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FY 1985 Annual Report

ENERGY EFFICIENT BUILDINGS PROGRAM

July 1986

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APPLIED SCIENCE DIVISION

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

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LBL-20203

APPLIED SCIENCE DIVISION ANNUAL REPORT

ENERGY EFFICIENT BUILDINGS PROGRAM

FY 1985

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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 $155 billion worth of energy, mainly as electricity. Of the total annual U.S. electricity sales of $135 billion, most ($100 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.

Table 1. U.S. energy expenses, 1983.[a]

Sector	Fuel [10^9]	Electricity [10^9]	Total [10^9]
Buildings	60	100	155
Residential	(40)	(55)	(90)
Commercial	(20)	(45)	(65)
Industry	65	35	100
Transport	150	0	150
Total	270	135	405

[a]Excluding federal subsidies and rounded to the nearest $5 billion.

Source: *State Energy Price and Expenditure Report,* 1983, DOE/EIA 0376(83) (February, 1986).

To update these costs to 1985 in 1985$ would raise the electricity costs, lower the fuel costs, and probably give a few percent total reduction. [Between 1980 and 1983 total energy bills rose 3% per year, electricity bills rose 6% per year, and the difference (fuel) dropped very slightly.]

In addition to the tabulated costs paid directly by customers in 1984, there were federal subsidies (11%) of $44 billion, bringing the energy total to about $450 billion, larger than all private and public expenditures for Health ($400 billion), Defense ($300 billion), Education ($200 billion), or farm income ($140 billion). For source of $44 billion energy subsidies see Heede, Morgan, and Ridley, "*The Hidden Costs of Energy,*" Center for Renewable Resources, Washington, DC 20036 (1985).

Since 1973 rising energy prices and awareness have remarkably reduced our energy bills. Our real GNP is up 30%, yet our primary[1] energy use is unchanged. If our energy efficiency were still frozen at 1973 levels, we would today be paying $526 billion annually instead of the $405 billion shown in Table 1; i.e., we are actually saving $121 billion each year, a very significant sum, comparable to our highly publicized national budget deficit.

In buildings the percentage savings are comparable. Since 1973 our stock of households has grown by 25% and commercial floor space has increased by 32%, yet primary energy use in buildings is up only 11 percent.[2] So energy use per square foot has fallen by 13%, and we are actually saving $22 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,[3] 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 $155 billion to $75 billion.

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.

Table 2 lists several examples of the remarkable successes of DOE-sponsored Buildings R&D projects, and we are pleased to point out that our EEB Program was responsible for the first two columns—Solid-state ballasts for fluorescent lights and Low-emissivity ("heat mirror") films for windows.

Table 2. Lead times and net savings[a] for successful DOE-sponsored buildings energy R&D projects.

	Solid state ballasts	Low-E window films	Residential absorption heat pump	Advanced electric heat pump	High efficiency refrigerator compressor	High efficiency refrigerator-freezer	Heat pump water heater
1. DOE project duration	1976–1980	1976–1990	1978–1988	1977–1986	1977–1981	1978–1983	1977–1982
2. Est. 50% penetration of sales	1995	2000	2001	1998	1990	1996	1995
3. Years by which DOE advanced commercialization	5 yr	5 yr	5 yr	2 yr	2 yr	2 yr	3 yr
4. Cost of conserved energy (CCE)[b]	2¢/kWh	$2/MBtu	$2.50/MBtu	$2.75/MBtu	1¢/kWh	3¢/kWh	3¢/kWh
5. Cost of DOE project	$3M	$2M	$6.8M	$2M	$1M	$0.8M	$0.7M
6. Net annual savings in 1985	$11M	$14M	$0M	$0M	$0.4M	$0.2M	$6.5M
7. Net annual savings at saturation (i.e., 10–15 years after 50% penetration)[c]	$5,000M	$3,000M	$2,400M	$2,500M	$1,100M	$850M	$3,000M
8. Cumulative net savings (line 7 × line 3)	$25,000M	$13,000M	$12,000M	$5,000M	$2,200M	$1,700M	$9,000M
9. DOE project ROI (return on investment, =line 8 ÷ line 5)	8,000:1	7,000:1	1,500:1	2,500:1	2,000:1	2,000:1	13,000:1

a. All dollar savings in energy costs are **net** of increased costs for purchase of the improved equipment (ballast, window, etc.).

b. For cost of conserved energy (CCE), we use a real discount rate d = 7%, and the useful life of the product: e.g., 10 years for ballasts, 20 years for windows. The CCE of low-E films, now still a novelty, is currently $4/MBtu, but as the market matures, we estimate that the CCE will drop to $2/MBtu.

c. Net annual savings at saturation are in 1985 dollars, uncorrected for growth in the building stock, changes in real energy costs, or discounted future values. We decided **not** to account explicitly for these three factors, since all three are uncertain and their combined impact probably small, as shown by the following calculation. To translate savings in 2000 or 2010 to 1985 terms, one multiplies by: $\exp[(g + e - d)T]$, with the following annual rates:

$$\left.\begin{array}{l} g = \text{growth rate of building sector (3\%)} \\ e = \text{real price escalation for electricity or fuel (1–2\%)} \\ d = \text{real discount rate (4–7\%)} \end{array}\right\} \quad g + e - d = (-3 \text{ to } +1\%)$$

T = years between 1985 and the est. saturation date, 20–25 years.

Source: "Federal R&D on Energy Efficiency; a White Paper," American Council for an Energy Efficient Economy, 1986, available from ACEEE, 1001 Connecticut Ave. NW, Suite 535, Washington, DC 20036, or LBL.

Several conclusions can be drawn from Table 2 (for more details, see the 1986 ACEEE White Paper cited below the table):

1. Gestation time, from initiation of research to 50% market penetration, is 25–30 years, even though the development was very cost effective and fairly obvious (indeed inevitable, eventually).
2. The payback times for the consumer are typically only 2–3 years. Put more precisely, line 4 shows that the cost of the conserved energy is typically 3 times cheaper than the current purchase price of energy.
3. The annual dollar savings to consumers are huge. Line 7 lists annual savings after the new technology saturates the market:
   a. For the high frequency ballasts, the savings are $5 billion per year, comparable with the output of 18 standard 1000 MW power plants. Related to the development of small solid-state high-frequency ballasts are the new compact fluorescent light bulbs, like the Phillips SL-18, which replace a 75-watt incandescent light for 18 watts. When they saturate high-use light sockets throughout the U.S. they will save another $5 billion, and another 18 power plants.
   b. For the low-emissivity window films, the annual fuel savings at saturation will be $3 billion, corresponding to about 1/5 the output of the entire Alaska pipeline.
4. The societal returns on the federal R&D costs are also huge—much greater than 1000 to 1 (line 9).

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 six 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 Energy Performance of Buildings 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 group is investigating new techniques for measuring air leakage, using AC pressurization. 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. 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.

The group has 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.

As lead lab for the multifamily sector in DOE's Retrofit Research program, the group conducts numerous projects in how to diagnose, monitor, analyze, and evaluate the energy conservation potential in multifamily buildings nationwide. A related series of projects focuses on the energy savings potential in public housing.

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 and exhaust air heat pumps to provide independent data on these devices.

An interesting conclusion that can be drawn from the work of the BVIAQ Group 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 while a modest reduction in air exchange rates occurs. 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 performance of buildings. Starting in 1978, the group developed a family of computer programs that simulate building energy performance, the most current version of which is known as DOE-2. These programs are now widely used by architects and engineers in the design of new buildings and in the retrofit of existing ones. DOE-2 is also used extensively by researchers and educators 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, as well as capabilities to allow the study of new and emerging technologies. DOE-2 has become the standard against which other calculation procedures or programs are compared. It has been used to develop simplified approaches ranging from hand calculation methods or slide rules to microprocessor programs, ASHRAE handbook tables and procedures, and 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 BES Group is also undertaking projects that are designed to lead to the production of the next generation of building performance simulation programs. The main efforts in the advanced simulation area at this time are the creation of a simulation "kernel" system and organization of the simulation development community to enhance collaboration. The kernel system will provide the basic tools and information to allow the BES and other groups to develop more advanced simulation programs. It will also provide a mechanism to facilitate exchange of research results and technology advances, and provide a basis for integrating performance simulation into computer-aided design (CAD) and expert system software. The organization of the simulation community through the creation of a professional society will enhance the exchange of information and allow more widespread dissemination of the new technologies into the design and research communities.

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 measurements 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 develop and 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 significant 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 ultimately save consumers $3 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. Results are used to validate and upgrade SUPERLITE, a powerful and versatile daylighting simulation model. Computational procedures for thermal performance are being validated with the Mobile Window Thermal Test facility (MoWITT), now collecting winter and summer performance data in Reno, Nevada, and Livermore, California. 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 three major categories: technical engineering, building applications, and impacts on health and visibility.

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.

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 such as visual display terminals in an advanced lighting environment.

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

Facilities for technical engineering are located at LBL; the productivity 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 the invention of a new high frequency surface wave lamp whose efficiency is more than 30% better than the common fluorescent lamp. A 2-year test of solid-state ballasts in a large office building showed an electricity savings of 40%. Scaled to the entire country, this represents an annual savings of $5 billion. The energy-efficient surface wave lamp promises to provide major reductions in energy use while considerably extending lamp life.

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 con-

tains 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.*

Project RICH (Residential Integrated Cooling and Heating). 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 125 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 residential and small commercial 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 that 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. 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."
2. *Overview of Building Energy Use and Report of Analyses–1985,* U.S. Department of Energy, DOE/CE-0140, October 1985, reprinted April 1986.

3. *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 retrofit research. In this article, the work carried out over the last year is split into four overlapping sections: 1) building energy retrofit research, 2) air infiltration, 3) air leakage, and 4) integrated ventilation. The emphasis in our work is on whole building performance. We collect, model, and analyze detailed data on the energy performance of buildings, including the micro-climate, the building's thermal characteristics, the mechanical systems, and the behavior of the occupants. Because of the multidisciplinary approach we work closely with other groups, both at the Laboratory and elsewhere.

BUILDING ENERGY RETROFIT RESEARCH (BERR)

While new buildings—both residential and commercial—are responding to higher energy prices and stricter energy codes by becoming more energy efficient, the existing stock represents a large area for energy conservation activity. Of the three buildings sectors, single-family, multifamily, and commercial, multifamily has had the least level of activity, and presents some of the greatest challenges. Over one quarter of the U.S. housing stock is in multifamily buildings. The Office of Technology Assessment estimates that while current levels of retrofit activity in multifamily buildings are likely to save 0.3 quads of energy (320 petajoules) by the year 2000, the *potential* savings are more than three times as much.[1] The reasons for this untapped energy savings are complex, and involve institutional as well as technological barriers. While we know something about the performance of retrofits in single-family houses, we have very little understanding of the interactions and performance of retrofits in multifamily buildings. The measured savings from retrofits in multifamily buildings are typically 25–50% less than the predicted savings, with a large spread around the mean.

The explanations for this wide divergence are usually hindered by the limitations of the available data. The Building Energy Retrofit Research project was initiated to address these problems in all three building sectors, Single-family, Multifamily, and Commercial. The Department of Energy has designated LBL as the primary lab for carrying out research in the multifamily sector. Several projects are being carried out in this area, including sector characterization and analysis, monitoring protocol development and demonstration, building diagnostics, occupant surveys, case studies, and technology transfer. In addition, special emphasis has been given to a sub-sector of multifamily buildings, specifically, federally-assisted housing.

Accomplishments During FY 1985

Our BERR work in the last year can be broken down into three areas: 1) Planning, 2) Retrofit monitoring and diagnostic demonstration, and 3) Utility data collection and analysis.

Two major planning documents were prepared this year, one dealing with multifamily retrofit research and the other with federally-assisted housing.[2,3] Both plans characterize the existing building stock, discuss barriers to retrofit activity, outline previous activities—private and public, and identify research needs. In addition, a cost benefit analysis using net present value was made for all of the multifamily research projects. The multifamily plan was done in conjunction with similar documents on the single-family and commercial sectors written by Oak Ridge National Laboratory (ORNL). Input on private sector activities was provided by Princeton University. The document has input from over forty organizations, and has had a preliminary review by a dozen organizations. The federally-assisted housing plan was done in-house, with input from several public housing authorities, as well as substantial review and comment from HUD.

Three main activities were undertaken in our retrofit monitoring and diagnostic demonstration work: 1) the development of a protocol for multifamily retrofit monitoring, including a survey of available equipment, 2) the demonstration of innovative diagnostics and evaluation of retrofits in a multifamily building in Minneapolis, and 3) the

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long-term monitoring of hot water retrofits in a public housing project in San Francisco.

The objective of the protocol is to provide a comprehensive standard for data collection and evaluation of retrofit performance.[4] Accompanying the development of the protocol is our work in documenting existing monitoring instrumentation. The first phase of gathering manufacturers' literature has been completed and a preliminary report was presented at the *Field Data Acquisition Workshop* in Dallas in October, 1985.[5]

The diagnostic demonstration project focused on a one-week investigation of a 7-unit apartment building in Minneapolis, working in conjunction with the Minneapolis Energy Office (see Fig. 1). The diagnostics involved using simultaneous measurements with six blower doors to investigate air leakage in the apartments—both between units and to the outside—and an evaluation of the building's ancient steam boiler, quantifying total energy losses (see Figs. 2 and 3). In addition, a short-term measurement using tracer-gas was made of a vent damper retrofit installed on the boiler.

The long-term monitoring of the hot-water system at Holly Courts (a complex of 10 buildings) is part of our collaborative work with the San Francisco Housing Authority. We are currently monitoring the hot water systems in four buildings (48 units total) to understand patterns of hot water use and the performance of the active solar retrofits. The residents were also interviewed to understand hot-water-use patterns and the effect of the residents on the performance of the retrofit.

