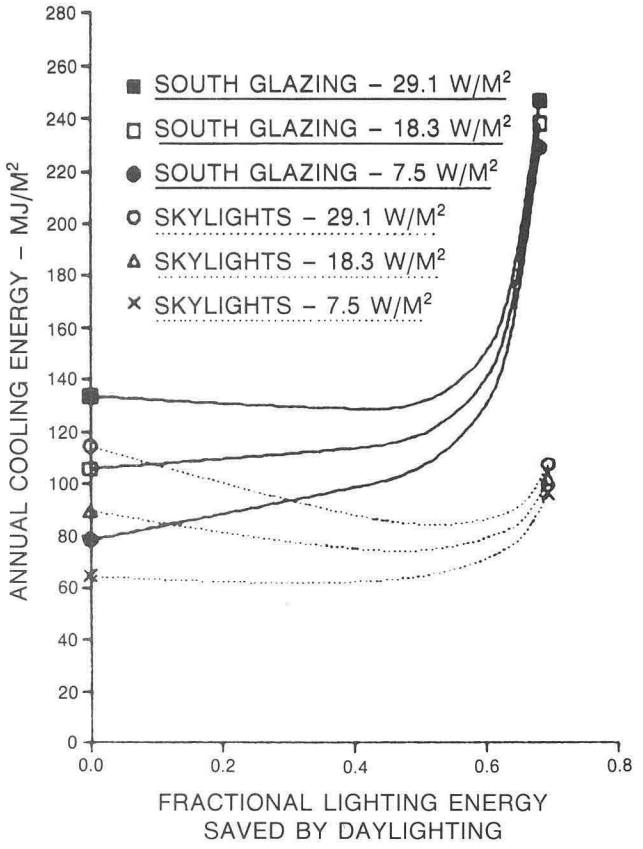


Figure 18. Cooling energy per unit floor area of daylighted space as a function of fractional electric lighting savings in Lake Charles, Louisiana. (XBL 856-2801)

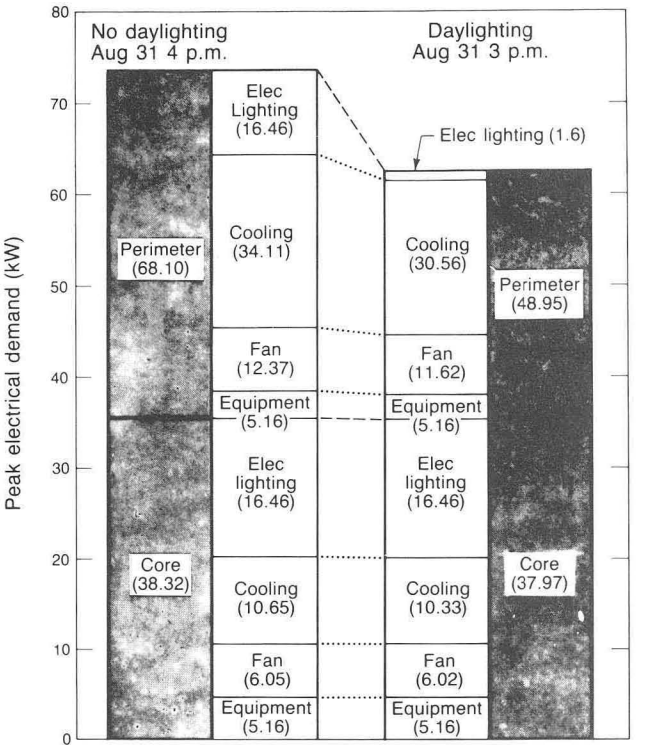


Figure 19. Peak electrical demand, broken down by end-use components, for an office building in Madison, Wisconsin. Nondaylighted (left) and daylighted cases are compared. Component breakdown is shown for the building's core (930 m^2) and perimeter (560 m^2) to reveal how daylighting can reduce peak demand in the outer zone. Numbers in parentheses indicate demand (W/m^2). Glazing area is 71% of floor-to-ceiling wall area; visible transmittance is 69%; lighting power density is 18.3 W/m^2. (XBL 8312-7444)

cooling load impact of daylighting is less than with vertical fenestration. As effective aperture is increased beyond the minimum energy value, cooling loads rise rapidly to adversely affect net annual energy performance. Sample results for several climates are shown in Fig. 21. In FY 1984 these studies were extended to a wider range of climates, and additional sensitivity studies on key performance factors were completed.

The large number of DOE-2.1B parametric runs for window and skylight studies provided a data base large enough for multiple regression techniques to develop analytical expressions of energy requirements as functions of glazing parameters. This approach offers the potential for developing a generalized expression to accommodate climate variables. These simple expressions correlate well with DOE-2 results and offer the prospect of a design tool for easily assessing energy and cost trade-offs among fenestration options. The regression equations developed in our skylight studies have been adapted by the American Institute of Architects Foundation for a workbook on skylight design.

Simulations of advanced glazing materials having passive and active response functions indicate a large potential for these materials. The modeled performance compares favorably with conventionally managed windows and skylights, and automatic operation of the advanced glazings should be more reliable. Analysis in FY 1984 continued to examine the response of advanced glazing materials and the interaction of active fenestration control systems with building lighting and HVAC controls.

The DOE-2.1C program has new functional keyword features that allowed us to investigate the performance of optical switching materials. The shading coefficient and/or visible transmittance can be varied as an inverse function of incident solar radiation, optical properties and setpoints can be altered, and the resulting effects of these still-hypothetical materials can be examined. Initial results suggest that simple control logic can provide performance

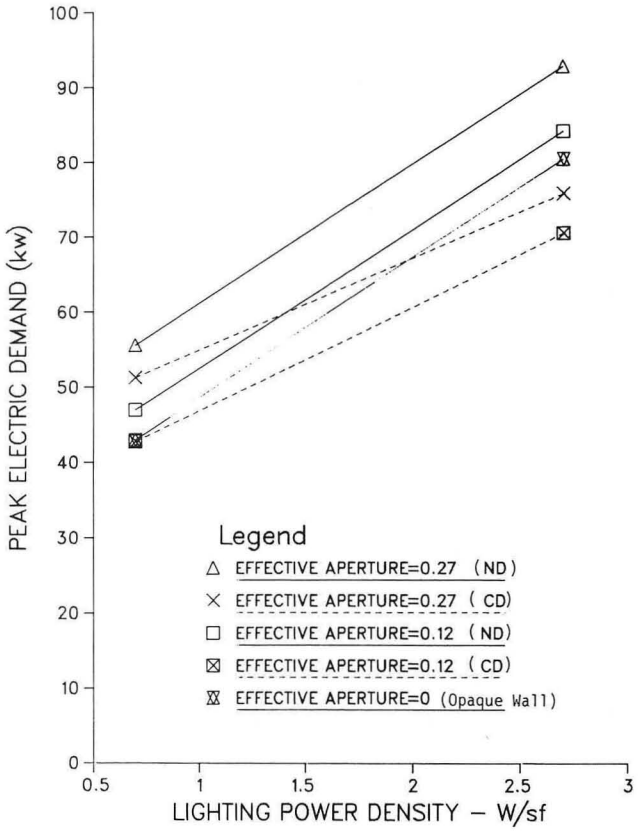


Figure 20. Peak electrical demand for an office module in Fresno as a function of installed electric lighting power density at two effective apertures in both daylighted (CD) and nondaylighted (ND) cases and an opaque wall.
(XBL 856-2815)

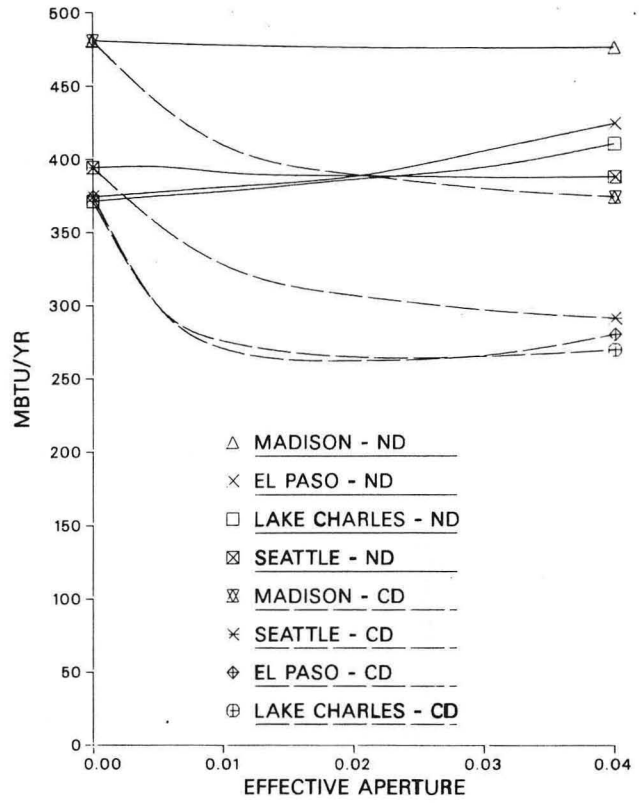


Figure 21. Energy consumption in a skylighted zone, showing variation in net annual consumption with effective aperture (skylight area and transmittance) for a nondaylighted (ND) and a continuously dimmed daylighted (CD) case in four climates. Installed lighting power density of 1.7 W/ft^2 provides 50 fc illumination.
(XBL 8411-4635)

equal to a conventionally operated window shade. We expect performance will improve with more sophisticated control logic. Electrically switched coatings could readily be made responsive to very sophisticated control algorithms to optimize energy, cooling loads, and costs. Since net cooling loads do not have an instantaneous relationship to transmitted solar gain due to time lags, "intelligent" anticipatory controls may prove to be beneficial. One control approach now being studied is to link the glazing transmittance to the daylight levels in the space so that excess light and solar gain are controlled. Sample simulation results are shown in Fig. 22. Ultimate control logic would integrate solar gain and daylight control with the operation of the building HVAC system. Simulations of this control mode will require additional modeling capabilities in DOE-2.

Planned Activities for FY 1985

Simulation studies to date have examined the energy impacts of many of the more important fenestration parameters within reasonable limits of design and have explored the potential of new optical materials. There are still important fenestration parameters to be studied, in particular shading devices for which adequate solar optical data do not exist. Optical properties of shading devices will be selectively measured in our laboratory and their annual performance simulated. We will also continue to look at variations in window-shade energy performance and 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 cost implications of

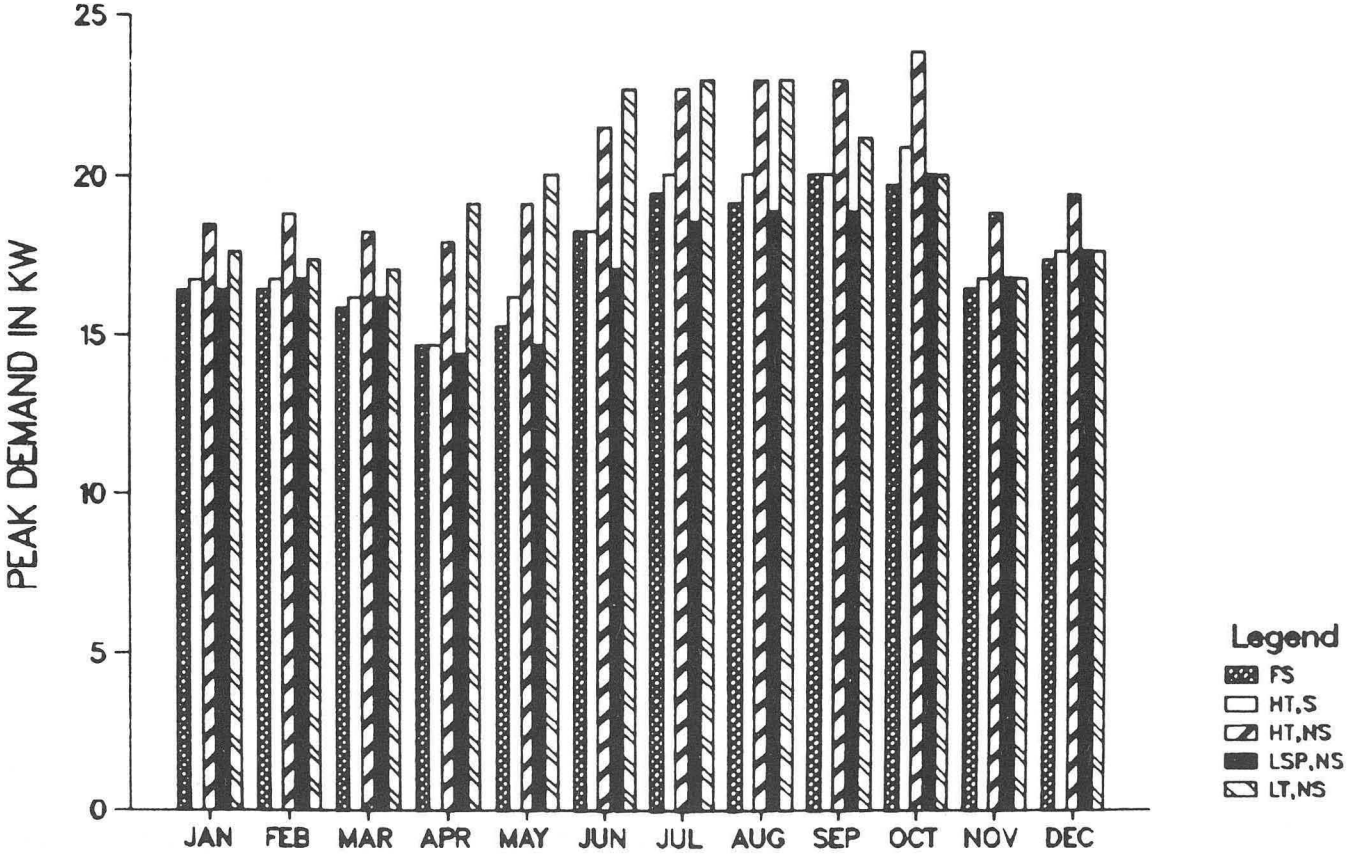


Figure 22. Monthly peak electric demand for an office building module in Madison, Wisconsin, comparing conventional glazings with two types of optical switching films. *FS*: electrochromic film with solar intensity control; *HT,S*: high-transmission glass with operable shading; *HT,NS*: high-transmittance glass without shading; *LSP,NS*: electrochromic film that maintains constant illuminance level; and *LT,NS*: low-transmission glass without shading. (XBL 856-2799)

fenestration design and daylighting as influenced by peak electrical demand, annual energy use, and chiller size will be examined.

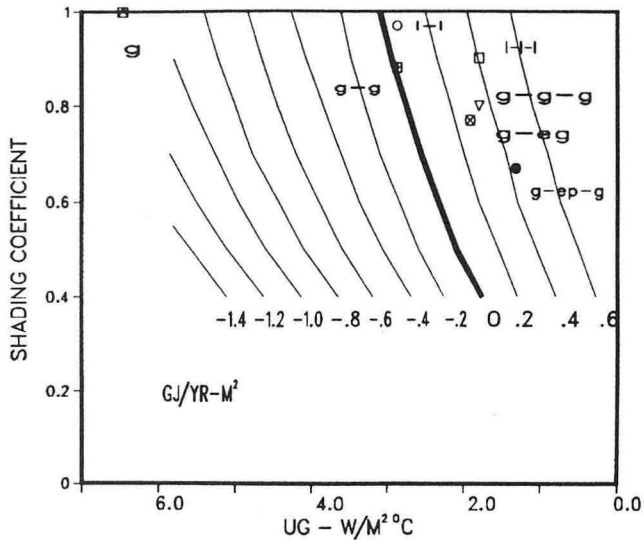
Collaboration will continue with the Building Energy Simulation Group to develop improved window modeling capabilities. In particular development of improved exterior shading algorithms will be explored in conjunction with new measured data on solar shading devices.

SIMULATION STUDIES: RESIDENTIAL BUILDINGS

In previous residential simulation studies we examined the impacts of movable insulating systems on fenestration performance and compared them with the performance of several multiglazed insulating window alternatives. In FY 1983 we began to examine in more detail the tradeoffs between heat conductance and solar transmittance. The study uses the regression analysis techniques developed in our studies of commercial buildings and is part of our contribution to the International Energy Agency cooperative study on fenestration performance.

Accomplishments During FY 1984

A full set of sensitivity analyses was completed to select the base case building design and its operational characteristics. Extensive sets of simulations were completed for two climate extremes: Madison, Wisconsin and Lake Charles, Louisiana. Using previously developed regression analysis techniques, we derived a set of simplified predictive equations for energy and cost performance. These equations were solved to directly predict fenestration properties that minimize cost and/or energy use. For a given climate, orientation, and window size, we developed graphic plots that allow one to quickly evaluate seasonal energy performance between many alternative existing or speculative fenestration systems (Fig. 23).



Glazing	U (W/m²°C)	SC
g	6.46	1.0
g-g	2.87	0.88
g-g-g	1.8	0.8
g-eg	1.92	0.77
g-ep-g	1.32	0.67
l-l	2.87	0.97
l-l-l	1.80	0.9

g: 1/8 in. DS float glass
l: 1/8 in. low-iron sheet glass
e: low-emittance coating, $e = 0.15$
p: 4-mil polyester
All air gaps are 12.7 mm (1/2 in.)
U-value: standard ASHRAE winter conditions
SC: standard ASHRAE summer conditions

Figure 23. Net heating-season useful flux in Madison, Wisconsin, for a primary window area of 24.53 m² oriented due south. The performance of typical glazing systems is indicated in the table. (XBL 856-2800)

Planned Activities for FY 1985

One limitation of the simulation approach we have been developing is that a large set of simulations must be completed for each residential prototype in each climate. Initial studies conducted in FY 1984 suggest that it may be possible to extend results analytically between prototypes and climates. Efforts in FY 1985 will focus on developing the theoretical and analytical base for this approach and on testing its feasibility.

IN-SITU TESTING—FIELD VALIDATION

Net energy performance under actual conditions of use is the single piece of information most relevant to assessing the benefit to be derived from a window or window improvement. This is a dynamic property, essential for predicting the performance of managed window systems (windows having thermal and optical properties that can be manually or automatically changed by building occupants). Most laboratory testing facilities, however, are designed primarily to conduct steady-state measurements of static materials and devices. No experimental methodology exists for measuring the net performance of windows *in situ*.

In 1981 we began constructing a Mobile Window Thermal Test (MoWiTT) Facility to fill this experimental gap (Fig. 24); the facility will consist of one or more measurement modules and an instrumented van. The measurement modules—each containing twin calorimeters surrounded by an air guard—will enable dynamic studies to be made of combined solar, infiltrative, conductive/convective, and radiative heat transfer as a function of window type and orientation.

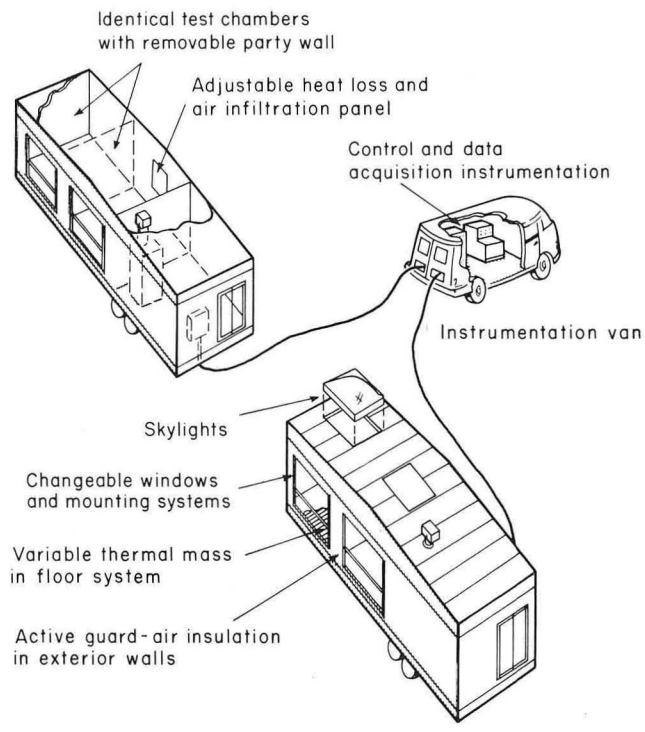


Figure 24. Schematic of Mobile Window Thermal Test (MoWiTT) Facility. One of the two double-module trailers has been built. (XBL 811-30)

An outgrowth of work on the MoWiTT facility was the development of a new heat-flow sensor. Instead of measuring the temperature difference with a deposited thermopile across a known thermal resistance (the usual method), this heat-flow sensor uses ac resistance thermometry. Such sensors can be made economically in sizes large enough to cover entire walls, and we have incorporated them into the MoWiTT facility.

In FY 1981 a successful 1-ft^2 prototype was built and tested, and larger units were built during FY 1982. In FY 1983 and FY 1984 these full-size units were calibrated with a large calibrated hotplate constructed at LBL for the purpose. Figure 25 shows the inside walls of a MoWiTT chamber completely covered with the sensors.

Accomplishments During FY 1984

The MoWiTT facility was readied for field deployment (Fig. 26). Basic construction was completed, and our efforts focused on calibration of all components and systems. Major accomplishments included the following:

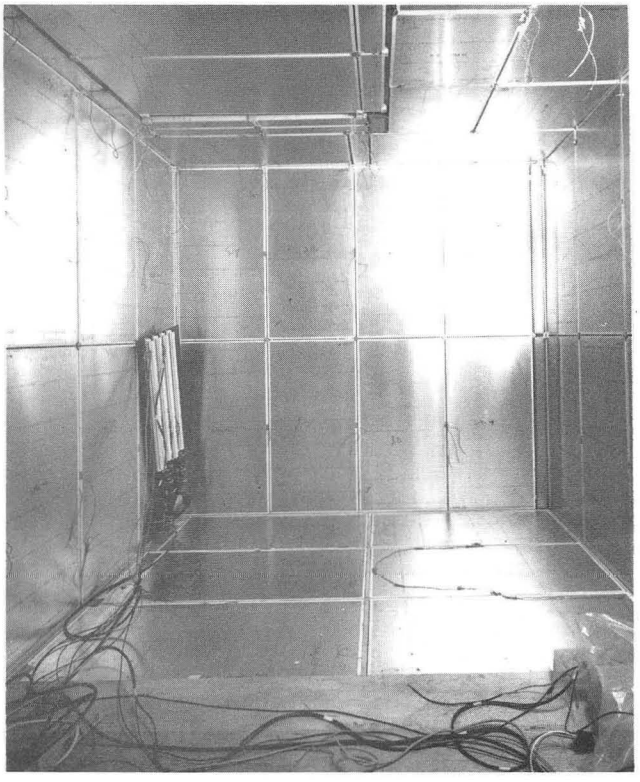


Figure 25. A MoWiTT calorimeter chamber completely instrumented with heat-flow sensors. Window will be mounted in far wall after calibration is complete. (CBB 838-7737)

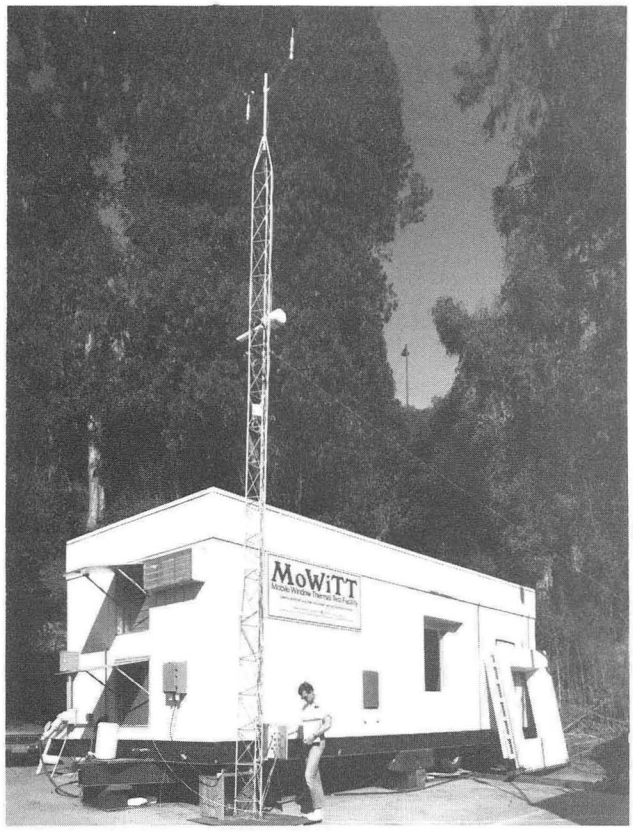


Figure 26. The MoWiTT Facility undergoing calibration and trial field test at LBL. Left chamber is fitted with a window; right chamber is undergoing a "sealed box" calibration test, after which it will be fitted with the frame system shown leaning against the wall. Left section of trailer contains chiller, fans, and pumps and the computerized data acquisition system that controls operation of the facility and records relevant data. (CBB 830-9555)

- Tests of guard temperature-system capacity completed
- Guard air-handling system reconfigured to reduce air infiltration
- Air infiltration tests of both calorimeter chambers completed
- Hotplate calibration of large-area heat-flow sensors for two chambers (83 m^2) completed
- Multiplexing and operation of wall-sized heat-flow sensor ensembles demonstrated

We meet twice each year with an industry advisory panel to review technical progress and discuss future plans.