The retrofit to the domestic hot water system involved installing a total of ninety-four 4 ft × 10 ft solar collector panels on the roofs of all ten buildings. The solar collectors were plumbed into storage tanks located in the boiler rooms in the basements of the buildings. The solar storage tanks were connected into the existing domestic hot water system for the building. Installation of the collectors began in November, 1984, and by January, 1985, the solar systems were operational in all ten buildings. By March, 1985, we installed the first of our monitoring systems (described below) in the boiler room in one of the buildings. In the next few months, three additional data loggers were installed in different buildings. A weather station was installed on the roof of

Figure 1. Exterior view of apartment building in Minneapolis, Minnesota, where building diagnostics were demonstrated. (XBB 8512-10273)

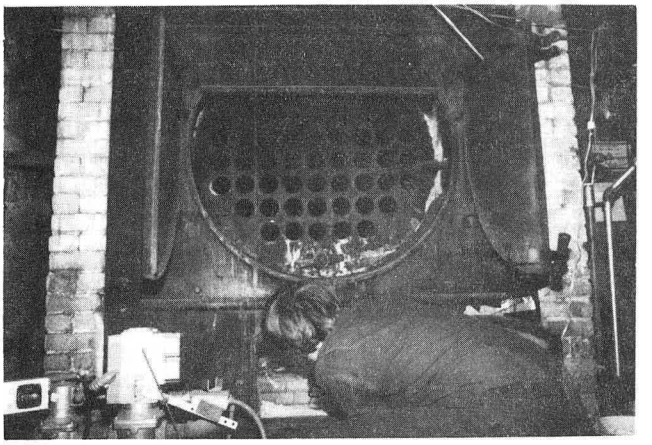

Figure 2. Large fire-tube boiler examined in multifamily case study. (XBB 8512-10277)

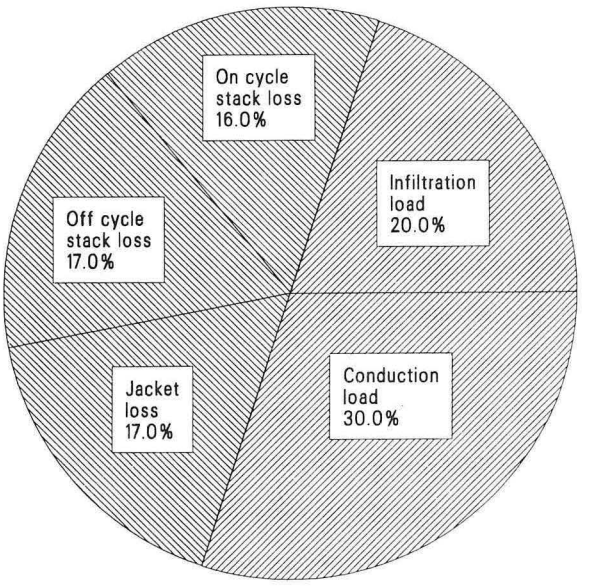

Figure 3. Boiler energy balance without stack damper. (XCG 853-106)

one of the buildings to collect local temperature, wind, and solar data.

The data acquisition system chosen for this project was the μMAC-5000. It is a programmable modular system that operates unattended in the boiler rooms at Holly Courts. Real time data for on-site weather, individual building domestic hot water use, and the contribution of the solar system are collected and converted to hourly averages. Data are stored in the system's memory and are transferred weekly to LBL by a telephone modem.

A total of thirteen sensors are used for each building, plus an additional four for the weather tower. The temperature sensors are all type T thermocouples, attached to the outer surface of the appropriate water pipes (using nylon wire ties and thermal contact grease) and insulated. The circulation pump for the solar system is monitored with a clamp-on ammeter. A water flow meter is installed in the domestic hot water supply line. It was important during this installation to minimize the disruption of the hot water service to the building residents. The only interruption required was roughly two hours at each building during the installation of the water flow meter.

The quantities calculated from the monitoring include the following:

- quantity of hot water used
- temperature of hot water delivered to occupants
- heat loss in building hot water pumped loop
- temperature of cold and solar preheat water supply
- operation time and average collection efficiency of the solar system

Six months of hot water data have been collected (with a data capture rate of 95%). Findings to date show high hot water use per household, different consumption patterns from those presented in the literature, and surprisingly close agreement between the measured hot water use and that calculated based on the occupants' reported usage patterns.

Our work in utility data collection and analysis has concentrated on federally-assisted housing, where we have been analyzing the performance of retrofits in public housing. Utility billing data along with information on building characteristics and retrofit strategy have been collected for over forty public housing projects. The study will attempt to determine the energy savings and cost-effectiveness of the conservation retrofits. Particular indicators include resource energy savings, the cost of conserved energy, and the internal rate of return. Preliminary results indicate that there is a wide variability in energy savings.

Planned Activities for FY 1986

Our monitoring work will include completion of the multifamily monitoring protocol and demonstration of its use on buildings in Minneapolis/St. Paul and Chicago. These measurements will be done in collaboration with the Energy Resource Center in St. Paul, the Minneapolis Energy Office and Minnesota Department of Energy and Economic Development, and the Center for Neighborhood Technology in Chicago. In addition to using the protocol to determine the performance of heating system retrofits, we will look at additional factors that affect retrofit adoption and performance, including moisture effects in sealed attics and behavioral effects. Limited diagnostics will also be performed on the heating systems. We currently plan to instrument four buildings, two in each city. We will also continue monitoring hot water use in one of the San Francisco public housing buildings.

The analysis work of utility bill data will continue with new retrofit data on the public housing projects. We will also collect and analyze baseline energy use from over 40,000 public housing units. We will calculate weather-corrected consumption levels for several years and compare them to estimates provided by an earlier study of estimated energy use in public housing.[6] We will also attempt to determine the influence of building and operating characteristics on variations in energy consumption.

In addition to our multifamily retrofit research we have some related projects in single-family housing. Some examples of these projects include the continuation of the warm room project and several of the infiltration projects described in the next article.

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 thermostat. In 1984 Kansas City was awarded a grant from the Urban Consortium to demonstrate the warm room approach, with LBL providing technical assistance. As part of our technical assistance we worked with city officials in selecting potential houses for the project. Twenty 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 reading 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.

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 multizone model, multigas tracer measurements, and wind tunnel measurements of wind pressure distributions around buildings.

Multizone Model

Computer programs have been developed that calculate the energy consumption due to infiltration. A review showed that the majority of the programs found in the literature use an empirical power-law expression to relate air pressure to air flow and use Newton's method of iteration to solve the set of nonlinear equations.[7] These programs, which treat the true complexity of flows in a building by recognizing the 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,[8] 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 (see Fig. 4). A simplified multicell infiltration model capable of providing the same accuracy as the established single-cell models is therefore being developed at LBL.

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.

Accomplishments During FY 1985

Multizone Modeling

For purposes of modeling infiltration, buildings are classified as one of the following:

(a) row house (terrace house)
(b) detached house
(c) story-type house
(d) shaft-type house

These four basic categories reflect different permeability distributions of the building's envelope (which influences the wind effect) and different vertical flow resistances inside the building (which influences the stack effect).

The distinction between the four categories can be expressed by two permeability ratios. One param-

Comparison of Modelling Strategies

	advantage	disadvantage
single-cell	easy to handle few input data reasonable accuracy	only single cell no internal partitions no internal flows
detailed multi-cell	large buildings internal flows good accuracy	extensive input mainframe computer
simplified multi-cell	large buildings internal flows micro computer reduced input	reduced accuracy

Figure 4. Comparison of air infiltration modelling strategies. (XBL 858-3493)

eter, the envelope permeability ratio (epr) is used to describe the whole building for a given house type in categories a or b.[9]

The epr of row houses can be described by the average permeability ratio of the leeward side to the overall permeability of the building envelope of epr = 0.5, whereas the corresponding value for a detached house rises to epr = 0.75.

In the latest issue of the German standard, DIN 4701,[10] another parameter, the internal vertical permeability (ivp), was introduced to further differentiate construction types in categories c and d. For further considerations, it is useful to also introduce the ratio of the permeabilities from one floor to another and the overall permeability of the building envelope (vertical permeability ratio, or vpr). With regard to the thermal pressure distribution, two extremes exist: story-type buildings with no permeability between floors (vpr = 0) and shaft-type buildings with no air-flow resistance between the different stories (vpr = 1).

To describe the air-flow distribution for the different zones at the story level, we defined two more lumped parameters: the outside permeability ratio (opr) of the zone (which describes the influence on cross ventilation of the zone, cross ventilation being the portion of the air flow that exfiltrates out of the same zone where it infiltrates) and the inside permeability ratio (ipr) of the zone (which describes the stack influence of the zone).

In a previous study, the use of a detailed multizone infiltration model showed a strong relationship between the two latter ratios and the flow distribution in buildings.[11] With increasing values for opr and decreasing values for ipr, the zones become more wind-dominated. Consequently, increasing ipr in combination with decreasing opr shows the opposite effect.

With the two lumped parameters describing the flow for the whole building, we were able to describe the air flow through a multizone, multistory building with a very simple floor plan.[12] The use of the two lumped parameters describing the air flow through the zones will allow us to calculate the air flow through buildings with more complicated floor plans, too.

Multigas Tracer Measurements

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 mass flow controller for each zone, a gas chromatograph with two columns, an electron capture detector (this detects all species that are electronegative), and a mechanism for sampling the different zones. A peristaltic pump draws sample gas from each zone into sampling bags for a 6-minute period; the content of the bags is analyzed, the bags are evacuated, and the sampling cycle continues.

Software development for the programs controlling the sampling and data acquisition has been finished. Our first tracer gas measurements took place in one unit of a 60-unit garden-apartment complex for the elderly in Oroville, California. In addition to the tracer concentration data for the different zones, weather data were recorded. 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. Measurements in multistory buildings showed air transport in vertical shafts and its distribution inside the building.

Wind Pressure Studies

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 help analyze the measurement data has been developed.

Pressure measurements in the wind tunnel have been carried out for the Oroville houses. Scale models of all the houses in which we did perform tracer gas measurements have been built (see Fig. 5). The measurements show a strong influence of the building's surrounding on the pressure coefficient distribution.

Planned Activities for FY 1986

Multizone Modeling

The use of the preliminary model is still somewhat limited. Our task is to incorporate the two lumped parameters which describe the air flow for the zones to be able to simulate buildings with more difficult floor plans. Therefore, a parameter study by using the detailed computer model will be carried out for a number of floor plans to find the minimum of input data needed to describe the air flow in the building.

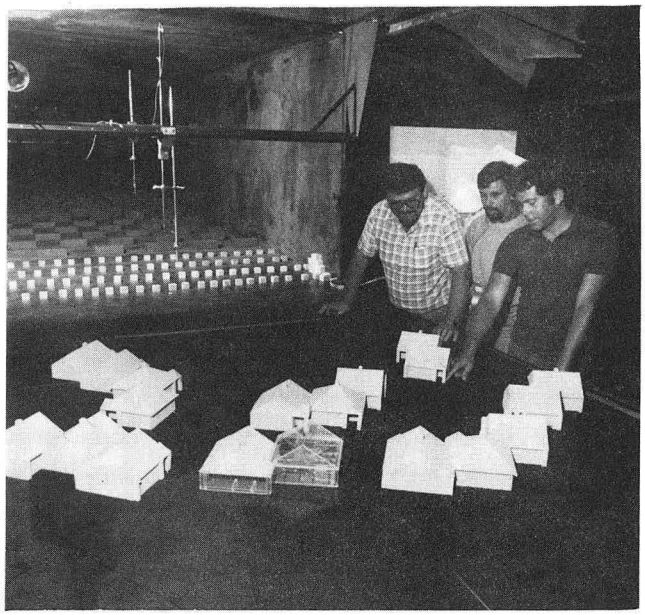

Figure 5. Wind tunnel measurements to determine pressure coefficients for the test house. (Surrounding buildings are included in the measurements.) (XBC 858-6285)

Multigas Tracer Measurements

As the collection cycle for the measurement system is very long (20 minutes for four chambers), real time comparison with the program was not possible. Therefore, the development of another measurement system is planned, using a residual gas analyzer to analyze the gas to overcome the long cycle time caused by the gas chromatograph. For more hardware reliability a new controller will be introduced and the necessary software will be developed.

Wind Pressure Studies

Pressure coefficient measurements will be carried out for a test building of the Ecole Polytechnique Federal de Lausanne for which tracer gas measurement and weather data have been collected. This test building contains nine zones on three different floors. It is shielded by adjacent buildings and pressure coefficient distribution is hard to predict. The wind tunnel measurements will help us to understand complicated flow pattern and will give us the necessary input data for our detailed computer model to simulate the internal flows. This will help us to validate both the detailed and the simplified model.

AIR LEAKAGE

The process of air flowing through a building envelope is called air leakage. Air leakage depends on the air tightness of the building as well as on the pressures driving the air flow. Air tightness is a property of the building alone and does not depend on the climate or other external properties. Typically, air tightness is quantified by the *Effective Leakage Area* (ELA), which is the amount of open area that would have the same air leakage as all of the leaks in a building under identical conditions. The measurement and study of air leakage allows us to: characterize the air tightness of buildings, better understand air flow through building envelopes, and estimate the effectiveness of retrofits on building ventilation.

Our air leakage research can be divided into three areas: leakage characterization, measurement techniques, and consensus standards. Our leakage characterization effort involves collecting and analyzing measured leakage data (primarily from North America) to determine the aggregate leakage behavior of residential buildings. The standard method for measuring building airtightness is called *fan pressurization*, and uses a device commonly known as a *blower door*. Over the last few years, we have developed a new method for measuring building airtightness, *AC Pressurization*, which allows us to determine the effective leakage area at low pressures, independent of wind effects. In addition, we are in the process of developing a technique for measuring air leakage in multifamily buildings. Finally, we are putting our experience to use in assisting the 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 1985

For the past three 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 of the results of this effort in FY 84 was a compilation of over 500 leakage measurements that included house characterization data.[13] During FY 85 a version of this database was installed in-house on a micro-computer.

The new database is based on the data compiled at the University of Alberta, Edmonton, Canada, which was expanded both in quantity of measure-

ments and in depth of specification. Requests for new data were made to: researchers, government energy agencies, house doctor companies, the military, and any other parties that might have blower door data. The database now contains approximately 700 measurements. It is made up of five separate databases: a leakage database, which contains basic leakage information for quick reference; a leakage characteristics database, which contains complete information on the data analysis and detailed information about the measurement conditions; a house characteristics database, which contains a detailed description of each house, including its retrofit history; an address database; and a zipcode database, which contains climate information, including infiltration degree days and specific infiltration.