Planned Activities for FY 1985

The accuracy of the calorimeters will be established by a series of redundant "closed-box" tests,

and measurements on simple fenestration systems will be made. A "shakedown" period of operation will be conducted at a nearby field site in Livermore. After evaluation of these tests field operation will begin.

MONITORED BUILDINGS

Buildings are rarely built as designed and even less frequently operated as planned. It is well known that occupants can significantly alter energy consumption patterns in buildings. Thus, for energy performance to be accurately quantified, it is essential to monitor fenestration performance in occupied buildings. Our monitoring studies will provide results of critical importance to designers, building owners, and utility companies. In 1984, with support from Pacific Gas and Electric Company, we began to develop plans to monitor an award-winning 500,000-ft^2 office building that incorporates a number of innovative daylighting and fenestration systems. The objective is not only to better understand how the fenestration systems perform but also to develop a building monitoring approach that collects better data, useful for quantifying fenestration performance, at lower cost than has been possible before. We expect to complete the monitoring plan and begin deploying instrumentation in FY 1985. We also hope to identify other buildings with innovative fenestration systems that might become part of this monitoring program.

FENESTRATION IMPACT STUDIES

OCCUPANT RESPONSE TO FENESTRATION AND LIGHTING CONTROL SYSTEMS

In FY 1982, to study office-worker responses to lighting and fenestration controls, we developed a survey methodology that includes a written questionnaire and related physical measurements. The questionnaire asks each office worker to rate his or her responses to lighting and related thermal and acoustical conditions. Also included are demographics characterizing each worker (sex, age) and the worker's workplace (floor level, location, and type of office).

In FY 1983 we tested this methodology in two office buildings, one retrofitted, the other designed to be "energy-efficient." Preliminary analyses indicate that the surveys identified issues of concern to office workers but that additional responses regarding work tasks and organization are needed to quantify causal effects between worker responses and related environmental conditions.

Accomplishments in FY 1984

We completed analysis of survey results to date and published our findings for the retrofitted office building. We further refined the survey methodology and conducted several walk-through surveys of buildings to better define key issues and select candidate buildings for future studies. A significant conclusion in our earlier surveys was the importance of quantifying the impact of daylight on the interior luminous environment. We therefore initiated a project to develop a luminance mapping capability for field studies of occupied buildings.

A survey and review of alternative imaging techniques was completed by Don Carner of Energy Conservation Associates, and a prototype photographic luminance camera was developed (Fig. 27). A 35-mm camera with a fisheye lens was modified to imprint an absolute optical density gradient scale on each exposure taken by the camera, so that an optical density map of the image can readily be converted into a luminance map, using an automated microdensitometer.

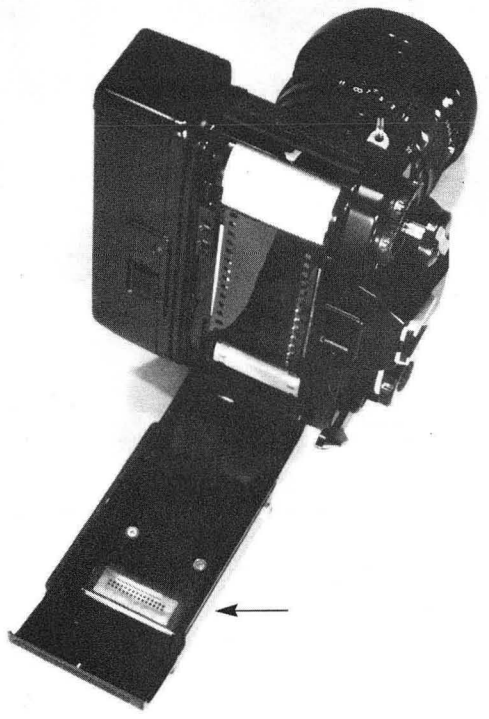


Figure 27. A prototype photographic luminance camera, with back opened to show panel for imprinting optical density scale (arrow). (CBB 857-5596)

Planned Activities in FY 1985

Calibration of the camera will be completed, and a prototype system for digitizing the negatives and manipulating the resulting data to create the luminance maps will be implemented.

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Lighting Systems Research*

S.M. Berman, R.R. Verderber, R.D. Clear, D.D. Hollister, D.J. Levy, O.C. Morse, F.M. Rubinstein, M.J. Siminovitch, and G.J. Ward

We estimate that approximately 50% of the electrical energy consumed by lighting, or about 12% 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 has divided its work into three major categories: engineering science, building applications, and impacts on human health and productivity.

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The engineering science component undertakes research and development projects in lamp technology that are both long range and high risk. These are projects in which the lighting industry has an interest but does not pursue on its own and from which significant benefits could accrue to both the public and industry if the technical barriers were surmounted.

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 as well as the interaction of lighting with building energy systems.

The impacts component examines relationships between workers and the physical lighting environment to ensure that energy-efficient technologies contribute to human productivity and health. These efforts are interdisciplinary, involving engineering, optometry, and medicine.

Since its inception in 1976, the LBL Lighting Program has produced more than 96 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, daylight availability, energy-efficient fixtures, lighting control systems, and visibility and human productivity. Its internationally recognized interdisciplinary staff spans the fields of engineering, physics, architecture, optometry, and medicine and 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 results are directed at 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.

Described below are highlights of the accomplishments realized in FY 1984 by each of our three major efforts—engineering science, building applications, and health impacts—and activities planned for FY 1985. Publications and conference presentations of the past year may be found in the Publications List at the end of this chapter.

ENGINEERING SCIENCE

The engineering science effort focuses on *advanced lamp technology* and light source development. To see what can be accomplished in this area, consider that today's fluorescent lamp has a luminous efficacy of approximately 80 lumens of light output per watt of electrical power input. Although this is nearly four times as efficient as an incandescent lamp, still greater efficacies are possible. White light can, theoretically, be produced at almost 450 lumens per watt. The advanced lamp technology program is working to supply the engineering science that will provide the basis for an efficacy of 200 lumens per watt within the next few years.

Two loss mechanisms should be improved to achieve more efficient fluorescent lamps. The first is a reduction in the self-absorption of the ultraviolet (UV) radiation that occurs within the lamp plasma before it strikes the phosphor-covered inner wall (the phosphor converts the UV radiation into visible light). The second is development of a more efficient phosphor matrix that will convert one energetic UV proton into two visible photons. Reductions in self-absorption could provide a 30% improvement, while a two-photon phosphor could double lamp efficacy.

LBL is studying two principal ways of reducing the UV self-absorption. The first method uses the naturally occurring isotopes of mercury. This element has seven stable isotopes that differ according to their resonance UV emission spectra. A small subgroup of isotopes will emit and absorb UV radiation with such a small spread in energy that a nearby subgroup of isotopes is not involved in its radiative transfer. Altering the natural isotope 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. One possibility for isotope alteration—enrichment with ^{196}Hg—is being pursued in a joint effort by LBL and GTE Lighting. Should isotope alterations prove economical, modified lamps would enter the market quickly, as lamps would simply be loaded with isotopically enriched rather than natural mercury, with other components remaining the same.

The other method of reducing UV self-absorption was recently discovered at LBL. It involves an applied magnetic field having a direction parallel to the main current. Axial magnetic field strengths of about 600 gauss can increase light emission by 12% to 15%. LBL and major firms in the lamp industry are studying practical ways to apply this technique.

The second principal loss mechanism that should be altered is the 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 the energetics are sufficient to permit the cascade conversion of a UV photon into two visible photons, this process must occur quickly, and the intermediate level in the cascade must be tuned carefully to ensure that both emitted photons are in the visible spectrum. LBL is studying phosphor chemistry to discover whether the two-photon phosphor is feasible. The lamp industry, long aware of the complexity of this problem and the extensive research effort required to provide solutions, is eagerly awaiting results.

If these research directions at LBL come to full 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, three times that of today's 60-cycle fluorescent.

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 the use of 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 would appeal to lighting designers. Table 1 summarizes these major targets of opportunity.

Accomplishments During FY 1984

Mercury Absorption Studies

Detailed studies have been carried out to determine exactly how much mercury is absorbed in the walls of quartz lamps. This information is essential to accurately describe what happens to lamp efficacy when isotopes are added and the resulting UV output is measured. The lamp shown in Fig. 1 consists of glass coils at each end to control the temperature

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	135	1990
Two-photon phosphor	initiatives	200	1992
Gigahertz/electrodeless		230	1994
HID Lamps			
Today with (high-freq. ballast)			
1000-W high-pressure sodium		130	1984
1000-W metal halide		90	1984
1000-W mercury vapor		55	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

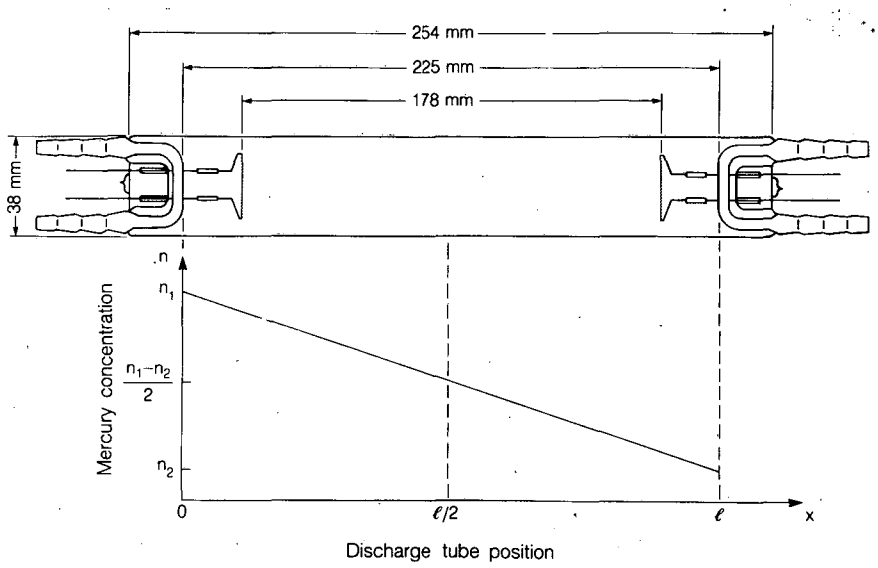

Figure 1. Schematic of mercury-vapor quartz lamp designed for studies of Hg depletion. The glass coils at each end control the temperature (Hg pressure) and permit the Hg to be pumped from one end to the other. Since the sweep time of the Hg increases as more of the Hg becomes absorbed in the glass walls, measuring the sweep time over several traverses gives a measure of the rate of depletion. (XBL 846-8979)

(and thus Hg pressure) and permit the mercury to be pumped from one end to the other. By measuring the time required for the mercury to make this sweep in repeated traverses, a measurement of the amount of Hg can be made, and its rate of depletion can be determined. Figure 2 shows the data for two types of glass lamps. The slope of the curve is a measure of the diffusion of the Hg into the glass walls. The technique will be used to study several types of glasses and phosphor-coated lamps.

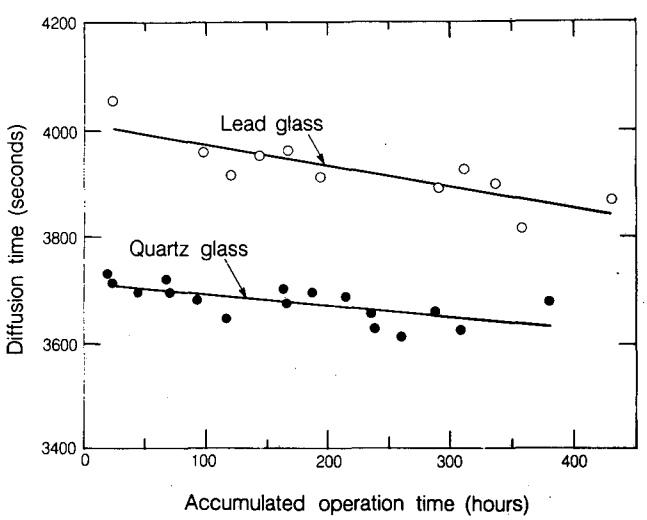

Figure 2. Experimental data on mercury diffusion for two types of glass lamp. The slope of the curves is a measure of Hg diffusion into the glass walls. (XBL 846-8980)

High-Frequency Fluorescent Lamp

Initial surface-wave lamp experiments (operating at gigahertz frequencies) were set up by designing and constructing a means to launch the waves and measure the input and output characteristics. The test set was developed so that the system could initially ignite the lamp and maintain the discharge. The comparative improvement in efficacy was measured for the commercial F-15 fluorescent lamp. Compared with 60-Hz operation, more than 20% improvement was obtained.

Electrodeless Lamp

The initial work in developing an electrodeless high-intensity discharge lamp was completed. A subcontract to General Electric resulted in the development of a test lamp and a means to drive it at megahertz frequencies. Electrodeless prototype lamps with standard gas mixes showed an improved efficacy from the elimination of the electrodes. Another important aspect of this lamp is the study it affords of halide gases (Cl and Br) of Al and Sn that cannot be used with filaments because they are corrosive.

Planned Activities for FY 1985

A lamp has been constructed and enriched with ^{201}Hg, increasing its concentration from 15% to amounts ranging from 30% to 60%. Measurements on the lamp will be made to confirm the Richardson-Berman theory, which predicts that a maximum increase in lamp efficacy will occur in this isotope concentration range. The result will have a significant bearing on the final method used to separate the Hg.

The theory for the surface-wave lamp has been developed, and an improved launcher will be designed, based on existing measurements. This work will be directed at obtaining an optimum lamp configuration. The magnetically enhanced lamp will also be measured with a large Helmholtz coil system so that the entire lamp can be immersed in the axial field to assure that any efficacy improvements are correctly assigned to the magnetic field configuration. Diagnostic techniques including the spectrograph, rf measurements, and laser systems will be put in place.

New programs include the development of plasma diagnostic techniques to study changes that occur in the plasma due to these isotope, magnetic-field, and surface-wave changes and their ultimate effect on the efficacy of transforming electrical energy into visible light.

BUILDING APPLICATIONS

This component of the Lighting Program considers ways to apply energy-efficient lighting to buildings. Specific applications must take into account building type, location, type of work, schedule, climate, and other real-life factors that affect lighting criteria. The program therefore considers computer simulations of possible energy-efficient lighting with concomitant control systems, the effects of high-frequency lighting systems on the general electromagnetic compatibility of buildings, and the interaction of lighting with a building's HVAC systems.

Accomplishments During FY 1984

CONTROLITE 1.0

The CONTROLITE 1.0 microcomputer program for determining the cost effectiveness of automatic lighting controls was validated and made user friendly. The program documentation was prepared and will be available on disc for use with an IBM Personal Computer. Good agreement was found between data taken from a scale model on the roof of an LBL building and the results of simulating the room performance with CONTROLITE. The program will be presented at a 2-day workshop in January 1985 at LBL.

The work in advanced efficient lighting design has progressed with the construction of a lamp/ballast thermal test chamber. This apparatus can study the performance of fluorescent lamp/ballast systems over a range of thermal environments from 10° to 80°C. Figure 3 shows the effect of minimum lamp-wall temperature on lamp/ballast system efficacies at lamp-wall temperatures between 20° and 70°C. This is an important design tool for achieving the specified lighting level in a lighting layout. With the introduction of many new lamps and ballasts, there has been considerable confusion about light output, resulting in light levels that are too low in newly designed spaces. This work is also part of our effort to determine the influence of thermal dissipation from lighting systems on the heating and cooling loads of buildings.

Applications to Naval Vessels

The DOE Lighting Program has a continuing effort in support of transferring energy-efficient lighting technologies into the marketplace. As part of this support, LBL coordinated the efforts of industry that developed a more efficient fluorescent-lamp ballast system for naval ships. Table 2 shows the improved performance to be realized. Compared with the existing system, a 23% improvement in system efficacy will be attained.

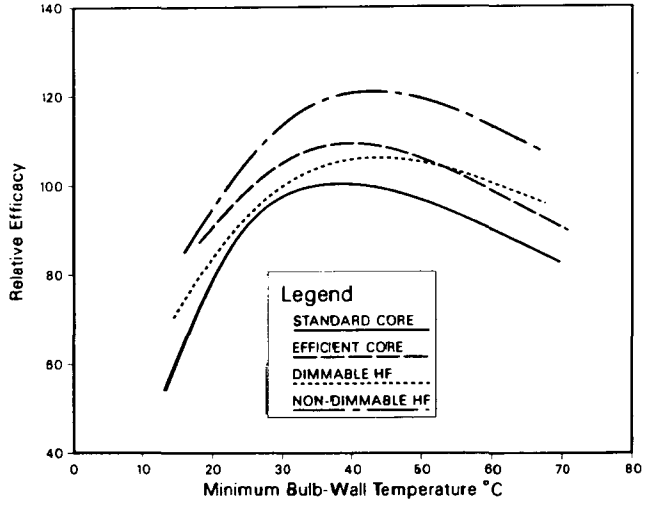

Figure 3. Effect of minimum bulb-wall temperature (in °C) on the relative efficacy of four lamp/ballast systems. (XBL 855-2538)

Table 2. Comparison of performance of lamp ballast systems.

Performance parameter	Standard ballast (F-20 lamp)	Advanced efficient ballast (F-17 lamp)	Relative change (%)
Input			
Voltage (V)	118	118	---
Current (A)	0.362	0.176	−51
Power (W)	25.4	19.0	−25
Power factor	0.60	0.92	+53
Output			
Light flux (lm)	1220	1120	−8
Third harmonic (%)	8	1	−88
System			
Ballast efficiency (%)	76	83	+9
Lamp efficacy (lm/W)	63	71	+13
System efficacy (lm/W)	48	59	+23

Electromagnetic Compatibility of High-Frequency Lighting

The successful development of high-frequency, solid-state ballasts provided the impetus for adopting high-frequency lighting and control systems in commercial and industrial buildings. Many benefits can be realized by operating at high frequencies: lower starting voltages, increased efficacy, ease of dimming, etc. The electronics industry is rapidly developing the less expensive high-power transistors and amorphous magnetic materials needed to ensure that high-frequency ballasts will be cost effective and thus enter the market rapidly.

High-frequency lighting, however, can produce electromagnetic energy, which could affect sensitive machinery, computers, and electronic systems. Because of the widespread use of these lighting systems, studies of their effects must include a variety of building operations. LBL leads the effort to obtain information needed for industry and government agencies. The major technical problem is establishing reliable near-field electromagnetic interference (EMI) measurements for lighting systems and relating them to what the Federal Communications Commission requires for far-field radio interference. Also, a methodology must be developed to determine near-field effects on electronic equipment and far-field effects when many EMI-generating systems are used.

Planned Activities for FY 1985

CONTROLITE 1.0

A 2-day workshop to introduce CONTROLITE 1.0 is scheduled for mid-January. We have invited approximately 50 professionals who are potential users. The workshop consists of invited speakers and the developers of the CONTROLITE program, who will provide hands-on instruction to participants; other programs will also be reviewed.

A thermal luminaire test chamber will be constructed to measure the thermal performance of several types of luminaires. Both the lamp/ballast and the luminaire test chamber will be used to characterize the complete thermal performance of lighting systems. The information will help to design energy-efficient lighting layouts and explore the thermal interaction between the lighting and HVAC systems of buildings.

Applications to Naval Vessels

The final solid-state ballast report on lifetime testing will be prepared. The Navy will continue developing a second-generation system that will further increase the efficacy of lighting on board ships and will develop the T-8 fluorescent-lamp ballast system. The improved power factor and reduced third harmonics of the new ballast system will result in a 51% reduction in line current. The new system will provide the same lighting but consume a smaller amount of a ship's limited electrical generating capacity.

Electromagnetic Compatibility of High-Frequency Lighting

The Federal Communications Commission and the National Electrical Manufacturers Association have recommended that LBL assist in collecting data on the EMI generated by high-frequency lighting systems. The development at LBL of a standard source and measuring method for determining near fields is essential to make convenient and reliable procedures available to industry. Computer models for stray EMI are being developed at LBL to further study the physical characteristics of external electromagnetic fields generated by high-frequency lighting.

IMPACTS OF NEW LIGHTING TECHNIQUES ON PRODUCTIVITY AND HEALTH

The idea that lighting might negatively affect health has appeared often in the lay press in the past

few years. Many factors have been implicated, but scientific data are lacking, especially to ascertain whether new energy-efficient technologies have adverse effects on human health and productivity.

Factors that may influence performance and productivity (as well as energy efficiency) may be associated with the lamp, the electronics and associated controls, the fixture, or the geometry and location of the lighting system. These lighting factors are: color variations; glare; intensity fluctuations; spectrum variations, including the ultraviolet region; electromagnetic fields generated by the lamp, ballast, or controls; and flicker, all of which 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 the new technologies can produce responses in humans. If they do, the effects will be characterized and the necessary changes in lighting technologies identified. 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 nonsubjective responses to establish cause and effect and ensure repeatability.

The impacts program is divided into three areas: (1) direct effects of lighting on the human autonomic system (carried out at UCSF), (2) analysis of the general relationship between lighting and visual performance, and (3) interactions between lighting and visual display terminal operation that affect productivity or comfort (carried out at the UC School of Optometry).

In the first phase of this program, lamps to be evaluated include incandescent, cool-white fluorescent, full-spectrum fluorescent, high-pressure sodium, and metal halide. Human responses to exposure to various lighting conditions will be assessed by monitoring autonomic responses. Parameters to be monitored include heart rate, respiration rate, galvanic skin response, muscle strength, exercise tolerance, facial expression, and pupillary response. Behavioral 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 probably will be implemented.

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; as described below, they indicate that subjective psychological factors are the likely cause of reported effects.

Accomplishments During FY 1984

UCSF Program

Study I. Ten subjects who stated that they were bothered by fluorescent lighting were studied, using the maximal-strength forward shoulder flexion test. Each subject received 50 trials. To counterbalance the effects of fatigue in such a regime, the trials were conducted as a randomized sequence of paired 400-footcandle exposures to an incandescent and a cool-white fluorescent light. Over all subjects the mean difference in maximal muscle strength for the two lighting conditions was less than 0.2% of the usual strength. The standard distribution was 13 times the mean difference. A paired-t test showed that our results were likely due to chance ($p = 0.85$). Similarly, there was no statistical difference in the responses under the two lighting conditions ($p = 0.39$). Power analysis showed that 90% of the time we would have detected a difference in muscle strength of 4%. Since the effects of suggestion on maximal muscle strength have been reported to be about 10%, the effects of the lighting, as tested, are likely to be obscured by psychological effects.

Study II. The results of Study I are not in agreement with the popular writings of John Ott,[1] who used "kinesiology testing" to support his claim that muscle weakness was caused by both cool-white fluorescent light and lack of electric-field shielding. Mr. Ott agreed to test the effect of shielding, double-blind, using his kinesiological evaluation of subjects' strength. On the unblinded tests the reported strength agreed with Mr. Ott's knowledge of grounding in 97% of the trials, but in the blinded condition the reported strengths agreed with grounding only 53% of the time (range 31–75%). The likelihood of obtaining such a difference by chance was less than one in 100,000. We conclude that blinding the kinesiology testing significantly alters the result, which in the unblinded case is susceptible to suggestion; any claims based on this methodology, unblinded, are suspect.

Study III. Experiments using infrared pupillometry to investigate visual reactions to high-pressure sodium and other HID lamps are under

way. An important observation was recorded in the consensual pupillary flash reflex of subjects exposed to three types of light—incandescent, fluorescent, and high-pressure sodium (HPS). The results have shown a larger pupil diameter from HPS exposure compared with the other lights for the same levels of illumination. This initial result implies that, for equivalent visual acuity, higher illumination levels will be required with HPS lamps.