In late FY 84 we started a measurement program to examine seasonal changes in leakage area. The program involved measuring the leakage area and flow exponent of ten houses every month for a year. The data collected throughout FY 85 was compiled and analyzed to show the seasonal effects on leakage.[14] The monthly average leakage area for all of the houses is plotted in Fig. 6. While not all the houses showed seasonal variation, the Truckee houses had effective leakage areas up to 35% higher in the summer as compared to those measured in midwinter.

The measurement technique work in FY 85 was focused in two areas, multizone leakage measurement, and AC pressurization research. The multizone leakage measurements were made in a seven-unit apartment building in Minneapolis, Minnesota.

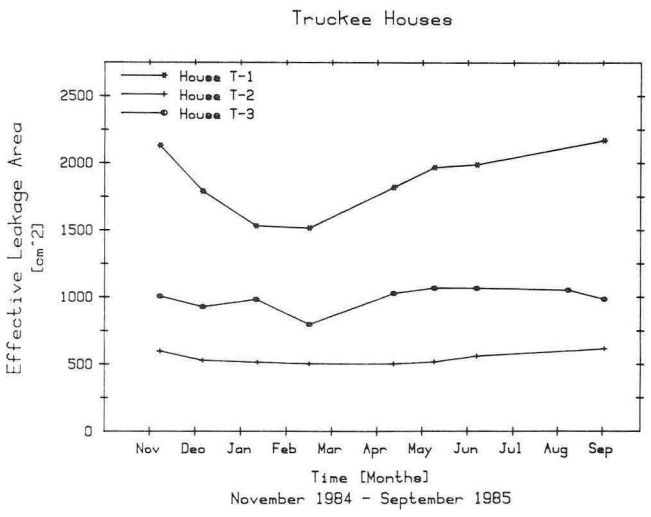

Figure 6. Seasonal leakage variation in three California houses. (XBL 8512-5237)

The measurement technique involved using six blower doors to pressurize the entire building to determine the total external leakage (see Fig. 7), as well as individual blower door tests to distinguish the leakage areas of different flow paths. The latter tests were made by testing individual apartments with and without simultaneous pressurization of adjacent apartments. These tests showed that only 40% of the leakage area of an individual apartment is in its exterior envelope, the majority of the leakage being to other apartments (see Fig. 8).

The major accomplishments for FY 85 in AC pressurization research were the design of a new field test prototype, and the filing of a patent application for the AC pressurization technique. The patent application, filed prior to the presentation of a technical paper describing AC pressurization, increased the probability that a commercial device will appear on the marketplace.

The new AC pressurization prototype is larger, sturdier and lighter than the first version (see Fig. 9). Because it displaces approximately 25% more volume it can provide our desired reference pressure

Figure 7. Air flow measurement in an apartment building in Minneapolis using six blower doors. (CBB 8512-10275)

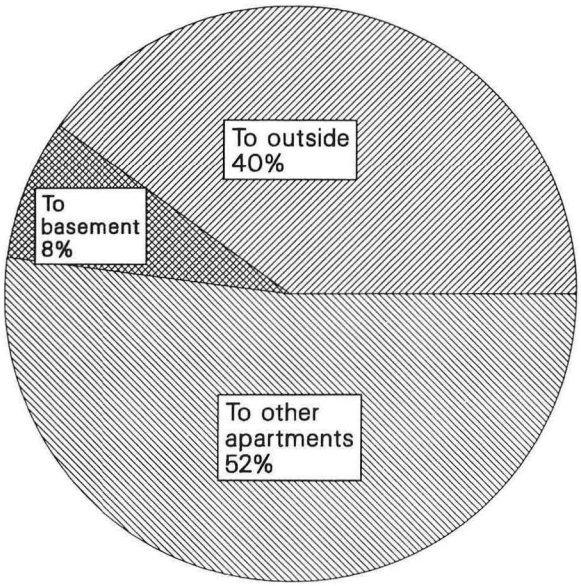

Figure 8. Leakage area of one apartment. (XCG 853-104)

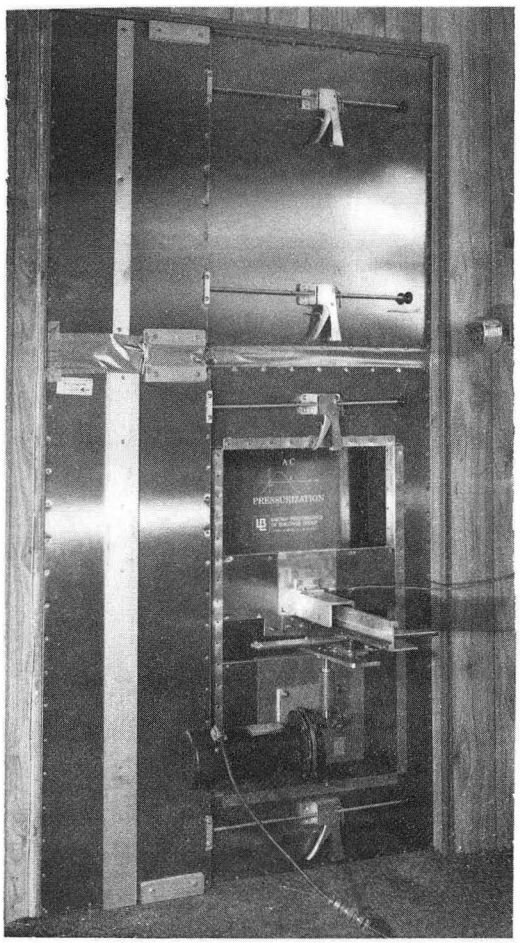

Figure 9. AC Pressurization. (CBB 862-997)

of 4 Pa at lower frequencies; because of the materials used and the quality of construction it can be operated at higher frequencies. The new device can thus be used to measure leaks over a wider frequency range, allowing a more careful examination of the large-area and high-volume leak effects. The FY 84 tests showed conclusively that AC pressurization did not measure the leakage area of fireplace chimneys (i.e., high-volume leaks). Tests in several houses also showed that as the size of a window opening was increased, after some point the incremental increase in leakage area could not be measured (large-area effect).

The lighter weight of the new device results from the choice of aluminum honeycomb, which is both lighter and stronger than plywood, as the structural material. This is particularly important for the piston, as the size of the motor required, as well as magnitude of the forces throughout the entire assembly, depends on the weight of the piston.

As part of our work with professional committees and organizations, we were primarily involved with two standard-writing organizations: the American Society for Testing and Materials (ASTM) and the American Society of Heating Refrigeration and Air-conditioning Engineers (ASHRAE). We are also the U.S. contact for the International Energy Agency's Annex V, the Air Infiltration Centre. The Centre maintains an extensive bibliography and distributes information to a large international audience including researchers throughout the U.S.

The main activity in ASTM during FY 85 has been the modification of Standard Test Method E 779, "Determining Air Leakage Rate by Fan Pressurization" to include improvements 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. During FY 85 the task group responsible for the standard has forwarded the updated and revised version for approval; it is anticipated that the revisions will be formally approved by the society during FY 86.

In addition to measurement-related standards such as E779, we are working with ASHRAE on various energy-related standards. Specifically, we are heavily involved with standard project 119P, which is intended to promote energy conservation by setting maximum values for air leakage in detached, single-family, residential buildings. During FY 85 the standard project committee came to agreement on many of the substantial issues involved and produced an internal draft. Current thinking is that the standard will be climate-based, use effective leakage area divided by conditioned floor area as the quan-

tity of interest, and create a classification method for houses that is independent of the air tightness requirements.

Planned Activities for FY 1986

The leakage characterization work will continue and expand during FY 86. While continuing to collect measured leakage data, we will use our computerized database to: correlate leakage characteristics with other whole-house characteristics, examine the effects of climate on leakage, quantify the importance of duct leakage, and evaluate the effectiveness of various air leakage retrofits.

In the measurement area, further field tests will be made with the new prototype to examine the discrepancies between AC pressurization and DC pressurization. Because the size of leak that can be measured depends on the frequency at which the device operates, field and laboratory tests performed with the larger, lower-frequency prototype will better be able to quantify the effects of large leaks. The AC pressurization research in FY 86 will also include some theoretical research on periodic flows in cracks and orifices.

The standards work will also continue during FY 86. We expect that in FY 86 the revised ASTM E779 will become official and that the ASHRAE standard 119 will be available for public review. Other ASHRAE standards that are in the formation stage include one on calibration of fan pressurization units and one on methods of leak detection. The International Standards Organization (ISO) will begin the process of making an international fan pressurization standard in FY 86.

WASTE HEAT RECOVERY/INTEGRATED VENTILATION

The waste heat recovery/integrated ventilation project addresses the possibilities for energy management in single-family houses. As 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 systems becomes relatively more important, the need to improve the efficiency in these areas also increases in importance. For many years there has been ongoing research on hot water systems, household appliance efficiency, and ventilation systems; however, there has been very little effort expended in trying to incorporate the resulting energy flows into an overall energy management strategy.

Integrated ventilation strategies are an important part of most waste heat recovery strategies, as conditioning of ventilation air represents approximately one-third of the space conditioning load of single-family residences. This fraction becomes even larger as the level of envelope insulation increases. Our research has concentrated on comparisons of infiltration (the predominant type of ventilation in the U.S.) with two mechanical ventilation systems with heat recovery: 1) two balanced fans with an air-to-air heat exchanger, and 2) an exhaust fan with a heat pump used to provide space heating or domestic hot water (DHW).

Accomplishments During FY 1985

The efforts in FY 85 on waste heat integration focused on integrated ventilation strategies, particularly on exhaust ventilation using a heat pump for domestic hot water. The model used for comparing different ventilation strategies was expanded and improved, using sensitivity runs to determine the importance of the assumptions used in our earlier comparisons. The effects of seasonal variations in supply water temperature and hot water demand were examined, as were the effects of DHW tank temperature and thermal stratification on COP and total heat delivered. It was found that average demand and supply water temperature provided results within 2% of one-year simulations that take into account seasonal variations. This result implies that we can save considerable computation time and cost. On the other hand, tank stratification was found to have an important impact on the total heat supplied by the heat pump. In addition, a new effective ventilation model was incorporated into the program. The average effective ventilation rate computed with this model uses the capacity of the room to compute an average exposure for constant pollutant sources.

Another part of the research in FY 85 was to reexamine the technique presently used for computing the total ventilation that occurs when mechanical ventilation and natural infiltration interact. The present technique, which is to add natural ventilation and unbalanced mechanical ventilation flows in quadrature, was compared against a true flow-balance model. The quadrature technique was found to provide estimates of the total flow within 10% of the actual values computed with the flow-balance model.

Planned Activities for FY 1986

There are three major activities planned for FY 86. The first activity is to use our new code, which includes the effective ventilation, flow addition model, and a stratified hot water tank model, to compare the economics of alternate ventilation strategies for different regions of the country. This will differ from previous activities of this sort in that it will include more detailed specification of hardware (both new and existing). The second activity is to use field data, both new and existing, to determine the energy and indoor air quality implications of leaky duct systems. This will include examinations of pressures inside duct systems, leakage measurements, and analysis of data in the air leakage database on duct leakage. The third activity, which depends upon completion of the first, is to evaluate more sophisticated cooling strategies, such as two-stage evaporative cooling, that require simulation of additional hardware, and more careful analysis of ventilation moisture flows.

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Building Ventilation and Indoor Air Quality*

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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 Buildings Ventilation and Indoor Air Quality Program include characterization of the emission of various pollutant classes from their respective sources, study of the effectiveness of ventilation in removing pollutants from indoor atmospheres, and examination of 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 other organics, arising from a variety of building materials and consumer products. In addition, other groups study techniques for controlling airborne concentrations, develop devices for monitoring pollutants in buildings, and design or carry out field surveys of indoor air quality. Significant efforts are also devoted to assessment of the health effects of indoor pollutant exposures, and to the establishment of a numerical data base of pollutant concentration measurements in buildings.

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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 the individual groups 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.

COMBUSTION POLLUTANT EXPOSURES

The pollutant emission rates of several new unvented combustion heating appliances were tested in FY 1985.[1] In addition, a new effort was initiated in FY 1985 to develop the groundwork for a macromodel of indoor combustion pollutant concentrations.[2] Overall, the thrust of the combustion-related research is shifting from the quantification of pollutant emission rates from a wide variety of indoor combustion sources to the overall evaluation of indoor exposures to combustion pollutants in U.S. residences.

Accomplishments During FY 1985

Pollutant Emissions from Unvented Combustion Space Heaters

By the end of FY 1985 we had conducted pollutant emission rate tests for all major unvented combustion space heating devices available in the U.S.[1,3,4] These appliances were unvented radiant, convective, and two-stage kerosene heaters, unvented infrared and convective natural gas heaters, and unvented infrared and convective propane heaters.

With regard to natural gas and propane unvented gas space heaters (UVGSHs), the following conclusions were made. For both infrared and convective heaters, no significant differences in emissions rates were observed between heaters with different fuel types (propane or natural gas). Carbon monoxide, nitrogen oxide, and nitrogen dioxide emission rates from infrared UVGSHs are stable with time and reproducible to within a few percent. CO emission rates from convective heaters are not as stable or reproducible and changes in emission rates with time of 50% were observed. The primary difference between infrared and convective heaters is the low NO_x emissions for infrared heaters. NO_x and NO_2 emission rates for infrared heaters are lower than those of convective heaters by a factor of approxi-

mately 10 for NO_x and 3 for NO_2. Changes in inlet pressure did not significantly alter emission rates. A slight increase in CO emission rates with decreased fuel consumption rates was observed in one heater. Finally, tuning was a factor in the CO emissions of some convective heaters, but was not a factor for other tunable convective heaters.

The CO and NO_2 emission rate results of the gas-fired space heaters are compared with the emission rate results of three types of kerosene heaters in Fig. 1. Clearly the multi-stage (actually two-stage) kerosene heater is a much improved product with regard to CO and NO_2 emissions relative to the other space heating appliances.

Groundwork for Developing a Macromodel of Indoor Combustion Pollutant Exposures

A macromodel of indoor combustion pollutant concentrations or exposures in U.S. residences must use a version of the indoor air pollution mass-balance equation as an integral part of the macromodel. A simple steady-state form of the mass-balance equation follows:

$$C = \frac{PaC_o + S/V}{a + k} \qquad (1)$$

where:

- C = pollutant concentration (ppm or $\mu g/m^3$);
- P = fraction of the outdoor pollution that penetrates the building shell (dimensionless);
- a = air exchange rate in air changes per hour (h^{-1});
- C_o = outdoor pollutant concentration (ppm or $\mu g/m^3$);
- S = indoor pollutant source strength (cm^3 or $\mu g/h$);
- V = volume (m^3);
- k = net rate of removal process other than air exchange (h^{-1}).

Figure 2 schematically shows how many factors combine to yield modeled indoor air pollution concentrations for unvented or partially vented combustion appliances. Conceptually, Fig. 2 represents an expanded form of Eq. 1. Throughout the remainder of this section, additional factors that may help to describe or model indoor combustion pollutant levels and that could be included in more complex versions of Eq. 1 will be explored.

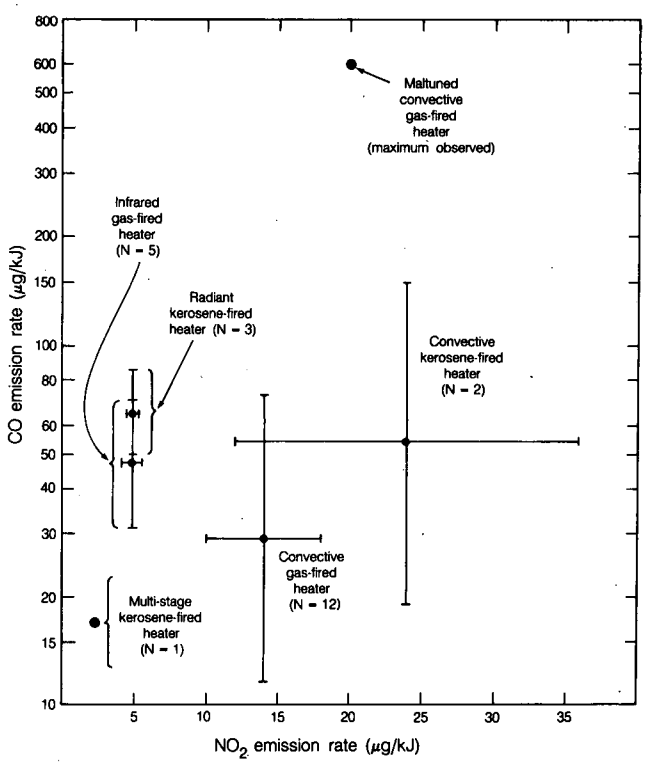


Figure 1. CO and NO_2 emission rates from well-tuned unvented gas-fired and kerosene-fired space heaters and the maximum observed for maltuned convective gas-fired space heaters. (XBL 851-9507)

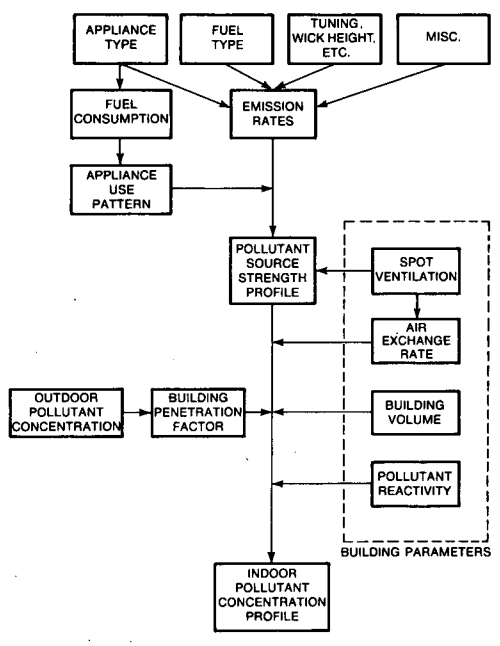


Figure 2. Schematic diagram of factors that affect indoor air pollution concentrations resulting from the use of an unvented or partially vented combustion appliance. (XBL 828-1054)

Many of the factors and quantities in Eq. 1 or Fig. 2 can be approximated by log-normal distributions.[4,5,6] Thus, it is useful to use the geometric standard deviation (GSD) as one measure of a parameter's relative importance in describing variations observed in indoor air pollution concentrations. In one regional study, the GSD's of combustion pollution source strengths (S) for kerosene-heater use and cigarette smoking were 2.9 and 3.1, respectively; the GSD of the outdoor pollutant concentration (C_o) was 1.7 for NO_2 and 1.8 for respirable suspended particles; the GSD for air exchange rates (a) was 1.8; the GSD of the house volumes (V) was 1.4; and the GSD for NO_2 reactivity (k) using an indirect measurement method was 2.4.[7] Therefore, the single largest factor influencing indoor combustion pollutant concentrations is the pollutant source strength. For NO_2, the indoor reactivity can also play a significant role in determining indoor air pollution concentrations. Outdoor pollutant concentrations were not useful in describing indoor concentrations in houses with relatively high indoor pollutant levels because the S/V term in Eq. 1 was much greater than the PaC_o term for such houses. Source strengths and NO_2 reactivity rates have received very little explicit attention in field monitoring studies, especially with regards to modeling, and future research efforts must address these important factors.

There are a wide variety of indoor combustion-pollutant sources, as shown in Table 1. Combustion sources can be categorized as smoking sources (i.e., cigarettes, cigars, and pipes) or combustion appliances. Combustion appliances can further be divided into three categories: unvented (e.g., portable kerosene heaters), partially vented, (e.g., gas ranges with range hoods), and vented (e.g., forced-air furnaces). A vented appliance is one that has a flue physically connected to the appliance that, under normal operating conditions, removes all, or almost all, of the pollution generated by the appliance.

An alternate and potentially useful way of categorizing combustion sources is by the force that drives the source usage. The use pattern of most of the sources listed on Table 1 is driven by the space heating requirements of the house, which do not affect other source use patterns, such as smoking and gas range use patterns. The usefulness of this type of categorization will be discussed later.

A very important factor that will affect macroassessments of population exposures to combustion pollutants is the market penetration of various sources. This critical parameter, although not discussed here, needs attention and the usefulness of existing surveys of market penetration conducted by utilities or other organizations needs exploring.

Table 1. Potential sources of indoor combustion pollutants.

Source	Type of Ventilation
1) Smoking (incl. pipes and cigars)	—
2) Unvented gas space heaters	Unvented
3) Portable kerosene space heaters	Unvented
4) Gas ranges without range hoods	Unvented
5) Gas ranges with range hoods	Mechanical ventilation
6) Wood stoves	Gravity flue
7) Coal stoves	Gravity flue
8) Forced-air furnace systems (gas, wood, coal, oil, etc.)	Gravity flue
9) Indoor gas water heaters	Gravity flue
10) Gas wall heaters	Gravity flue
11) Gas dryers	Gravity flue

Of all of the parameters in Eq. 1, the source strength is understood the least for U.S. houses. Modeling source strengths and extending the results to a variety of houses is not easy. Combustion source strengths depend upon a wide variety of factors. For example, the pollutant source strengths from unvented combustion appliances depend upon the appliance type, appliance use pattern, fuel type (including sulfur content), state of tune (or wick height for kerosene heaters), and other factors (see Fig. 2).

Of all the factors that significantly affect the strength of a combustion-related source, the least understood is the appliance use pattern and the force that drives the use pattern. Clearly, different sources or types of sources have different driving forces that affect their use pattern. Many use patterns are dependent upon the heating requirements of the house, others on the numbers of smokers, and others on the lifestyle of the occupants. Table 2 lists potential factors that can drive source usage. In Table 2, the source-driving factors fall into two gen-

Table 2. Potential factors for modeling combustion pollutant source strengths.

Factors Related to Space-Heating Sources (e.g., kerosene heaters, wood stoves, etc.)
— Meteorology (Indoor/Outdoor Temperature Differences)
— Insulation Level
— Volume
— Air Exchange Rate
— Other Sources of Heat
— Socio-Economic Factors
— Occupant Activity
Factors Related to Non-Space-Heating Sources (e.g., cigarettes, cooking stoves)
— Number of Occupants
— Home Volume
— Number of Smoking Occupants
— Socio-Economic Factors
— Occupant Activity

eral categories: those related to the heating requirements of the house, such as the house insulation level, and those not related to the heating requirements of the house, such as the number of smokers in the house. Source usage can also be influenced by socio-economic and other lifestyle factors. The development and validation of source usage models with inputs such as the outdoor temperature and house insulation level would greatly advance the current understanding of this subject.

It is neither feasible nor desirable to have models that account for all of the variation observed in indoor pollutant concentrations between houses. However, a model that is based on easily accessible data can be very useful for modeling exposures and for extrapolating results to larger populations. With the recent emphasis on energy conservation, large data bases are being created that contain house insulation levels and air exchange rates. Meteorological data, important to most existing air-exchange-rate models, are also widely available to assist in the modeling of space-heating appliance pollutant source strengths. Other sources of data on national or regional housing characteristics may also help in this effort.

There are many gaps in our knowledge of indoor combustion pollutant concentrations and the factors that affect them. With the development of a macromodel, information gaps can be identified and subsequent field studies can be designed to fill the gaps and test hypotheses that have been developed as part of the macromodel for indoor combustion pollutant exposures.

Planned Activities for FY 1986

The development of a macromodel for indoor combustion-pollutant exposure will continue in FY 1986. In addition, two studies started in FY 1985 will be completed. One study is aimed at quantifying organic emissions from kerosene space heaters. The other study is investigating the effectiveness of add-on catalytic devices for reducing pollutant emissions from kerosene space heaters.

ORGANIC CONTAMINANTS

The limited data on indoor/outdoor concentration ratios of volatile organic compounds (VOC) in residences, office and schools generally show that for many compounds, these ratios are greater than one and in many cases much greater than one.[8–11] These elevated ratios may result from the increased use of synthetic building materials, the introduction of new consumer products, and the development of construction practices which minimize ventilation. Considerably more data are needed on indoor concentrations and sources of VOC for even rudimentary assessments of population exposures and chronic health risks. Acute health problems, principally mucous membrane irritation, in some problem buildings have also been postulated to result from elevated indoor concentrations of VOC.

In FY 1985, our research efforts were directed toward (1) the fabrication of the air-handling system for an environmental chamber, (2) the characterization of methylene chloride emissions from consumer products including development of an exposure model, and (3) the validation of a multi-sorbent, thermally-desorbed sampler for VOC.

Accomplishments During FY 1985

Fabrication of the Environmental Chamber Air-Handling System

The design and construction of a 20-m^3 environmental chamber suitable for use in a wide variety of indoor air quality studies has already been described.[12] This past year we fabricated a more advanced air-handling system for the chamber. With the exception of the control system, the major components of the air-handling system for the chamber have been fabricated and installed in a loft adjacent to the chamber. In the order in which ventilation air passes through the single-pass system, the major components are: a variable speed blower; an air cleaning subsystem consisting of coarse filters, charcoal packs for scrubbing VOC, and HEPA filters; an

air-conditioning subsystem consisting of a pre-heater, a humidifier, chiller coils, and a final heater; and a volumetric flow monitoring system consisting of two turbine flowmeters mounted in parallel.

Standard components were used in the air-cleaning subsystem. However, to install the air-handling system in the limited space available and still create easy access for servicing, we had to design and fabricate housings and transitions for the components of both this subsystem and the air-conditioning subsystem.

The pre-heater and final heater, which are of our own designs, consist of two 3-kW and three 3-kW heating coils, respectively. The humidifier employs infrared heating of large pans of water coupled with dedicated mixing fans to insure uniformity of the humidification. The chiller coil has been installed in the air-handling system and a large chiller has been installed outside on the roof of the laboratory building. The chiller loop connecting the two components is not completed.

The volumetric flow rate of the ventilation air is monitored continuously by one of the two turbine flowmeters located just upstream of the chamber inlet. The smaller turbine flowmeter monitors ventilation rates from 0.5 to 3.0 air changes per hour with a precision of $\pm 3\%$; the larger flowmeter covers the range from 3.0 to 15 air changes per hour.

Methylene Chloride Emissions and Exposure from the Use of Consumer Products

A recently completed bioassay, which found methylene chloride (CH_2Cl_2) to be an animal carcinogen, has increased the concern about consumer exposure to this chemical.[13] To provide information on exposures sufficient to conduct a health risk assessment, CH_2Cl_2 source strengths and personal exposures were characterized in our 20-m^3 environmental chamber using typical applications of paint removers and aerosol finishes representative of the two major types of consumer products containing CH_2Cl_2. For each product, experiments were conducted at ventilation rates of ~0.5 and ~3 air changes per hour. Altogether, including duplicate experiments, a total of 10 experiments were performed.

Both the chamber concentration and the worker's breathing-zone concentration of CH_2Cl_2 were continuously monitored by infrared spectroscopy throughout each experiment. Figure 3 illustrates an experiment with a paint remover. In addition, the source strength of CH_2Cl_2 was determined from the product composition and the quantity of product used. Measured personal exposures resulting from the use of paint removers for work periods of ~90 min are listed in Table 3 and ranged from 1040 to 1200 ppm·h at the high ventilation rate and from 1970 to 2400 ppm·h at the low ventilation rate. Personal exposures from the use of aerosol finishes for work periods of 23 min or less ranged from 32 to 35 ppm·h for a single coat of a polyurethane finish and from 121 to 124 ppm·h for two coats of a metallic paint. Several occupational standards and guidelines for CH_2Cl_2 concentrations were exceeded during experiments with paint removers.