Visual Performance Program

In 1981 the International Commission on Illumination (CIE) released its publication CIE 19/2, *An Analytic Model for Describing the Influence of Lighting Parameters upon Visual Performance.* A review by LBL in FY 1982 of the original data used in the development of CIE 19/2 found serious errors, and in FY 1984 a fuller critique of the CIE 19/2 model of performance was completed. Statistical arguments show that the fitting parameters are not physically determined as was previously believed, and the curve fitting in CIE 19/2 does not constitute validation. Nevertheless, careful use of the material in CIE 19/2 could lead to better recommended light levels than the consensus of present practices put forth by the RQQ #6 committee of the Illuminating Engineering Society.

Interactions between Lighting and Visual Display Terminals

Besides studying the direct effects of lamps on humans, LBL is examining how lamp characteristics—in particular compound flicker—can affect workers using visual display terminals (VDTs). Compound flicker occurs when two independent light sources flicker at different rates that combine to produce a "beat." For example, light from a VDT with a refresh rate that differs slightly from its nominal 60 Hz will combine with standard fluorescent lighting flickering at 120 Hz to form a low-frequency beat. Experiments are being performed to ascertain the effects of beats in general, and the beat between VDTs and ambient lighting in particular, on the visual system.

Present results show that beats formed by independently modulated fluorescent luminaires cause subjects to exhibit frequency-specific declines in temporal contrast sensitivity and entrained pupillary oscillations when the flicker rates of the luminaires are below the critical fusion frequency (CFF). No evidence of these effects is found when the flicker rates are above CFF or when a VDT is viewed under flickering ambient illumination. High-frequency operation of the ambient lighting would eliminate any possible human response to these beats.

Planned Activities for FY 1985

UCSF Program

The health impacts work will continue; plans will be made to convene an advisory group to describe the results comparing incandescent lamps with high-pressure sodium lamps. Work will continue to confirm the initial findings. One confounding variable could be the flicker modulation of the HPS illumination: the HPS has much deeper modulation than the incandescent or the fluorescent lamps. Experiments will be set up with the HPS lamps operated by high-frequency ballasts, thus eliminating any possibility of flicker. The outcome of these comparisons could be significant because the use of HPS is increasing, especially with new applications in the interior environment.

Visual Performance Program

The results of the CIE 19/2 study will be used to develop experimental measures that will produce additional data to improve the performance model. A program will be developed to evaluate the quality of illumination, determine methods, apply them to lighting design, and relate it to performance. Size effects on visibility will be included in the model.

UC Optometry Program

The video display work will continue attempts to relate effects of the beat frequency between the refresher rate of the screen and the ambient lighting. Further experiments are planned to explain the observations associated with the white and green screens and the different ambient lighting situations. The optometry laboratory will also corroborate the effect of HPS lighting which were initially observed at the UCSF School of Medicine.

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Buildings Energy Data*

J.P. Harris, A.K. Meier, J.F. Busch, P. LeConiac, C. Conner, J.H. Eto, D. Flora, B.L. Gardiner, C.A. Goldman, K. Greely, S.E. Greenberg, M.A. Meal, E. Mills, A. Mitchell, O. de la Moriniere, M. Piette, A.H. Rosenfeld, A. Usibelli, and L.W. Wall

The Buildings Energy Data Group (BED) compiles and analyzes measured energy performance data of buildings and equipment. The group's goal is to identify designs and technologies that save energy and are cost-effective. We provide these results to institutions and persons responsible for improving energy efficiency in the buildings sector. The core of BED's activities rests in the Buildings Energy-Use Compilation and Analysis (BECA) series of data bases. Each compilation addresses a sector of building end uses. The major compilations include:

- *New low-energy homes* (BECA-A)
- *Retrofits of existing residential buildings* (BECA-B)
- *New energy-efficient commercial buildings* (BECA-CN)
- *Retrofits of existing commercial buildings* (BECA-CR)
- *Residential water-heating systems* (BECA-D)
- *Validations of computer building-load models* (BECA-V).

Although each compilation is independent of the others, all rely on the same computerized data base management system (DATATRIEVE). Each can be queried so as to produce buildings similar in features, location, and function.

It is desirable to compare the energy use of similar buildings and equipment in order to identify energy-efficient technologies. For automobiles a dynamometer test yields a single parameter of fuel efficiency (miles per gallon). Unfortunately we cannot measure a building's energy use under comparably controlled conditions. Instead we must collect detailed information about the building, including its energy consumption, physical characteristics, and operating schedule. This information permits us to extract and standardize parameters of energy performance. The sophistication of the parameters depends on the type of building and on the amount of information available. Thus an important research goal of the BED Group is to develop standard parameters of building energy performance.

The group is also active in two areas that straddle the core compilation effort: primary data collection and studies of conservation potential. In special circumstances BED measures energy use in specific buildings or equipment. This usually occurs after we have identified significant gaps in the compilations. The compilations also provide a valuable data base from which to estimate the potential for conservation. Such studies of potential typically examine a series of conservation measures, calculate the costs of the conserved energy, and develop supply curves of conserved energy to express the aggregate potential for conservation.

THE BUILDINGS ENERGY-USE COMPILATIONS (BECA)

Accomplishments During FY 1984

New Low-Energy Homes

The compilation of new low-energy homes (BECA-A) now contains over 300 entries. Every major energy-efficient design is represented, including superinsulated, double-envelope, active and passive solar, earth-sheltered, and combinations of these. During FY 1984 we developed and applied a procedure to automatically standardize the energy consumption of these houses.[1] This procedure derives common parameters of thermal performance from measured energy consumption and outside temperatures after adjusting for variations in inside temperatures and internal gains—the two major occupant-controlled variables. These thermal parameters permit a more realistic comparison of buildings. Table 1 summarizes the results of the analysis of the buildings currently in the data base.

Earth-sheltered homes perform the best, having the lowest average k value (an indicator of overall heat loss and ability to exploit solar gains) and balance temperature. However, the sample of earth-sheltered homes is still small, and cost-effectiveness could not be verified. Passive solar and superinsulated homes perform nearly as well; they also are the most cost-effective. Figure 1 shows the furnace output of the houses presently in the data base compared to a base case. Nearly all of the low-energy homes have lower annual fuel consumption than homes built to current practice. Nevertheless, the

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Table 1. Summary of BECA-A results.[a]

Category and number of homes	k value[b] (W/°C)	Balance temp. (°C)	Cost of conserved energy: Elec. homes ($/GJ)	Cost of conserved energy: Gas homes ($/GJ)
All homes 319	114 ±68	12.2 ±4.5	7.81 ±7.7	5.01 ±2.58
Passive solar 197	104 ±55	11.0 ±4.9	5.63 ±8.1	4.20 ±2.7
Active solar 26	163 ±110	12.9 ±3.8	15.9 ±2.0	–
Earth-sheltered 9	91 ±32	7.6 ±1.7	–	–
Superinsulated 196	96 ±50	12.9 ±4.0	5.8 ±8.0	3.92 ±2.7

[a]Standard deviations are listed below values.

[b]All k values have been normalized to 100 m^2.

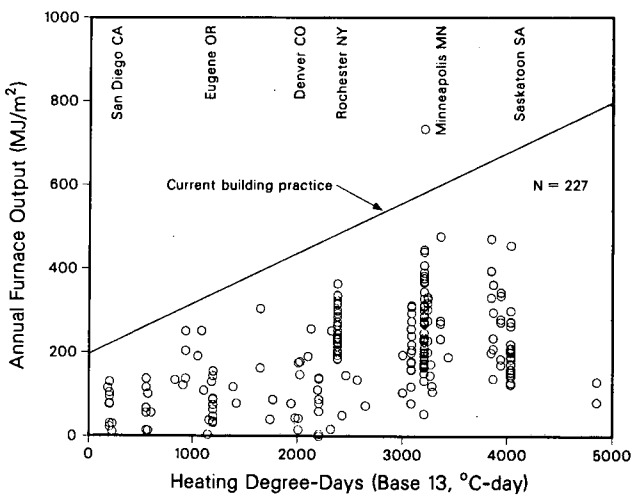

Figure 1. Thermal performance of 227 low-energy homes presently in the BECA-A compilation, compared with current building practice (straight line). Climatic severity is in degree-days with base 13°C, rather than 18.3°C, because 13°C coincides with the average measured balance temperature. Energy consumption is given in terms of furnace output to avoid confusion with furnace efficiency. Plotted energy consumption is based on measured consumption and adjusted to standard operating conditions. (XCG 848-13199)

variation is quite large, and homes in vastly different climates often have similar heating energy use, even after adjusting for floor area, thermostat settings, and internal gains.

Residential Retrofits

The compilation of measured energy savings from retrofits of residential buildings (BECA-B) now contains more than 115 entries, representing over 60,000 buildings.[2] Retrofit activities fall into four major categories: utility-sponsored conservation programs, low-income weatherization programs, research studies, and multifamily buildings. Sample size for each project varies widely, from individual buildings to 33,000 homes. Retrofits to the building shell of single-family homes (to reduce space heating) make up the greatest fraction of the compiled studies. As a result, much of the data compilation and analysis this year has focused on multifamily buildings and retrofits to heating systems.

Space heat energy savings from conservation measures are typically 20 to 30% of pre-retrofit consumption. Median savings range from 15 to 38 GJ/year in the four categories, although, again, the range is great. Figure 2 shows the range in savings among households in the same geographic location that installed similar conservation measures. Energy savings seem to be more variable with some measures than others. For example, savings were greater, and more uniform, in homes that installed retention head burners than in homes that kept conventional burners and installed other options, such as vent dampers, stack heat exchangers, or boiler controls.

Several retrofit strategies employed in multifamily buildings were very successful in reducing energy consumption. For example, space heat and hot water use declined by 44% in a New Jersey public housing complex after installation of a microcomputer-based boiler control system. Approximately 60% of the savings in eight multi-unit buildings in Chicago were attributed to heating system retrofits, including derating burners, installation of temperature-sensing burner controls, and balancing radiators and steam lines. Approximately 75% of the retrofit projects have costs of conserved energy below their respective space heating fuel or electricity price. The combination of shell and system retrofits appeared to be twice as cost-effective as shell measures alone.

New Energy-Efficient Commercial Buildings

The compilation of new energy-efficient commercial buildings (BECA-CN) now includes over 133 entries, 14 of which are from Europe, Canada, and

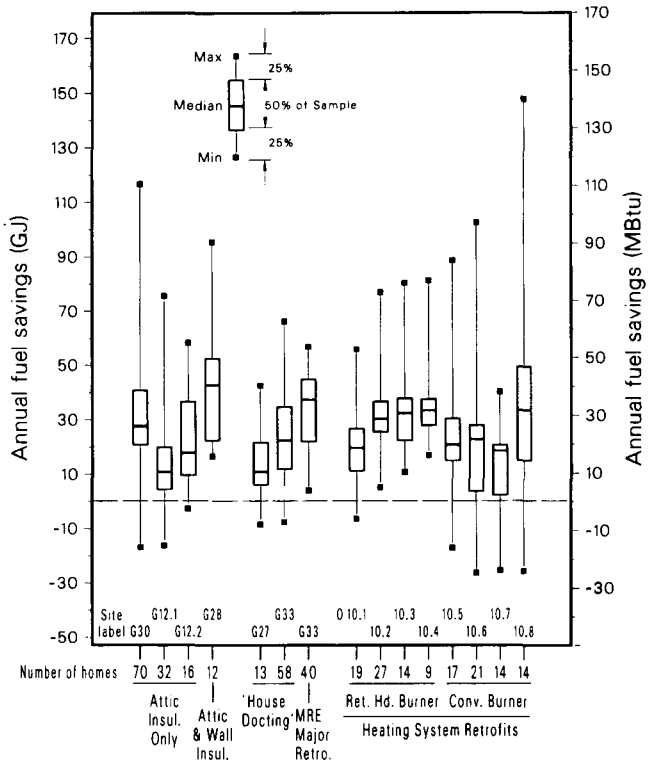

Figure 2. Range in annual fuel savings among households installing similar measures. The site label, number of homes in the project, and type of measure are listed below each distribution. In most cases, the savings apply to space heating only, except for the heating-system retrofits and the house-doctor experiments where consumption includes all end uses of the space heating fuel. For the middle 50% of the homes, the spread in savings is typically ± 70% of the median. (XCG 841-13003B)

Japan.[3] This data base actually includes all nonresidential building types; at present offices and schools predominate. Most of the buildings are publicly or government owned, which reflects the difficulty of obtaining energy and operating data from private building owners. Many of the buildings earned awards for their energy-conserving design (sometimes prior to a year of operation). Although buildings from all over the United States were collected, our efforts focused on energy-efficient buildings in California and the Pacific Northwest.