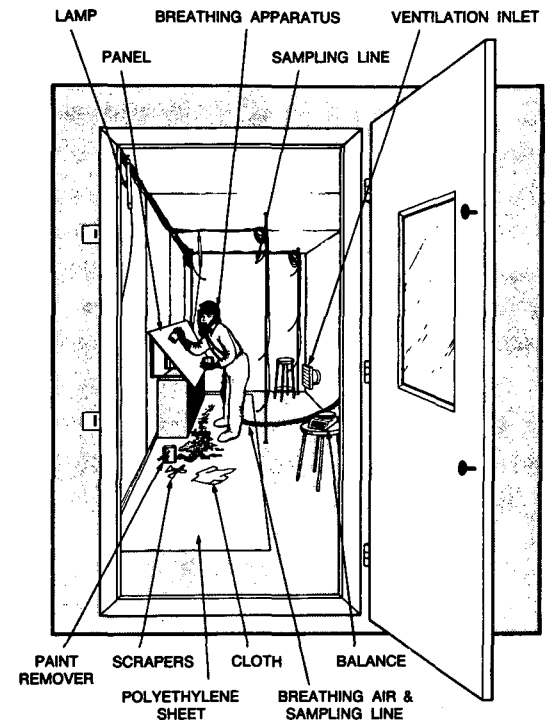


Figure 3. Lawrence Berkeley Laboratory's 20-m^3 environmental chamber setup for experiments with paint removers. For illustration, door with observation window is shown in open position and foreground sampling lines are omitted. Breathing-zone sampling line terminates at worker's right shoulder. (XBL 855-9537)

When chamber concentrations of CH_2Cl_2 were integrated over the work periods and compared to measured personal exposures, agreement was good at the low ventilation rate but differed by 21% at the high ventilation rate (Table 3). Temporal profiles of CH_2Cl_2 concentrations were calculated from the source strengths, the ventilation rates and the chamber volume using single-equation, mass-balance models. As illustrated in Figs. 4 and 5, these theoretical concentrations were in good agreement with measured concentrations. Exposure models based upon the concentration models were also developed and then evaluated by comparing theoreti-

Table 3. Measured personal and chamber exposures compared to theoretical exposures of CH_2Cl_2.

Product[a]	Exp.No.	Total Vent. Rate (h^{-1})	Work Period (min)	Mass used Product[b] (g)	Mass used CH_2Cl_2 (g)	Personal Exposure (ppm·h)	Chamber Exposure (ppm·h)	Theoretical Exposure[c] (ppm·h)
PR-A	1	3.19	90	316[d]	262[d]	1040	889	972
	5	0.62	86	325	270	1970	1970	1900
PR-B	2[e]	3.23	89	363	314	1120	921	1180
	3	3.20	91	389	337	1200	1010	1240
	4	0.63	88	385	333	2400	2350	2530
MP	6[e]	3.10	23	151	38.9	124	103	88.5
	7	3.12	21	161	41.6	121	103	85.7
	8	0.54	23	150	38.6	160	137	120
PF	10	3.11	10	72.8	19.6	31.6	23.9	31.2
	9	0.53	14	58.5	15.7	35.2	35.5	45.0

[a]PR = paint remover; MP = metallic paint; PF = polyurethane finish.
[b]Average density of paint removers was 1.18 g cm^{-3}.
[c]Calculated assuming a time-dependent source in a mass-balance model.
[d]Approximate value since some product was spilled during application.
[e]Duplicate experiments.

cal and measured exposures for the experiments. The exposure models appeared to have sufficient accuracy and precision for use in assessment of health risk from the use of consumer products containing CH_2Cl_2. A complete description of the study can be found in a recent report.[14]

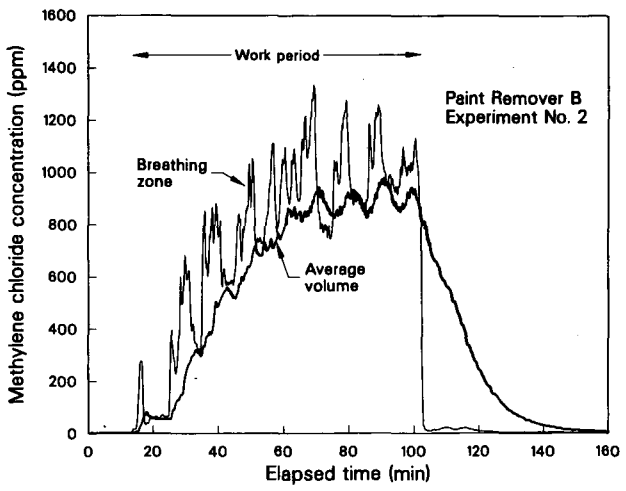


Figure 4. Temporal profiles of chamber and breathing-zone concentrations of CH_2Cl_2 during Experiment 2 with paint remover B at a ventilation rate of 3.23 air changes per hour. Duration of work period is shown above curves. At end of work period, breathing-zone sampling line was switched to laboratory air external to chamber. (XCG 861-7054)

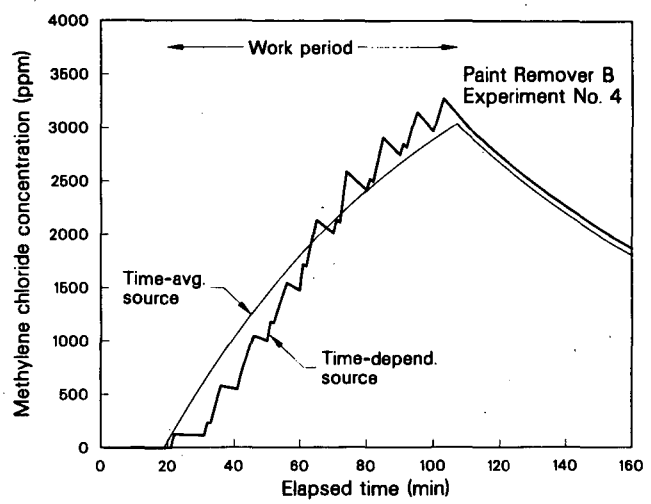


Figure 5. Temporal profiles of theoretical chamber concentration of CH_2Cl_2 for Experiment 2 with paint remover B at a ventilation rate of 3.23 air changes per hour. Concentrations were calculated using both time-dependent and time-averaged source strengths. Duration of work period is shown above curves. (XBG 861-7058)

Validation of a Multisorbent, Thermally Desorbed Sampler

Qualitative and quantitative methods for VOC which are rapid, reliable and relatively inexpensive are needed to survey a variety of buildings, to identify sources of potentially harmful compounds and to evaluate the efficacy of mitigation strategies. The present paucity of data on VOC concentrations can be largely attributed to the difficulty and expense of analysis for a wide range of VOC. Because most VOC occur at relatively low concentrations, a concentration step is generally required prior to chromatographic analysis, typically with a solid sorbent. However, no single sorbent is adequate for the wide range of VOC encountered.

An obvious solution for a generalized sampler for VOC is to use several complementary sorbent materials in series. One such sampler, containing glass beads, Tenax-TA, Ambersorb XE-340, and activated charcoal, is commercially available from Envirochem, Inc. for use in their sample concentrator/thermal desorption unit. We are evaluating this sampler, which was not previously validated for air sampling applications, and a modified version of it which omits the activated charcoal for the quantitative determination of a wide range of VOC simultaneously present in air at concentrations from a few nanograms to several micrograms per liter.

The solid sorbent sample concentrator/thermal desorption unit (Model 810A, Envirochem, Inc.) has been interfaced with a bench top capillary gas chromatograph/mass selective detector (Model 5970B, Hewlett Packard, Inc.). To achieve satisfactory chromatographic peak shape and separation for the lowest-boiling compounds, an on-column cryofocusing device which uses liquid nitrogen was developed for the oven of the gas chromatograph.

Optimal storage procedures for samplers have been determined. Upon complete thermal desorption, blank samplers are sealed with nylon caps with Teflon ferrules and placed in individual culture tubes with screw caps. These are then stored at $-10°C$. Air samplers are similarly stored prior to analysis.

A major component of the study is the determination of maximum sample volumes at standardized conditions for highly volatile compounds representative of a variety of chemical classes. The 20-m^3 environmental chamber has been employed for these experiments because it allows us to control experimental parameters while closely simulating real sampling situations. Triplicate samples have been collected at sample flowrates of $\sim 100\ cm^3\ min^{-1}$ regulated with electronic mass-flow controllers. The analytical precision and overall accuracy of the method is excellent as demonstrated in Table 4, which shows the results of analyses of chamber samples.

Breakthrough volumes have been determined for samplers containing Tenax and Ambersorb and compared to samplers containing Tenax alone. For this comparison, significant breakthrough has been defined as the loss of more than one percent of the mass of the compound entering the sampler. As shown in Table 4, the sampler with both Tenax and Ambersorb had significant breakthrough only for Freon-11. This is in contrast to the sampler with Tenax alone, for which case several compounds had breakthrough volumes of less than one liter.

Planned Activities for FY 1986

The control system for the environmental chamber will be completed and the performance of air-handling system will be evaluated. We will initiate a chamber study evaluating mitigation strategies for VOC emissions from realistic assemblies of building materials. The validation of the multisorbent sampling system will be completed by determining the effects of elevated humidity and competing compounds such as butane on breakthrough volumes. A field study to confirm the applicability of the exposure models developed for consumer products containing methylene chloride is underway and will examine the effects of variations in volume, ventilation patterns and rates and product use patterns.

CHARACTERIZING THE SOURCES OF RADON IN BUILDINGS

Radon and its immediate radioactive decay products are widespread contaminants in indoor air. The immediate parent of ^{222}Rn is ^{226}Ra, which is a ubiquitous constituent of crustal material, and is therefore present in soils and in building materials having rock- and soil-based components. The chemically inert radon gas, formed from the alpha decay of radium, can be transported through these materials by diffusive or convective flows and into the interior of homes.

While no national survey of indoor radon concentrations has been conducted, measurements from a variety of studies from around the United States indicate that indoor radon-222 concentrations in residences average $\sim 60\ Bq\ m^{-3}$ (1.6 pCi/L),† and

†The SI units for airborne concentration of radionuclides are $Bq\ m^{-3}$; the units in more common usage, until recently, have been pCi/L, where 1 pCi/L = 37 $Bq\ m^{-3}$.

Table 4. Measured and prepared concentrations of ten volatile organic compounds in a 20-m^3 environmental chamber are compared for a sampler containing Tenax-TA and Ambersorb XE-340. Breakthrough volumes for the same compounds with this sampler are also compared to those for a sampler containing only Tenax-TA.

Volatile Organic Compounds	Prepared Chamber Concentration (ng/L)	Measured Chamber Concentration[a] (ng/L)	Breakthrough Volume[b] Tenax-TA + Ambersorb XE-340 (L)	Tenax-TA (L)
Trichlorofluoromethane (Freon-11)	277	330±4	<4	<0.5
n-Pentane	229	223±6	>10	<0.5
Methylene Chloride	240	228±5	8–10	<0.5
n-Hexane	238	246±8	>10	1–2
2-Butanone	218	218±7	>10	1–2
Chloroform	265	257±8	>10	1–2
Ethyl Acetate	241	246±6	>10	>4
1,1,1,-Trichloroethane	245	255±3	>10	<0.5
Benzene	239	256±8	>10	2–4
Pentanal	220	194±6	>10	0.5–1

[a]Average of three replicate samples ± standard deviation of measurement.

[b]Breakthrough is defined as the loss of more than one percent of the mass of the compound entering the sampler.

concentrations above 6000 Bq m^{-3} have been observed in some homes. Based on the distribution of these radon concentration data, the number of homes with indoor concentrations averaging above 300 Bq m^{-3} can be estimated to be 1 to 2% of the U.S. housing stock—approximately one to two million single-family dwellings. These data also show a geographical variation in indoor radon concentration, apparently due to regional differences in radon source strengths. The available dose-response data suggest that even average radon concentrations may produce several thousand cases of lung cancer per year in the U.S.[15]

The goals of the LBL radon research effort are to 1) provide a method of predicting or identifying those geographical areas where houses with high indoor radon concentrations might be found; 2) improve our understanding of the mechanisms for the production and transport of radon through soils and into buildings; and 3) develop or identify means of controlling high indoor radon concentrations. Studies on the behavior of the radon decay products—radon progeny—are described in the following section, **Particles and Radon Progeny**.

Accomplishments During FY 1985

There are five potential sources of radon: the soil surrounding the building, outdoor air, building materials, potable water, and natural gas. Of these, the first two are often the most significant, based on a comparison of the range of expected source strengths with the frequency distribution of entry rates that have been observed in single-family residences. This is illustrated in Fig. 6, where the observed entry rate is the product of the indoor radon concentration, C_i, and the air exchange rate, λ_V.

The solid line in Fig. 6 summarizes time-averaged data from 73 homes in several cities in which C_i and λ_V were measured simultaneously. The dashed line represents the entry rate distribution derived from the observed distribution of indoor radon concentrations and the distribution of measured air exchange rates from 578 houses. With the exception of the unattenuated soil flux, the strength of the other sources illustrated in Fig. 6 contribute only to the lower end of the entry rate distribution.[16] The importance of water as a potential source of

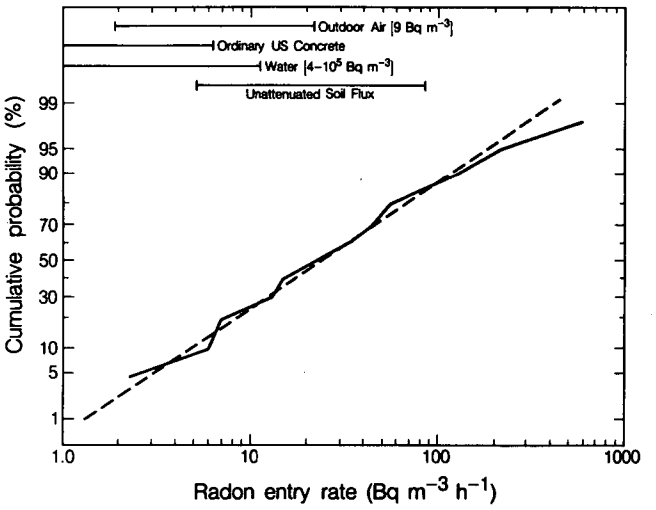


Figure 6. Cumulative frequency distribution for radon entry rates and a comparison with the range of source strengths from various radon sources. The range of source strengths at the top of the figure is based on an assumed single-story house with a 100 m^2 floor area, 2.4 m ceiling height, and 0.2 m thick concrete slab floor. References for data on these sources of indoor radon are given in Ref. 16. (XBL 858-9875)

indoor airborne radon varies with the source of the water. In some cases, high concentrations of radon dissolved in groundwater have been reported, and the resulting contributions to indoor air radon levels may be significant. A review of radon from potable water[5] was summarized in the FY 1984 Annual Report.[12]

The diffusive flux of radon from uncovered soil is, potentially, a significant source of radon, although a soil covering, such as a concrete slab floor, will substantially attenuate the radon flux from soil. On the other hand, it appears that convective flow of radon into building interiors may account for high radon entry rates. Bulk flow of gas from the soil into the building shell may occur through cracks or other openings in the building substructure driven by the slight negative pressure difference between the inside and outside of the building. Thus the nature of both the building substructure and the surrounding soil are important variables helping to determine the radon entry rates.

Factors Influencing Soil as a Source of Indoor Radon

In order to understand the influence of soil on indoor radon concentrations, a significant portion of our radon research effort has focussed on a) a review of important soil characteristics having a role in radon emanation, migration through soil and transport into buildings, b) the development of a framework for a geographically-based predictive capability, and c) an examination of relevant data and data sources for assessing the geographic variations in radon source strength.[17] The key elements in the production and migration of radon in soil and into buildings are shown schematically in Fig. 7. Two principal concepts are illustrated, radon availability, which is the amount of radon available for movement in the soil, and radon transport, which is the movement of radon through soil and into the building.

Important physical characteristics of soils include the size distributions of the soil grains and of the pores, and the soil moisture contents. The physical characteristics of representative soils are shown in Table 5. The grain size distribution is used to classify soil into three components, clay, silt or sand. The relative proportions of these components determine the basic soil texture, and therefore influence the fluid flow properties of soils. The void fraction of a soil is known as the porosity; these voids may be either air- or water-filled. The moisture content of soils also has an important influence on both radon emanation and migration. A well-drained soil often contains water in the smaller pore spaces and air in the larger pores. The presence of this capillary water increases the radon emanation fraction by absorbing the energy of the recoiling radon atom, formed in the alpha decay of its radium parent. Since most of the convective movement of air

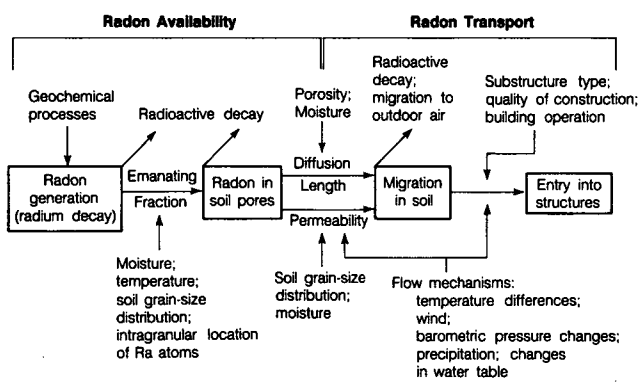


Figure 7. Schematic representation of radon production and migration in soil and its entry into buildings. The boxes illustrate the major states of radon in soil; the labels on the horizontal arrows connecting the boxes indicate a characteristic of the particular transition; parameters and processes that affect the rate of transition from one state to another are illustrated by the vertical arrows; and, finally, the diagonal arrows show the loss mechanisms for radon in soil. (XBL 8510-11933)

Table 5. Representative values of physical characteristics of soils.[a]

Texture class	Grain Size (μm)	Soil bulk density (g cm^{-3})	Porosity	Field Capacity Saturation[b] (%)
Sand	50–2000	1.44–1.58	0.40–0.46	15–20
Sandy loam		1.18–1.64	0.38–0.55	20–30
Loam		1.27–1.49	0.44–0.52	30–45
Silt	2–50		0.5	58
Silt loam		0.98–1.45	0.45–0.63	30–50
Clay loam		1.27–1.54	0.42–0.52	45–60
Silty clay loam		1.27–1.49	0.44–0.52	45–60
Silty clay				55–90
Clay	<2	1.18–1.54	0.42–0.56	55–90

[a]See Reference 17.

[b]Field capacity is defined as the fraction of the total pore volume that is filled with water after a soil has been throughly wetted and then drained for approximately two days.

through the soil occurs through the larger soil pores, the presence of this water does not increase the resistance to air flow. Thus, radon availability in soil appears to be greatest for moist soils.

Air permeability is one of the more important physical characteristics of soils that influences radon production and movement. In its simplest form, permeability is the relationship between the velocity of fluid flow through the medium and the applied pressure gradient, i.e., Darcy's law. Again, the moisture content of the soil influences the air permeability of the soil. This is illustrated by Fig. 8, where the value of the air permeability remains constant until water fills just over 40 percent of the pore space. As water content increases beyond this fraction, air permeability decreases dramatically.

The importance of soil permeability in understanding the sources of indoor radon arises from the range of permeability values for common soils, which can span over 10 orders of magnitude. At the upper end of this range, usually associated with large-grained soils, convective flow is the dominant transport process, and the potential radon entry rate into buildings increases correspondingly. At the

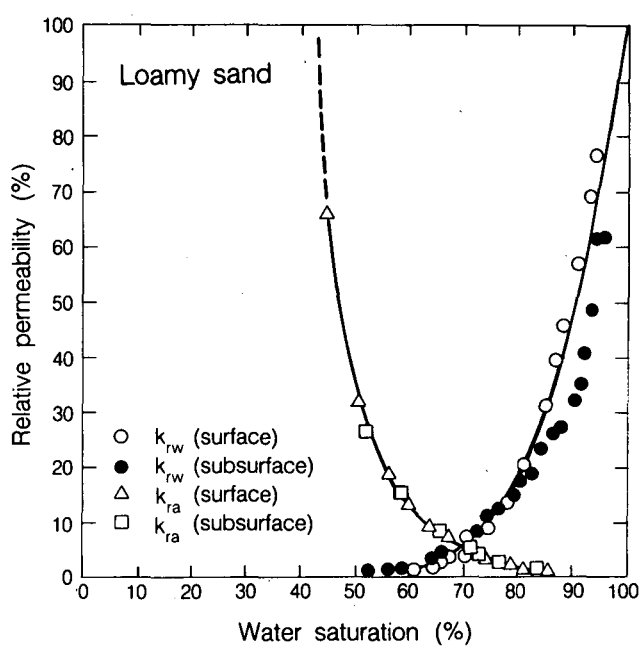


Figure 8. Relative permeability of loamy sand for air (k_{ra}) and water (k_{rw}) as a function of soil water saturation (from Ref. 18.). (XBL 8511-9030)

lower end of the permeability range, often associated with clayed soils, molecular diffusion is the more important radon transport process. Mathematically, a general transport equation for convective and diffusive flow for radon in soil can be derived, assuming the soil is isotropic:

$$\frac{\partial I_{Rn}}{\partial t} = D_e \nabla^2 I_{Rn}$$

$$+ \frac{k}{\epsilon \mu} \vec{\nabla} P \cdot \vec{\nabla} I_{Rn} + G - \lambda_{Rn} I_{Rn} \quad , \qquad (1)$$

where I_{Rn} is the activity concentration of radon in the soil pores, D_e is the effective diffusion coefficient, k is the intrinsic soil permeability, ϵ is the soil porosity, μ is the dynamic fluid viscosity, ∇P is the pressure gradient, G is the radon generation rate in the soil pores, and λ_{Rn} is the radon decay constant. The first term in this equation is transport due to diffusion, while the second describes convective flow.

In its most general form, this equation cannot be solved analytically. However, dimensionless analysis of this equation provides some very useful insights, as well as possible simplifications for its solution. Converting this equation into dimensionless form (see Ref. 17 for details) and choosing some typical values for pressure, porosity, viscosity and diffusivity, the intrinsic permeability then determines the relative importance of diffusion and convective transport. Thus in coarse textured soils, such as sands and gravels, the first term in equation 1 can be neglected, and convective flow dominates. In fine soils, with much smaller permeabilities, the second term can be neglected and diffusive transport is more important.

When the insights provided by analysis of the transport equations are combined with what is known about soil characteristics and the role of buildings in developing the driving forces for radon movement, a general predictive framework emerges. The utility of this approach in determining which geographic areas have potentially elevated indoor radon concentrations will depend upon the availability of data on soil characteristics. As noted earlier, some of the important soils data include air permeability of soils, radium content, soil moisture, and climatological factors. The availability of geographical data and/or indicator variables has been reviewed. Although air permeability has not been measured or estimated for most soils, two approaches may provide reasonable estimates. Water permeabilities of soils have been measured, and if a reasonable correlation between air and water permeabilities can be shown for a range of permeability values, then the extensive water permeability data for soils compiled by the Soil Conservation Service (SCS) may be extremely useful for geographically-based radon source strength assessments. Air permeability is also a function of soil texture and structure; data on both these parameters have also been compiled by the SCS.

As noted earlier, the radium content of the soil is another potentially important parameter in estimating the radon source potential of soils. Data covering most of the U.S. exist for shallow radium concentrations. These data were acquired by the National Airborne Radiometric Reconnaissance (NARR) survey, which employed aerial γ-spectrometry to measure concentrations of ^{40}K, ^{214}Bi (a radon-222 decay product) and ^{208}Tl (a radon-220 decay product) in the near-surface soil. The data tapes containing the complete data set have been processed at LBL, and the data gridded to approximately a one mile spacing along each flight line. From these average data several types of maps can be produced. One such map, a three-dimensional surface plot of shallow radium concentrations for a 1° by 2° quadrangle area, based on a least-squares approximation to the data, is illustrated in Fig. 9. Analysis of these data is also being used as part of a project to assess possible correlations between lung cancer data and surficial radium concentration (as a proxy for indoor radon concentration). See the section on **Risk Assessment** below.

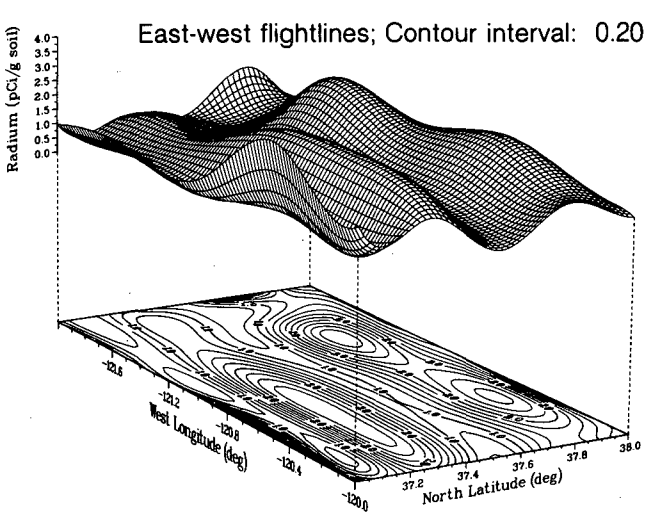


Figure 9. Surface mesh plot of values for radium concentration in the soil surface for the San Jose Quadrangle (1° latitude by 2° longitude). Data are from the NARR aerial radiometric survey. (XBL 862-494)

Planned Activities for FY 1986

Having developed a general framework for assessing the radon source potential based on geographic variables, future work will be directed toward 1) assessment of additional data bases, and 2) initiating experiments to verify some of the critical relationships, including the multiple role of soil moisture on radon availability. In addition, experimental work will focus on further examination of the coupling between the building substructure and the surrounding soil, and an evaluation of the correspondence between air and water permeabilities in soils of various textures. Finally, work will begin on the development of numerical models for radon movement in soil, based on the general transport equation discussed earlier.

PARTICLES AND RADON PROGENY

Particles are important indoor pollutants, with a number of indoor sources ranging from combustion processes to consumer product sprays. The physical and chemical composition of particles can be used to help identify the particle source. Because particles may themselves be toxic, or be carriers of adsorbed toxins, such as benzo(a)pyrene or radon progeny, their physical and chemical characteristics also help determine the health impacts associated with their inhalation.

Radon progeny, the radioactive decay products of radon, are also radioactive and are responsible for most of the health effects associated with radon. These airborne radionuclides interact with particles in the indoor air, and the specific alpha radiation dose to the lungs depends upon whether the radon progeny are attached or unattached to aerosols. Thus indoor particle concentrations are important determinants of radon progeny behavior.

Our present research efforts have focussed on 1) investigations to characterize the physical and chemical makeup of particles emitted by indoor sources, 2) further experiments to study the behavior of radon progeny under a variety of indoor environmental conditions, and 3) additional studies to model radon progeny behavior.

Accomplishments During FY 1985

Chemical and Physical Characteristics of Indoor Particles

In a previous collaboration with researchers at the California Department of Health Services, we began to investigate the chemical and physical nature of particles emitted from two sources, cigarette smoke and natural gas combustion. During the past year, this effort has been extended to several additional sources of particles, including cooking, an unvented kerosene heater, and several aerosol spray products.[19,20] One goal of this research has been to use the qualitative results to compare emissions from each source and to determine whether there are combinations of physical and chemical characteristics that can be used to identify individual particle sources uniquely.

Experiments were conducted in a 36-m^3 room within the Indoor Air Quality Research House for five of the six emission sources studied, including tobacco combustion, natural gas stove, cooking (frying hamburger), and two aerosol spray consumer products. Due to the high heat output of the sixth particle source, an unvented kerosene heater, experiments with this source were conducted in a 27-m^3 chamber which incorporated two copper solar collector panels to help absorb radiant energy from the heater. The chamber walls are uninsulated plasterboard, through which additional heat loss occurred, and the floor of this chamber is concrete, which provided an additional heat sink.

Individual sources were operated periodically for four to eight hours in order to provide the sampling quantities needed. Some of the mutagenicity experiments extended over two days to ensure that sufficient sample mass was available. A number of sampling procedures were used for both off-line and real-time measurements. The measurements, sampling procedures and analytic methods are summarized in Table 6. The real-time particle size analysis instrumentation, computer control and data logging have been described elsewhere.[21] In order to minimize infiltration of pollutants into the chambers due to the sampling flows, make-up air was supplied through a HEPA-filter and orifice-plate system at 230 to 300 L min^{-1}. Mixing fans mounted on the wall of the chambers with fan axes parallel to the walls were operated continuously to ensure that well-mixed conditions were maintained.

Tobacco smoke was generated using a cigarette smoking machine, modified to include an extinguishing mechanism. Emissions from natural gas combustion were produced by operating two burners of a cooking stove for 15 min. every half hour. Emissions from cooking were generated by frying 1.1 kg of hamburger in two cast-iron skillets for a 10 min. period, followed by a seven min. cooking period 3.5 hours later. Thus the total period of natural gas stove operation for cooking was a small fraction of that used to characterize emissions from the stove alone. The aerosol spray products, an

Table 6. Physical and chemical characterization measurements and methods.