About three-quarters of the buildings in BECA-CN use between 30 and 70 kBtu/ft^2-yr (measured at the site), which is considerably less than similar existing buildings. Office buildings in the compilation use about half as much energy as current U.S. stock. In 34 cases we gathered data on predicted energy use prior to construction. Twenty-three of those buildings used more energy than predicted; however, the predicted consumptions were often based on less demanding conditions or ignored miscellaneous receptacle loads, exterior lighting, and computer facilities. Figure 3 shows the distribution of site energy use across the types of buildings presently in the compilation.

Careful investigation of buildings with higher loads than predicted revealed that some failed to fully install special energy-conserving features or had a change in operating characteristics that rendered some features unusable. For example, a nighttime cooling system could not be used as planned because building use was switched from a schedule of 10 hours per day to 24 hours per day. The nighttime occupants could not function with the high ventilation rates needed to flush the building. Many new buildings appear to have higher internal loads than planned. To date, very few commercial buildings have been submetered, so it is impossible to confirm that increased loads are responsible for the diminished building performance.

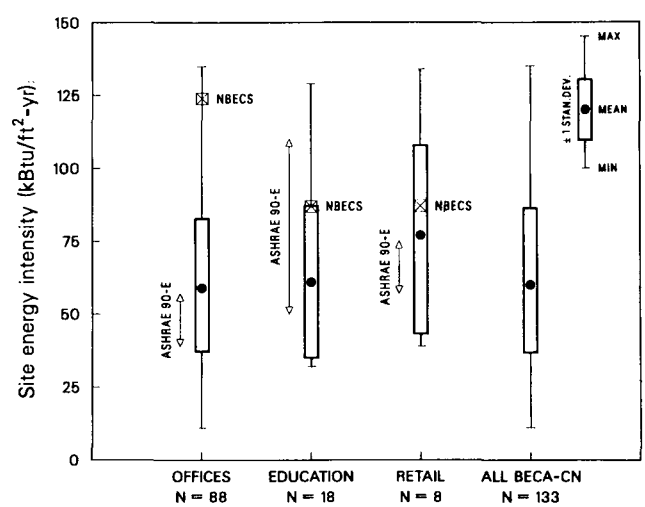

Figure 3. Summary of energy performance by building type for BECA-CN compared with the 1979 average U.S. stock (Nonresidential Building Energy Consumption Survey [NBECS]) and a proposed standard (ASHRAE 90-E). The minimum, maximum, mean, and standard deviation are presented for each category. NBECS data and Standard 90-E are not applied to the whole compilation because it represents a variety of building types. For each subsector, the average of the compiled energy-efficient buildings is below the average of the U.S. stock. The ASHRAE prototypes only approximately correspond to the building types in our compilation and those in NBECS and should be considered only a rough reference. The ASHRAE ranges approximate building performance under the standard and are derived from simulations of prototype buildings incorporating seven U.S. climate zones, two HVAC system configurations, a daylighting design, and a normal lighting configuration. (XCG 851-24)

Commercial Retrofits

The compilation of measured energy savings from retrofits in nonresidential buildings (BECA-CR) now includes over 300 entries.[4] The median annual energy savings (in site energy) for the 94% of the buildings that saved site energy is 31 kBtu/ft^2-yr, or about 25%. The most common retrofits involve HVAC operations and maintenance, and lighting. The median retrofit cost is \$0.40/ft^2, for a median payback time of only 1 year.

Figure 4 shows the range in energy savings for buildings in the data base. There is no simple correlation between energy savings and original energy use. Similarly, no correlations are observed between savings and level of investment. Table 2 shows the breakdown of energy savings by building type.

Energy management in commercial buildings is often a continuing process without clear "before" and "after" periods. This complicates the analysis of energy savings. During FY 1984 we began to examine multiyear energy consumption data to extract energy savings from long-term trends. Tracking buildings for several years during and following retrofitting can provide insight into building energy performance, including the effects of successive retrofits, their durability, and buildings' response to weather.

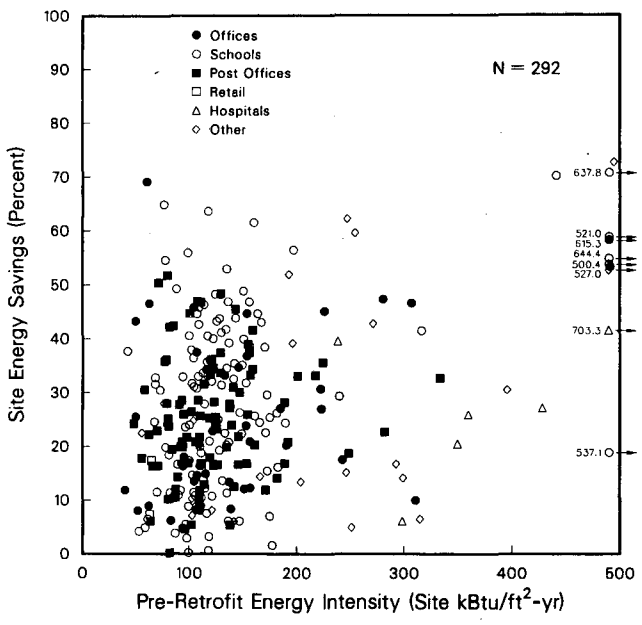

Figure 4. Percent site energy savings from retrofits versus site energy intensity for buildings in the commercial buildings compilation (BECA-CR). No simple correlation exists between the pre-retrofit consumption and the percentage savings achieved. (XCG 805-13075)

Table 2. Summary of median site energy savings from retrofits of commercial buildings.

Building type	N	Percent savings	Energy savings (kBtu/ft^2-yr)
Schools:			
Elementary	82	27.7	30.4
Secondary	28	24.5	37.7
Colleges	13	44.5	100.7
Offices:			
Large	34	21.4	28.5
Small	13	20.8	32.6
Hospitals	6	26.4	93.4
Retail	2	12.3	8.0
Hotels	5	14.4	42.3
Other:			
Post offices	92	24.0	28.0
Assembly	2	52.2	188.6
Correctional	1	6.0	8.5
Other	14	23.6	23.6
Total	292	24.6	30.8

Residential Water Heating

In FY 1984 we established a compilation for the measured energy performance of water-heating systems (BECA-D). The compilation includes studies of the performance of new water heaters, including heat pumps; retrofits such as tank insulation; and baseline energy and water use measurements. The compilation now contains 75 entries, including measurements of over 11,000 water heaters.[5] In spite of the great amount of monitoring activity, very few of the projects had sufficient data on temperature, water use, and tank characteristics to make valid performance comparisons of their results. Our preliminary conclusions are summarized in Table 3.

Model Validation

We continue to compile validations of building load programs against measured energy performance (BECA-V). Computer models of building energy use play a fundamental role in theoretical studies of energy conservation and in conservation programs. The success of these studies hinges to a large degree on the accuracy of model predictions. At present the compilation contains over 25 studies, comprising about 100 simulations of building energy use, performed with 18 computer models.[6] We found that accuracy of prediction depends on several factors

Table 3. Summary of BECA-D data base on measured performance of residential water-heating systems.

Action	Amount	Number of households
Average hot water use	17.7 gal/person-day (4.1 sd)	273
Average electricity use	3890 kWh/year (1483 sd)	7115
Average savings from thermal traps	340 kWh/year (158 sd) 16 therms/year	74 1
Average savings from insulation blankets	460 kWh/year (163 sd) 11 therms/year (12 sd)	79 25
Heat pump water heater seasonal COP	1.98 (0.25 sd)	500

Note: "sd" is standard deviation.

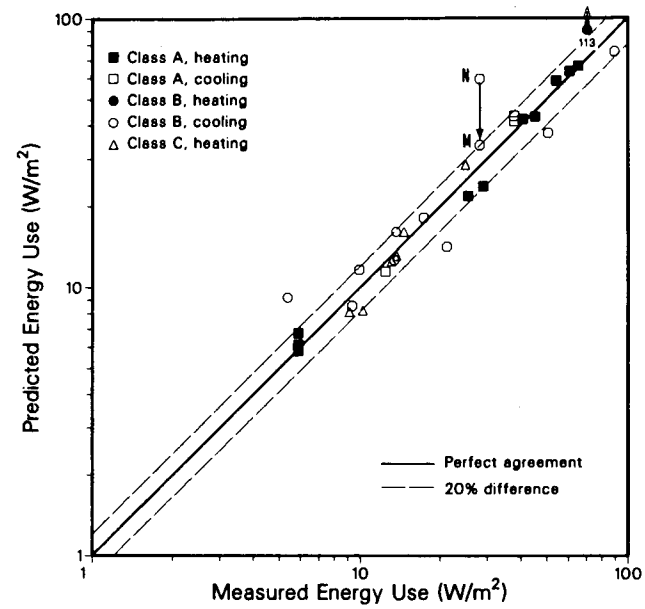

Figure 5. Measured vs. predicted average energy use in individual occupied buildings. All simulations used weather data for the monitoring period. Varying levels of detail in audit and consumption data (Class A = most detailed, Class C = least detailed) are indicated, as well as end use modeled. Point N represents a house modeled initially with incorrect occupancy data; the error was verified and corrected (point M). All other buildings were modeled "blind" or with corrections to input only if verifiable mistakes were discovered. Note log-log scale.

(XCG 843-13023)

beyond the validity of algorithms, including who performs the simulation (authors of the model usually achieve the best results), opportunities to compare simulations with measurements for a limited time, and verification of input errors. Figure 5 shows that many models can predict energy use within 20% of the actual value for occupied buildings.

Planned Activities for FY 1985

We plan to continue collecting and analyzing data for all of the compilations during FY 1985, but the focus of activities for each will vary. Some compilations will expand to include new measures or building types. Work on others will concentrate on analyzing existing data and on developing techniques to extract parameters of thermal performance.

For the compilation of new low-energy homes (BECA-A), we will investigate the contribution of specific components to energy performance. We are particularly interested in the influence of south-facing glazing area, furnace type, and house-tightening measures. We will begin compiling measured data on cooling, which will serve as the first step in developing an analysis similar to that for space heating. We will also add several hundred low-energy homes from the Pacific Northwest. These buildings have been particularly well monitored and will include consistent incremental cost data.

We will concentrate on multifamily buildings in FY 1985 in our residential retrofit data base (BECA-B) because there are still few retrofits that have been documented. We are participating in several monitoring projects of multifamily buildings and expect to include them in the data base. Sophistication in monitoring residential retrofits has evolved rapidly. We will improve the methodology used to calculate energy savings to accommodate submetered measurements, indoor temperatures, and other changes in operating conditions.

The commercial buildings compilations (BECA-CN and BECA-CR) demonstrate the kind of information that can be extracted from billing data. We believe more detailed investigations of commercial buildings are needed to better understand their performance. (Monitoring of commercial buildings is 10 years behind residential; only in 1984 did extensive submetering of such buildings begin.) We will focus on collecting more information for fewer buildings, especially buildings with submetered data.

We will also selectively compile buildings having similar functions, such as banks, restaurants, department stores, etc. It is possible to standardize performance with respect to operating characteristics in

such groups, thus permitting comparison and investigation of other energy-related factors. Our present compilations have shown that internal loads represent a major unknown in commercial buildings. We will investigate actual energy use of these loads, especially computers and electronic equipment. In a separate effort, we will study, through simulation, the weather responsiveness of commercial buildings. We hope this exercise will provide useful guidelines to adjust a building's energy use for variations in weather.

Load management has become increasingly important in commercial buildings. We will begin a compilation of load management measures, emphasizing thermal storage and energy management systems. We will continue to add data points to the water-heating compilation, emphasizing natural gas and solar-assisted units. In addition, we will begin developing standardized measures of water heater performance that permit comparisons among units in the field and with laboratory test procedures.

PRIMARY DATA COLLECTION

Accomplishments During FY 1984

The BECA and conservation potentials research often reveals gaps in the measured performance or consumption of buildings and equipment. Where possible, we undertake small monitoring programs to bridge these data gaps. We also develop and test measurement protocols with other groups at LBL to assist persons monitoring buildings and equipment.