Parameter Measured	Sampling Medium	Sampling Rate (L min^{-1})	Analytical Method
Airborne particle concentration	Continuous flow sampling	5	Condensation nucleus counter
Particle size distribution	Continuous flow sampling	5	Optical particle counter; Differential mobility analyzer
PAH composition of airborne particles	Teflon filter	8	High-pressure liquid chromatography
Elemental composition of airborne particles	Teflon filter	10	Energy dispersive X-ray spectrometry
Mutagenicity of airborne particles	Fiber glass	45	Modified Ames assay
Volatile organic compounds	Tenax tubes 50 mg per tube	0.5	gas chromatography/ mass spectrometry
Mutagenicity of gaseous compounds	Directly exposed *Salmonella* plates	0.5	Modified Ames assay

antiperspirant spray and a furniture dusting and polishing spray, were released remotely on a periodic basis until the spray cans were exhausted. Finally, emissions from the unvented kerosene heater were generated by a blue-flame, radiant model. This device was operated for four hour-on, hour-off cycles using a manual start-up, shut-down procedure, requiring entry into the chamber.

Real-time particle size distribution data are shown in Fig. 10 for each source. These measurements were made during or just after particle source operation. Figure 10a shows data for the experiment in which no source was operated but the chamber was operated normally, including supply of filtered air. The peak of the particle size distribution is ~0.2 μm, typical of outdoor particles that might have infiltrated into the chamber. Natural gas combustion, shown in Fig. 10b, produced large numbers of very small particles with diameters <0.01 μm. On the other hand, cooking hamburger produced significantly larger particles, as shown in Fig. 10c. Tobacco combustion resulted in the particle size distribution shown in Fig. 10d, with the peak near 0.15 μm. Particles from operation of the kerosene heater are peaked at very small sizes, ~0.02 μm (Fig. 10e), while the aerosol spray products yielded much larger particles with broad size distributions, as shown in Figs. 10f and 10g.

The results of the chemical and mutagenic tests are summarized in Table 7. The mutagenic analyses were done using a modified Ames test procedure. Particle samples were collected on filters, then extracted and tested using a microsuspension assay technique. In the case of particles, the *Salmonella typhimurium* strain TA98 was used, both with (w/ S9) and without (w/o S9) rat liver extract. A mutagenic response in the former case (w/ S9) indicates the presence of indirect-acting mutagens, whose metabolites are mutagenic, while in the later case (w/o S9), a mutagenic response represents the presence of direct-acting mutagens. In addition particle testing was also done using strain TA98NR, which is deficient in nitroreductase activity. Thus, a finding of mutagenic activity with TA98 but not TA98NR suggests the presence of nitroaromatic compounds. A complete discussion is provided in Ref. 20. Analysis of vapor phase mutagens was done by exposing the *Salmonella* plates directly to polluted air by drawing an airstream from the chamber and passing it through a dessicator-jar containing the plates. Strains TA98 and TA100 were used for these analyses. Particle phase mutagenicity results are shown in Fig. 11.

Since these experiments were conducted to provide sufficient amounts of sample, and not necessarily to replicate normal use patterns, the resulting

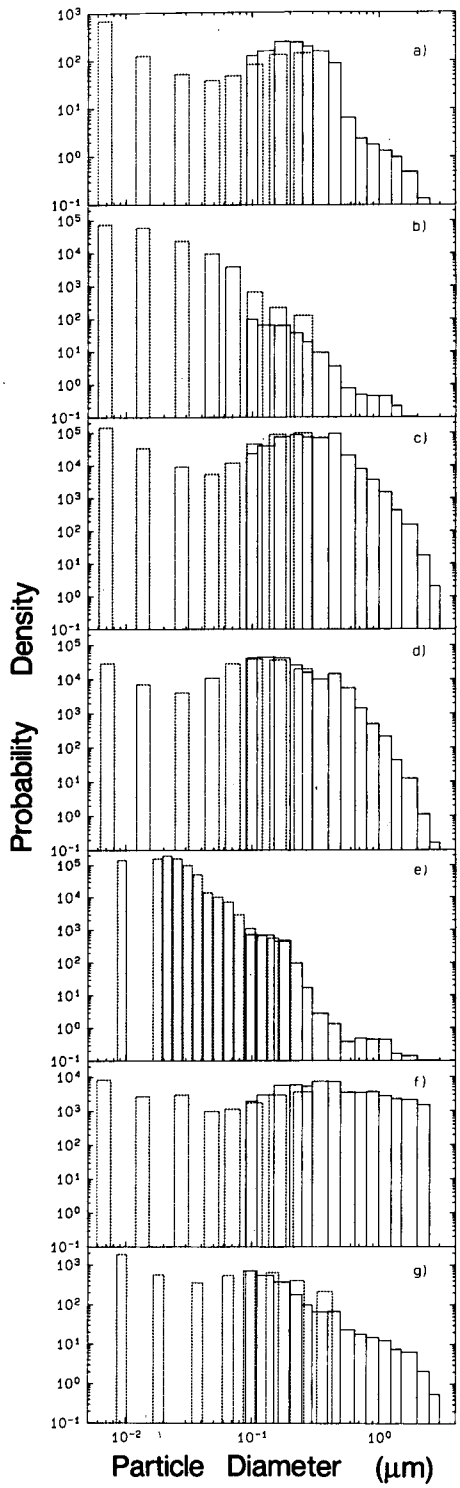


Figure 10. Particle size distribution data from the real-time measurement of particles from a) no source, b) natural-gas fired stove, c) frying hamburger, d) tobacco combustion, e) kerosene heater, f) antiperspirant aerosol spray, and f) dusting/polishing aerosol spray. (XBL 856-2716)

data aren't suitable for direct intercomparisons or for source strength determinations. Nevertheless, these data indicate that there are variations in the chemical and physical characteristics of particle emissions from different indoor sources that might provide unique source identifiers. It is also interesting to note that all the combustion sources tested contribute to mutagenicity, as measured by at least one of the modified Ames assays.

Radon Progeny Behavior and Air Circulation

The effects of air circulation on radon progeny concentrations under various initial particle concentrations have been investigated in a room-size chamber. In previous studies, air circulation alone produced only a small reduction in progeny concentrations in some experiments,[22] while in others larger reductions in airborne progeny concentrations have reported.[23]

The experiments were conducted in a 36-m^3 chamber at the Indoor Air Quality Research House. Real-time instrumentation was utilized to monitor particle concentration, particle size distributions, and airborne radon and radon progeny concentrations. Data logging and experimental control are provided by two dedicated computer systems. This instrumentation and control system are described elsewhere.[21,22] In addition to the airborne measurements, an array of CR-39 nuclear track detectors was placed on the walls, floor and ceiling of the test space in order to measure the deposition of radon progeny with and without air circulation and under differing conditions of particle concentration. Track detectors were also placed on both sides of the fan blades of the fan used for air circulation in the room. The results of the airborne measurements are reported here.

The experiments were conducted at three particle concentrations. In the first experiment, particle concentrations were initially reduced to less than 10 particles cm^{-3} using a portable HEPA-filter system placed in the room. After turning the filter system off, radon gas was injected into the test space to give an initial radon concentration ~15000 Bq m^{-3}. Particle concentrations remained between 100 and 300 particles cm^{-3} during the course of the experiment. Initially the air circulation fan remained off for a five hour period, followed by a four-hour on period, and finally a five to six hour off period. The CR-39 detectors were replaced at the beginning of each time period. This protocol was used for all three experiments.

Table 7. Comparison of emission characteristics from several indoor sources.

Source	Elemental Composition	PAH[a]	Volatile Compounds[b]		Mutagenicity[c]
Gas stove	Si,S	—[d]	—	Particles:	TA98 (w/ and w/o S9) TA98NR (w/ and w/o S9)
				Vapors:	TA100 (w/ and w/o S9)
Frying hamburger	S,Cl	—	aldehydes, ketones, amines	Particles:	toxic to assay
				Vapors:	TA98 (w/ S9) TA100 (w/ and w/o S9)
Cigarette smoke	S,Cl,K	BKF, BAP, BGP,	alcohols, ketones halides	Particles:	TA98 (w/ and w/o S9) TA98NR (w/ and w/o S9)
				Vapors:	TA98 (w/ and w/o S9) TA100 (w/ and w/o S9)
Kerosene heater	Si,S,Cr	BKF, BAP	—	Particles:	TA98 (w/ and w/o S9) TA98NR (w/ and w/o S9)
				Vapors:	TA100 (w/ S9)
Antiperspirant spray	Mg, Al, Si, Cl	—	alcohols, ketones, aldehydes		nonmutagenic
Dusting/Polishing spray	—	—	alcohol ketones, halides		nonmutagenic

[a]Polycyclic aromatic hydrocarbons: BKF: benzo(k)fluoranthene, BAP: benzo(a)pyrene, BGP: benzo(ghi)perylene.

[b]Excluding C_2–C_{12} alkanes and aromatic compounds, which were present in all samples.

[c]For particles, mutagenic tests are considered to be positive if the number of revertants measured in the sample is greater than a factor of two larger than the spontaneous revertants on a control plate. For the vapor phase, the tests are considered to be positive if the revertants measured in the sample are more than a factor of two larger than the spontaneous revertants on the control plates, *and* if the revertants on the sample also exceed by a factor of two the number of revertants measured simultaneously in air outside the test chamber.

[d]None detected.

The second experiment was conducted at moderate particle concentrations, averaging between 9000 and 20000 particles cm^{-3}. In this case, the gas range in the chamber was used periodically to add particles to the chamber air to compensate for the slow decay in particle concentrations. For the third experiment, particle concentrations were maintained between ~80000 to above 100000 particles cm^{-3} using tobacco combustion in a manually-operated cigarette smoking machine.

The effects of air circulation on radon progeny concentrations were seen quite clearly for the low and medium particle concentration experiments, while for the experiment done with high particle concentration no effect with air circulation was observed. At lower particle concentrations, a larger portion of the radon progeny remain unattached, and thus have a higher diffusivity than progeny attached to particles in the chamber air. The deposition rates of the unattached species are therefore much higher, and when the forced circulation fan is operating, the deposition rates are enhanced. In the case of high particle concentrations, almost all the progeny are attached to particles, reducing their deposition rate and concomitantly, reducing the effect of air circulation.

Planned Activities for FY 1986

Investigations of radon progeny behavior under a number of indoor environmental conditions will continue. Methods for direct measurement of unattached progeny will be improved. The experimental data will be compared with existing theoretical predictions of radon progeny behavior indoors.

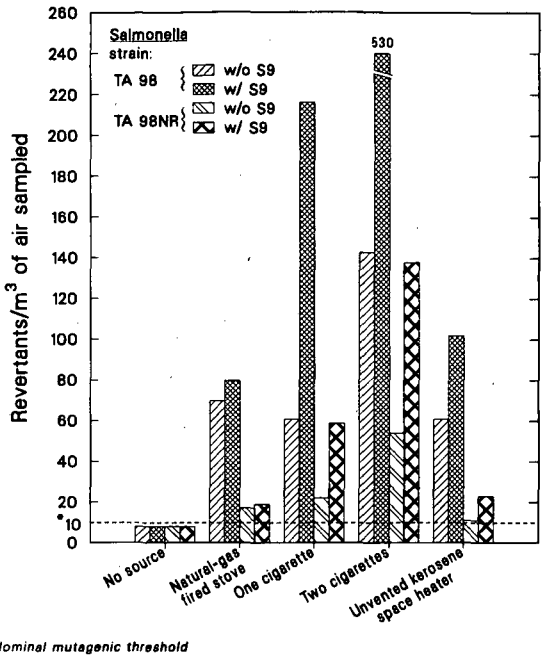


Figure 11. Particle-phase mutagenicity data from three indoor particle sources. The two aerosol sprays did not show any particle-phase mutagenicity and the particle extract from hamburger frying was toxic to the test bacteria; thus no mutagenicity assessment could be made. (XCG 855-266)

INDOOR AIR QUALITY CONTROL TECHNIQUES

Research on IAQ Control Techniques during FY 1985 focussed primarily on the following two topics: 1) multi-tracer measurement of ventilation rates, ages of air, and ventilation efficiencies in large mechanically-ventilated buildings, and 2) residential exhaust ventilation with heat-pump heat recovery. Our accomplishments during FY 1985 on these two topics and plans for FY 1986 are described below. In addition to these efforts, we collaborated with staff of the Radon and Field Survey Projects to plan investigations of radon mitigation techniques in twelve Pacific-Northwest houses. The results of these radon mitigation studies will be described in the FY 1986 Annual Report.

Accomplishments During FY 1985

Introduction: The efficiency of a ventilation process in removing indoor-generated pollutants and supplying or removing heat and moisture to and from a building, depends on numerous factors including: 1) the nominal air exchange rate; 2) the overall pattern of air flow between supply diffusers and exhaust registers; and 3) the spatial pattern (e.g., evenness) of outside air distribution throughout the building.

The nominal air exchange rate is simply the rate at which outside air enters the building divided by the indoor volume. A nominal time constant or turnover time can be computed by taking the inverse of the nominal air exchange rate.

The second factor, the overall airflow pattern, can, in theory, vary from one extreme, in which much of the air exiting the supply diffusers rapidly short circuits to the exhaust registers, to the other extreme, in which the flow between supply and exhaust approaches a piston-type displacement flow. Between these extremes is perfect mixing of the indoor air. In general, the efficiency of the ventilation process increases as short circuiting is reduced. The "nominal ventilation efficiency" is a performance parameter that characterizes the overall airflow pattern. The most unambiguous interpretation of this parameter is provided by an application of age distribution theory to ventilated buildings.[24] In this theory, the age of a parcel of air is the elapsed time since that parcel entered the building, and the nominal ventilation efficiency equals the turnover time (described above) divided by the mean age of all air parcels within the building. The nominal ventilation efficiency has a value of zero with complete short circuiting, a value of unity with complete mixing, and a theoretical upper limit of two for a perfect displacement flow.

The third factor, the spatial pattern of outside air distribution throughout the building, is indicated by the "local ventilation efficiency" which equals the turnover time, i.e., the age of all air within the building if the air were perfectly mixed, divided by the age of air at a specific point of interest. By comparing local ventilation efficiencies measured at different locations, the evenness of ventilation can be assessed.