The BED Group conducted three small monitoring experiments, in addition to numerous informal measurements, during FY 1984. Earlier investigations had found that loads in commercial buildings were poorly documented. Commercial reach-in refrigerators and drinking-water coolers are just two examples.[7,8] Our limited monitoring demonstrates that these two end uses consume significant amounts of electricity and deserve attention. We estimate that, for the U.S. as a whole, commercial food-service refrigerators use the electrical equivalent of two 1-gigawatt power plants and drinking-water coolers 0.5 GW. Even our brief experiments demonstrated that both appliances could be designed to use 30% less electricity with only small additional investments. We also monitored the energy use of five public housing buildings in San Francisco that received shell retrofits. The data will be entered into the residential retrofit data base as it becomes available.

Planned Activities for FY 1985

We expect to increase our monitoring of commercial buildings and their associated equipment in conjunction with the emphasis on case studies in the commercial buildings compilation. We will also continue, at a low level, to monitor and compile data on many poorly documented appliances and equipment, including furnace accessories, vending machines, and refrigerators.

CONSERVATION TECHNOLOGIES DATA AND POTENTIALS

Accomplishments During 1984

We worked on two projects to estimate the potential for conservation. We use monitored data wherever possible and, in the future, will increasingly rely upon the BECA data bases as a source of measured energy savings.

We completed a study of the maximum technically feasible conservation potential in the residential sector of the Bonneville Power Administration's service area.[9] Over 300 conservation measures were analyzed and processed by a computer program, CPS 2.0. Each measure was ranked according to its "cost of conserved energy," and the potentials were displayed as "supply curves" of conserved energy.[10] This graphic technique permits rapid identification of cost-effective or regionally significant conservation measures. The technical potential for conservation achievable by the year 2000 was 42% more than forecast by BPA.

In a second study we examined conservation technologies for new and existing commercial buildings in California.[11] The study analyzed energy savings, costs, and limitations of emerging technologies for air conditioning, ventilation, refrigeration, motor efficiency, electric lighting, and daylighting. We relied on BECA case study data for some of our estimates of energy savings, costs, and other factors. The study demonstrated that both existing and emerging technologies could significantly reduce energy and power use in commercial buildings. The report resulting from this study assists utility program planners and forecasters, as well as individual field auditors.

Planned Activities for FY 1985

Both projects will continue in FY 1985. The BPA project will concentrate on improvements to the model, CPS 2.0, and on updating the data base.

The commercial technologies project will expand and revise parts of the existing report, while investigating performance of real buildings through direct measurement and simulations.

In addition, we will assist the Building Owners and Managers Association (BOMA) in developing an energy section for their annual survey. This project consists of a series of investigations, principally building simulations, to determine the key factors influencing commercial building energy consumption. Using these results, we will prepare a research instrument best suited to estimating energy consumption from survey data.

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Building Energy Simulation*

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The goal of this group has been to create, test, document, and maintain a user-oriented, public-domain computer program that will enable architects and engineers to perform design studies of whole-building energy use under actual weather conditions. The development of this program, known as DOE-2.1, has been guided by several objectives:

- The description of the building by the user should be in quasi-English so that the input can be easily understood by noncomputer scientists.
- When possible, calculations should be based upon well-established or proven algorithms, i.e., the calculational procedures should be acceptable to the engineering and research communities.
- The program should permit simulation of innovative as well as commonly available heating, ventilation, and air-conditioning (HVAC) equipment.
- The computer costs of the program should be minimal.
- The predicted energy use of a building should be acceptably close to measured values.

As can be seen in Fig. 1, DOE-2 is composed of two major segments: the Building Description Language (BDL) processor, which accepts quasi-English descriptions of building components, and the LOADS, SYSTEMS, PLANT, and ECONOMICS (LSPE) processor, which uses building descriptions to simulate building energy performance. Details of the development and structure of the DOE-2 program are available in past Annual Reports and other published material.[1–14]

ACCOMPLISHMENTS DURING FY 1984

The Building Energy Simulation (BES) Group maintains a research effort that continues to develop new versions of DOE-2. (The latest version, DOE-2.1C, is almost complete.) This ongoing research is divided into three parts. The first is the introduction of algorithm description techniques into the code. The second is the modeling of building-envelope components and systems. The third is the simulation of HVAC equipment and associated control systems. Major new features of DOE-2.1C in these three areas are described below.

Functional Values

Work was completed on a mechanism for introducing functional values into the LOADS subprogram of DOE-2. This feature will be available in DOE-2.1C and will be extended to SYSTEMS in the upcoming DOE-2.1D.

The new capability will allow users to enter one or more FORTRAN-like functions (and even subroutines) directly into the program input; these functions are then compiled by DOE-2 for use in the hourly simulation. We expect this ability to be especially helpful to the research community.

There are two applications for the functional values feature:

- Calculation of variables that influence program results such as the definition of specific parameters and logic control.
- Calculation of variables for reporting and debugging purposes.

The user-input functions are calculated before or after the various building components, such as walls and windows, are simulated. The functions have access to all global variables, such as dry-bulb temperature, wind speed, and sun position, as well as calculated variables specific to particular components, such as solar gain through windows, surface areas, and occupancy schedules.

Sunspace/Atrium Model

In a collaborative effort between the BES Group and the RAMSES group at the University of Paris-South in France, new capabilities were added to DOE-2 to allow residential sunspaces (such as attached greenhouses) and commercial atria to be simulated. Sunspaces and atria are currently very popular architectural elements, and, being quite complex from a thermal and daylighting point of view, require an accurate energy analysis to produce a design that is energy efficient and comfortable year-round.

The new algorithms allow the different forms of heat transfer that take place between the sunspace (or atrium) and adjacent rooms (Fig. 2) to be simulated. For example, the calculation of the solar radiation that passes directly through the sunspace into the

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

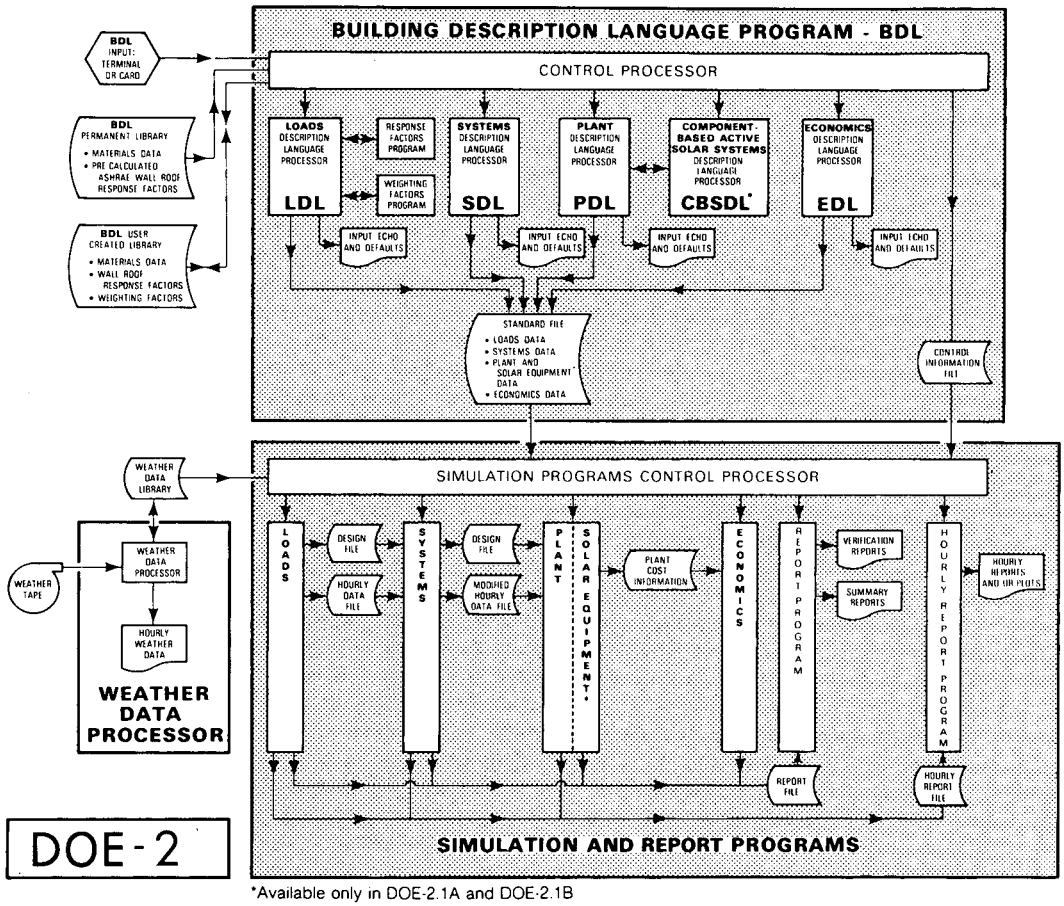

Figure 1. DOE-2 computer program configuration. (XBL 8010-2210B)

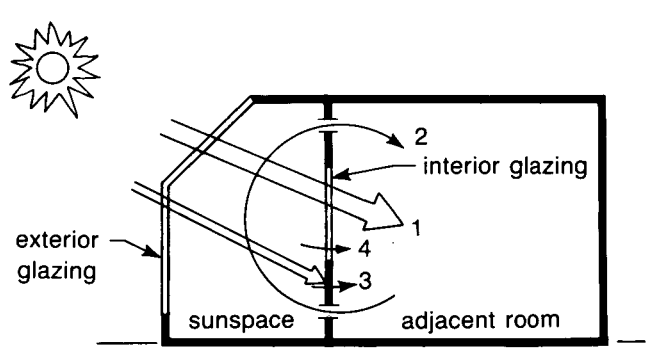

Figure 2. Cross section showing different forms of heat transfer between a sunspace and an adjacent room: (1) solar radiation passing from sunspace to room through interior glazing; (2) natural convection by thermocirculation through upper and lower vents; (3) delayed conduction through interior wall; and (4) conduction through interior glazing. (XBL 843-10167)

interior is done by using the DOE-2 shadow routines to project the solar image of each exterior window onto the different interior surfaces in the atrium or sunspace. Diffuse solar radiation incident on interior windows is also calculated.

In addition, the user can specify any of several different forms of convection between the sunspace and adjacent rooms, including fan-forced or natural thermocirculation between upper and lower vents, free convection through a doorway opening, and, for residential applications, use of a sunspace to preheat outside ventilation air. For commercial applications, the program allows return air from adjacent spaces to be passed to the atrium, where it is either exhausted or transferred back to the central air-handling system. A venting algorithm, which operates with any of the DOE-2 system types, allows outside air to be circulated through the atrium to

prevent overheating. To track the large temperature swings that can occur in sunspaces, the venting and interzone convection calculation is done in small time steps—from 0.6 to 3 minutes, depending on the sunspace heat capacity and the load in a given hour.

The interior walls in a sunspace are often fairly massive, so the delay in heat transfer by conduction through the wall is important. The DOE-2.1B program was modified so that interior wall response factors are passed from the LOADS to the SYSTEMS program where they are used to calculate delayed conduction, taking into account time-varying space temperatures. This conduction calculation also takes into consideration the effect of solar radiation absorbed on the atrium/sunspace side of the interior walls.

Figure 3 shows a sample simulation of a house with an attached sun space, as run by the modified program (DOE-2.1C).

HVAC Simulation Enhancements

Five items were completed in FY 1984:

- *Powered Induction Unit (PIU).* The PIU system consists of a variable-air-volume (VAV) terminal box with a small fan or blower that "induces" (draws) some amount of air from a ceiling plenum. The blower returns warm air from the core zone to the plenum, and from there to exterior zones requiring heat. It also provides increased air movement when the VAV damper throttles down the primary air, providing increased occupant comfort. Two types of PIU are modeled—series and parallel.
- *Heat recovery from refrigerated case work.* The user can specify refrigerated case work, with or without heat recovery, up to three temperature levels, and a corresponding load for each level.
- *Commercial air-to-air heat pumps.* Normally furnished with outside-air economizer cycles, these units previously could not be simulated in DOE-2. The heat-pump model was also expanded so that other types of supplemental heating, such as gas furnaces, could be simulated.
- *Updated curves for packaged air-conditioning units and coils.* In 1980,

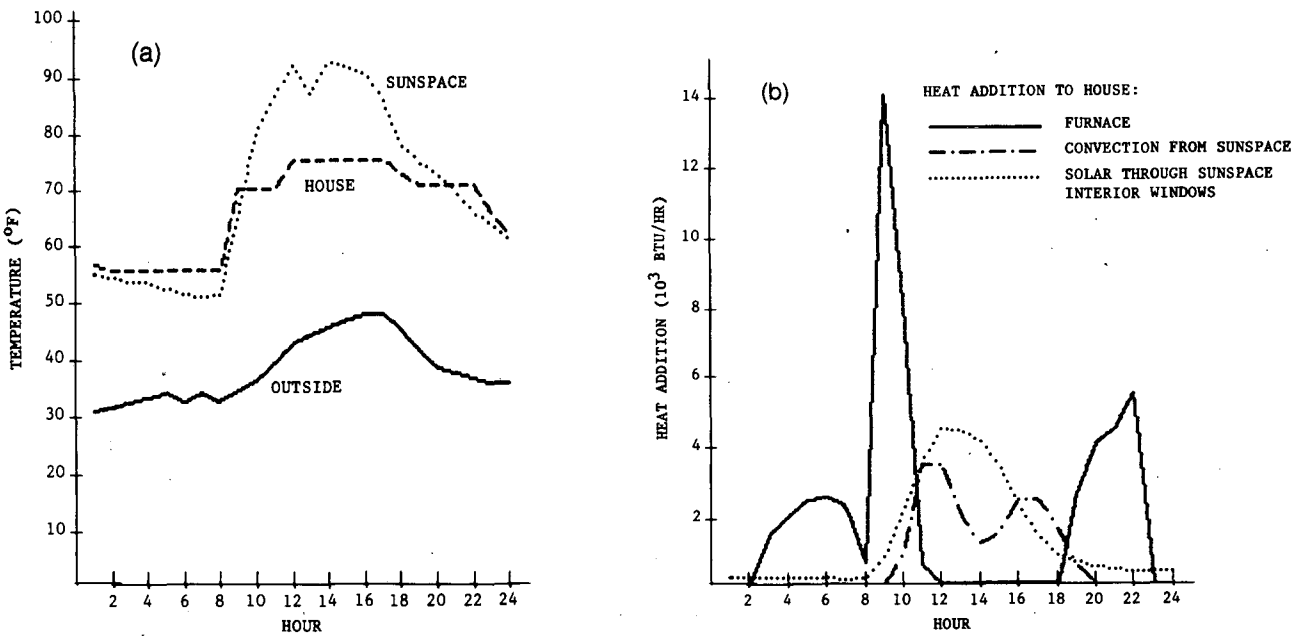

Figure 3. Sample hourly output for a clear January day in Chicago from a DOE-2.1C simulation of a house with an attached sunspace. (a) Outside, sunspace, and inside (house) temperatures; (b) breakdown of heat input to the house from space heating (furnace), convection from sunspace, and solar gain through windows on sunspace side. The heating setpoint of the house is 70°F during the day and 55°F at night. Warm air from the sunspace is circulated into the house at 200 CFM whenever the sunspace-house temperature difference exceeds 4°F and the house temperature is below 74°F. The sunspace is vented with outside air at 20 air changes per hour whenever the sunspace temperature exceeds 90°F.

[(a) XBL 851-941 and (b) XBL 851-940)]

when we first added packaged air-conditioning units, we had great difficulty in getting part-load performance curves from the manufacturers of this equipment. We have since collected better part-load information, making it possible to replace the original curves.

- *Optimum fan start.* Many buildings now have energy management control systems (EMCS) that allow the start-up of fans to be delayed until what is called "optimum start time." Because of its popularity, this energy conservation measure has been added to DOE-2.

Upgraded Energy Cost Structure

For many DOE-2 users the value of building energy requirements is measured in dollars, not Btu's. Furthermore, regulatory reforms in the pricing of electricity have prompted the development of increasingly complex tariff schedules, including time-of-day rates, sophisticated demand ratchets, and the sell-back of cogenerated electricity to utilities. For this reason, DOE-2.1C features a substantially upgraded treatment of energy costs for all utilities.

The most basic features of an energy cost tariff—fixed monthly charges, billing units, etc.—are defined with an ENERGY-COST command for each utility. A COST-ASSIGNMENT specifies a block rate or uniform cost for a utility. This command uses repeated keywords to define the size of consumption blocks and associated costs. The COST-ASSIGNMENT link to the utility can be direct (the COST-ASSIGNMENT applies all year long) or indirect, through a SCHEDULE. The SCHEDULE applies the COST-ASSIGNMENT to a defined window of time, which can be a season of the year or a specified number of hours during the day. For electricity, there is a final set of keywords, referenced through the COST-PARAMETERS command, to define the special features of demand charges and the sale of electricity. Demand charge ratchets can be specified as the highest demand previously recorded, some fraction of the highest demand, or an average of previous high demands. The ratchet can vary and be specified to apply for all months or a limited number of months in the run. Electricity can be sold by either of the accounting options mandated by the Public Utilities Regulatory Policy Act—net sale or simultaneous buy-and-sell.

Analysis Efforts for Others

An essential ingredient in the development of a computer program as large as DOE-2 is the ability to relate to the real needs of the program's users. Through involvement with studies such as those described below, the BES Group gathers the information necessary to ensure this relevancy and usefulness.

A study of the effects of fenestration parameters on residential energy use was made in collaboration with the Windows and Daylighting Group. An initial set of 450 DOE-2.1B parametric runs has been defined for this project. Among the quantities being investigated are window size, shading coefficient, glass conductance, orientation, and geographic location. Upon completion of the DOE-2 runs, it is expected that a simplified algebraic expression will be developed through the use of multiple regression techniques.

A study to compare BLAST (Building Loads Analysis and System Thermodynamics) and DOE-2 and their respective abilities to characterize the effects of thermal mass, wall position, and construction types was started in FY 1984.[15] Upon completion of the DOE-2 runs (the BLAST runs are being conducted by the Passive Solar Group), a definitive statement will be made as to the relative merits of using DOE-2 for such studies.

PLANNED ACTIVITIES FOR FY 1985

Future plans for the group lead in two directions. In one, the existing DOE-2 program will be maintained and supported and its documentation clarified and supplemented as areas of confusion are uncovered. Several additions will also be made to supplement its capabilities. These include (1) continued effort to improve window and daylighting simulation in collaboration with the Windows and Daylighting Group, (2) an expanded user-library capability, (3) completion of the functional values specification to include SYSTEMS, and (4) the addition of new HVAC equipment and controls. We will also continue to carry out building energy performance studies.

The other direction leads toward research into the development of the next-generation building energy analysis computer program.

Recent years have seen a number of building energy modeling systems such as DOE-2 reach the concluding phase of their development. Although

they offer sophisticated modeling capabilities, their numerous deficiencies restrict their ability to satisfy the needs of an increasingly demanding user community. Most of these systems were designed during the mid-1970s and are inflexibly tailored to a now-outdated computing environment. Furthermore, they were developed independently by groups around the world (mainly the U.S. and Europe) using different types of algorithms and solution techniques. Thus there is no easy way for researchers to compare or exchange existing approaches or to collaborate on improving existing systems. It is against this background that a new idea has begun to emerge simultaneously from a number of research groups: to develop collaboratively a plan of work that will lead to a clear specification and subsequent development of the next generation of building energy modeling programs.

During FY 1984, the BES Group began a plan for such a program to meet the simulation needs of the building research and design community of the 1990s. The work will be carried out over the next 5 years by LBL (with funding from the Department of Energy) and by other public and private sector organizations in the U.S., France, Great Britain, and China.

The new program is intended primarily for researchers in building energy science and engineering. However, because it will be easy to use (to be attractive to researchers), it will necessarily attract a wider audience of architects and engineers who require a detailed simulation program to produce a successful building design.

The need for the new program comes from both the research and commercial user communities. Commercial users want to model innovative buildings and building components that cannot be handled by the existing whole-building programs. Researchers need a straightforward means to integrate their detailed simulations into a whole-building model.

The most important capabilities of the new program will include the following:

(1) The envelope and HVAC systems calculation will be fully integrated, with interactive loops allowing both feedback and feedforward.

(2) The time step will be variable; it can be chosen by the user or be determined dynamically by the program, depending on the process being simulated. Different time steps for individual components in the simulation will be allowed.

(3) The user will be able to add, via the input language, algorithms to simulate innovative components that cannot be modeled by the basic program.

(4) The program will have built-in algorithms and solution techniques ranging from fast, simplified methods useful for conceptual design studies to slower, more detailed solutions where a high degree of accuracy is important.

(5) Detailed thermal modeling of the envelope will be possible, including simulation of multidimensional heat flow; convection and stratification of air; interior and exterior exchange of infrared, solar, and visible radiation; storage, release, and convection of moisture and contaminants; and combined illuminance distribution from daylight and electric lighting.

(6) Simulation of secondary and primary systems will be component-based. The user will be able to choose the configuration, connection, and control of components (fans, coils, chillers, storage tanks, etc.), allowing easy simulation of unconventional and innovative systems.

(7) The user will be able to simulate the complex control schemes that are becoming possible with microprocessor-based energy management systems.

(8) The program will be able to access a data base of building-related information (material properties, operating schedules, equipment performance curves, fuel costs, etc.). The user will be able to use the input language to augment or modify the data base to suit the particular building type, geographical region, and other constraints that he is working with.

The development of the new program will require a long-term effort in five major project areas:

(1) planning and coordination among the participating organizations in the development and overall management of the technical projects;

(2) research into mathematical models and computer algorithms;

(3) research into solution techniques to solve combined nonlinear partial differential and algebraic equations;

(4) development of user interfaces, including algorithms, languages, and report and building descriptions; and

(5) defining and integrating the overall structure of the program—how its parts fit together and communicate.

Many organizations will be involved in this project over its lifetime. The plan is to identify individuals and groups in the U.S. and other countries that have the requisite technical knowledge and experience and bring them together to work on the project. Meetings have begun to identify the level of interest, types of involvement, work time frames, and potential personnel commitments that can be made by the various participants.

A major challenge is that the new program will have to solve a combined system of algebraic and nonlinear differential equations. The algebraic equations may include discontinuities or constraints. We need to establish whether a general technique exists for solving such a combined system or, if not, what the most reasonable compromise is—e.g., linearization or separation of the problem into smaller pieces. The first step will be to find what solution techniques are available, implement them, and test their range of validity. The next step will be to combine the various techniques to solve the more general building analysis problem in as much detail as possible.

Making the program easy to use is another challenge, one that requires developing a user interface with different levels of complexity. At the lowest level, a user would simply specify the general characteristics of the problem (such as building type, orientation, number of floors, aspect ratio, location, accuracy desired, etc.). This would be transformed by the program into the input parameters and program control structures required to perform the simulation. The next level of input would be similar to the standard input for existing programs, which involves a component-by-component description of the building's envelope and systems. The highest and most detailed input level would have four subsections that would allow the description of:

- new component algorithms of arbitrary complexity;
- new input language structures and parameter default calculation sequences to allow the use of the new algorithms;
- the connectivity between components to allow them to be assembled in an arbitrary but physically sensible manner;
- solution techniques to be used globally or at the component level, including convergence criteria, iteration sequence, number of iterations, and other related parameters.

These capabilities will require an internal program structure completely different from existing programs. We envision four main components in this structure:

- a database system that contains user input information, detailed parameter description for simulation algorithms, intermediate and computed results, and other categories of information;
- algorithm routines that are the heart of the actual simulation;
- a computation control structure; and
- a user interface module.

A preliminary schedule has been proposed for this project. It has two main stages, development and maintenance. The development stage consists of (1) conceptual design, (2) prototype implementation and testing, and (3) final implementation, testing, and release. Development is expected to take approximately 5 years; maintenance follows development and will continue over the useful life of the program.

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This list of publications for the Energy Efficient Buildings Program covers the years 1981–1984. For earlier or more recent publications, please contact each group individually. This list is organized as follows:

- *Energy Efficient Buildings* (EEB)—general reports not specific to any group.
- *Buildings Energy Data* (BED)—reports on the compilation and analysis of building energy performance data.
- *Building Energy Simulation* (BES, including DOE-2)—reports concerning computer modeling and programming.
- *Energy Performance of Buildings*—reports specific to the energy performance of building envelopes.
- *Ventilation and Indoor Air Quality*—reports specific to building ventilation and indoor air quality.
- *Windows and Daylighting*—reports specific to the energy-efficient design of windows and use of daylighting.
- *Lighting Systems Research*—reports specific to the energy-efficient design of lighting systems, including daylighting.

Most reports have an LBL number and an EEB number, either of which may be used for ordering copies.

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