Each of the performance parameters described above can be measured using transient tracer gas techniques. Two common transient techniques, the tracer decay and the tracer step up, are described in Refs. 24 and 25. Equations for analyzing the tracer gas data are also provided in these two references. The data analysis relies primarily on integrations of tracer gas concentrations, and the products of concentrations and time, with respect to time.

Experimental System

During FY 1985, we worked on development and checkout of a highly flexible experimental sys-

tem suitable for measuring ventilation rates, ages of air, and ventilation efficiencies in large buildings. This multi-tracer system will be used to study ventilation system performance and to assess the impacts of changes to ventilation systems. Some of these future studies will be conducted as part of more comprehensive investigations of ventilation and indoor air quality in large buildings.

The experimental system consists of six tracer gases and instrumentation for measuring tracer gas concentrations, stand-alone tracer gas injection systems, and stand-alone samplers. In buildings with six or fewer ventilation systems, the step up or constant injection rate technique[25] can be employed by injecting a different tracer gas into each ventilation system. The injection of each tracer gas will be controlled by a distinct stand-alone injection system placed in the building near the point of injection. The stand-alone samplers will also be placed at various locations within the building near to points where the time-history of tracer gas concentration is required. These samplers collect and store small air samples taken at different times during an experiment (e.g., every 15 minutes during a step up experiment). The concentration of each tracer gas in the samples can then be determined in the laboratory after completion of the experiment.

After preliminary experimentation with a number of potential tracers, a group of five halocarbons plus sulfur hexafluoride were selected. The chemical formula, chemical name, molecular weight, and boiling point of each tracer are provided in Table 8. In experiments, the peak concentrations of SF_6 and R-12B1 will be 200 ppb, and the peak concentration of the remaining tracers will be 1,000 ppb. Tracer gas concentrations are measured using a gas chromatograph with an electron capture detector and associated instrumentation.[25] Figure 12 shows a typical chromatogram and information for characterizing each peak.

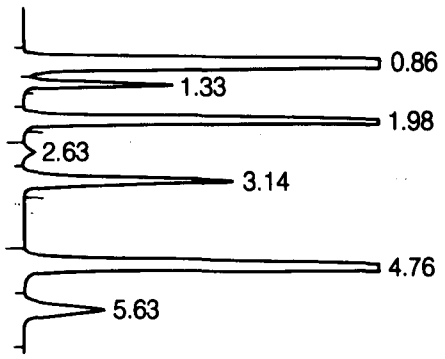
To meet sampling requirements, we are designing a programmable stand-alone sampler that will collect small air samples for analysis at a later time in the laboratory. A preliminary design for a highly-automated and flexible sampler is described in Ref. 25.

The final component of the experimental system is a simple, stand-alone tracer injection system that is well-suited for the step-up tracer technique. The major components are depicted in Fig. 13. Experiments indicate that this system injects tracer at a highly stable rate (i.e., 2% maximum variation in injection rate during an experiment).

Results of Tests of System Performances: Two tests of the system, excluding the sampler, have been completed. Figure 14 illustrates the local ages of air measured simultaneously with each tracer gas in the well-mixed test space of a research house using both a tracer step-up and a tracer decay. Ideally, the data from each tracer gas should yield the same local age of air; the step-up and decay should give the same result; and all the ages of air calculated from tracer

Table 8. Selected properties of gaseous tracers.

Refrigerant Number	Chemical Name	Chemical Formula	Molecular Weight	Boiling Point (°C)
—	Sulfur Hexafluoride	SF_6	146.1	−64
13B1	Bromotri-fluoromethane	$CBrF_3$	148.9	−58
115	Chloropenta-fluoroethane	$CClF_2CF_3$	154.5	−39
12	Dichlorodi-fluoromethane	CCl_2F_2	120.9	−30
12B1	Bromochlorodi-fluoromethane	$CBrClF_2$	165.4	−4
114	1,2-dichloro-tetrafluoro-ethane	$CClF_2CClF_2$	170.9	+4



Retention Time (min)	Area	Component	Conc. (ppb)
0.86	1.9700E+07	Air	—
1.33	529140	SF_6	5
1.98	3098700	R–13B1	50
2.63	74651	R–115	50
3.14	1426800	R–12	50
4.76	7478000	R–12B1	50
5.63	657790	R–114	50

Figure 12. Sample chromatogram and table of data for characterization of peaks. (XBL 8512-5131)

gas data should equal the reference measurement of age of air (i.e., the inverse of the nominal air exchange rate) made with an orifice plate flow meter. The test results indicate a maximum deviation between tracer gases of 14% and a maximum deviation from the reference measurement of 17%.

The second test of system performance was conducted in an office building served by a single ventilation system. Both local and nominal ages of air

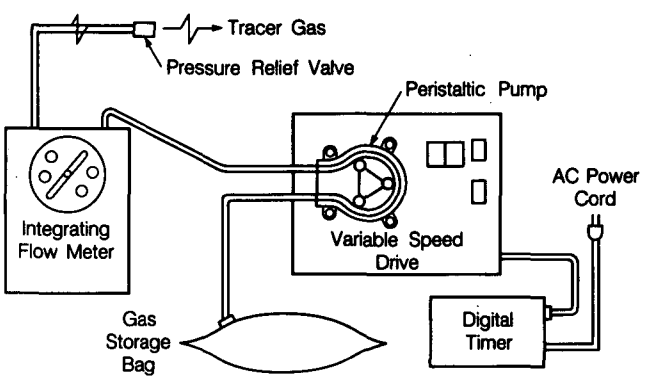


Figure 13. Schematic diagram of tracer gas injection system. (XBL 858-9898)

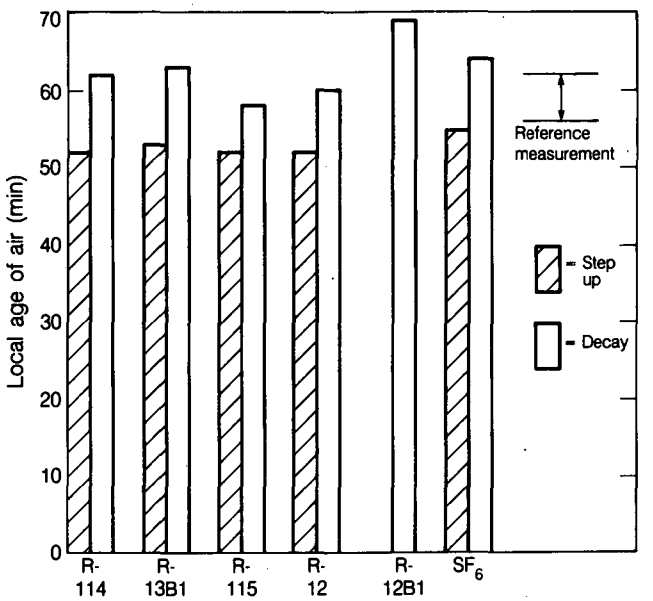


Figure 14. Local age of air based on tracer gas and reference measurements in the well-mixed test space of a research house. (XBL 8512-5130)

and ventilation efficiencies were computed from the data. The correspondence of the results from four of the tracer gases (R-13B1, R-115, R-12, and R-114) is quite good; however, the SF_6 and R-12B1 tracers yielded substantially different results especially for the mean age of air and nominal ventilation efficiency, which are difficult to measure accurately. We believe that the discrepancies with these two tracer gases may be due, in large part, to inaccuracy in our analysis of tracer gas concentrations and improved accuracy should be possible in the future.

Our FY 1985 efforts can be summarized as follows: 1) six tracer gases were selected and a suitable measurement technique was developed; 2) a stand-alone injection system was designed, fabricated, and tested (this system performs well); 3) a prototype stand-alone sampler was fabricated and tested (further evaluations are required); and 4) two tests of system performance (excluding the sampler) were completed with generally positive results.

Residential Exhaust Ventilation With Heat Recovery

Introduction: Controlled mechanical ventilation of residences is superior to uncontrolled ventilation from both indoor air quality and energy use perspectives. Controlled ventilation ensures a constant supply of fresh air to the building, permits convenient control of the ventilation rate, and allows air to be exhausted from areas with strong indoor pollutant sources. In addition, recovery of energy from the

exhaust air is possible when the ventilation is provided mechanically.

Balanced mechanical ventilation with heat recovery in an air-to-air heat exchanger is the only method available in the United States for providing controlled ventilation with heat recovery to residences. Another method that is being used in Europe is unbalanced, exhaust ventilation with heat recovery by a heat pump (see Fig. 15). With this latter type of ventilation system, air is exhausted mechanically from the residence but is not supplied mechanically. As a result, the building is depressurized slightly and outdoor air is drawn in through the building envelope. In a "leaky" building, the supply air enters the building through cracks and other incidental openings. In a tightly- sealed building, vent or slot systems are generally installed through the walls at appropriate locations to allow entry of the outdoor air.

Heat pumps designed to recover energy from an exhaust airstream are referred to as exhaust-air heat pumps. These heat pumps are ideally suited for heating the domestic hot water and can be used exclusively for this purpose. However, the amount of heat that can be extracted from the exhaust airstream by a heat pump is typically more than is required to meet hot water needs. Consequently, to maximize operation of the exhaust-air heat pump, a small fan coil can be utilized to supply heat to the indoor space from the hot water tank.

Packaged units for exhaust ventilation with heat recovery are available in Scandinavia. In addition, both a U.S. and Canadian manufacturer plan to market packaged units in the near future. Although this technique of ventilation with heat recovery appears promising, very few studies of system performance have been completed in Scandinavia and virtually no studies have been completed in the U.S. An examination of the suitability of this ventilation technology for U.S. housing is one of the efforts that was initiated in FY 1985.

FY 1985 Progress in Exhaust Ventilation Research: During FY 1985, we completed modifications to the existing computer model "TRNSYS" as required to simulate residential exhaust ventilation with heat recovery, and for purposes of comparison, to simulate balanced ventilation with air-to-air heat recovery and natural infiltration. The modified "TRNSYS" model simulates building loads, heating and cooling system operation, window opening, air infiltration and mechanical ventilation, hot water demands and storage, and operation of exhaust-air heat pumps, fan coils, and air-to-air heat exchangers.

An example of the results generated with the computer model is provided in Fig. 16, which shows the predicted total electricity usage in a highly-insulated, all-electric house located in Portland and ventilated by the different methods described above. The results indicate that exhaust ventilation with heat recovery is more energy efficient in this situation than natural ventilation or balanced ventilation with air-to-air heat recovery. The model also indicates that the ventilation rate is most stable in the case of exhaust ventilation.

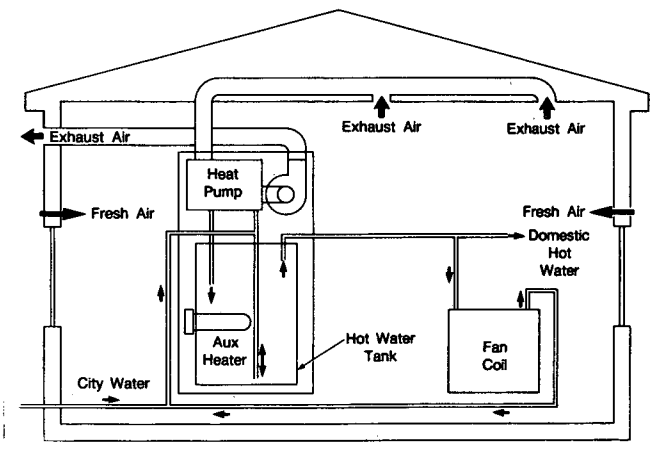


Figure 15. Schematic diagram of residential exhaust ventilation with heat pump heat recovery. (XBL 861-36)

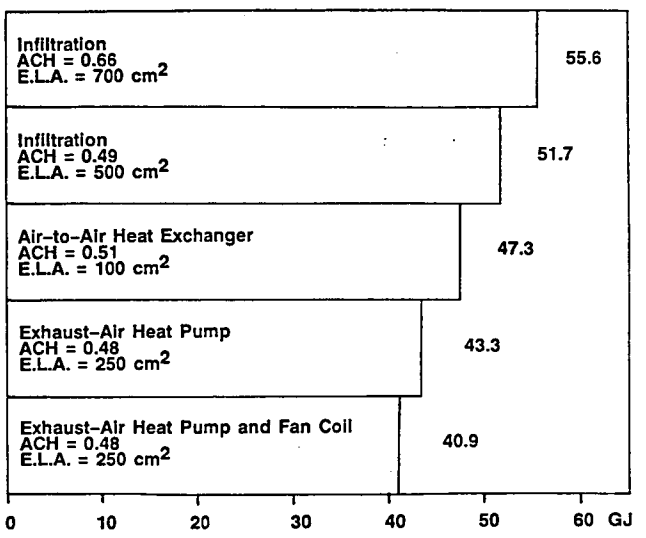


Figure 16. Predicted total electricity usage in a Portland-area, all-electric, 125 m^2 (1345 ft^2), highly insulated house (R38 ceiling, R28.5 walls, R31 floor) with four occupants and a total daily water demand of 300 kg (80 gal). The ACH value is an effective average air exchange rate for December 1 through February 28. E.L.A. = the effective leakage area of the building envelope. (XBL 861-37)

In addition to the computer modeling effort, during FY 1985 we initiated modifications to our experimental facility as required to study exhaust ventilation with heat recovery. Laboratory and field studies of this technology are required because of the highly limited amount of data on system performance that is available at the current time.

Planned Activities for FY 1986

Our research on the usage of multiple tracer gases to measure air exchange rates, ages of air, and ventilation efficiencies will continue during FY 1986. Major objectives are to complete development of the experimental system, to conduct additional tests as required to validate system performance, and to study ventilation in selected buildings.

Investigations of exhaust ventilation with heat recovery will also be continued in FY 1986. The output of the modified TRNSYS model and the results of a cost/benefit analysis will be documented in a publication. A numerical model will be developed and utilized to investigate the impact of exhaust ventilation on radon entry into residences. Finally, laboratory investigations of exhaust ventilation/heat recovery systems will be undertaken.

FIELD SURVEYS OF INDOOR AIR QUALITY

Three field studies examining indoor air quality funded by the Bonneville Power Administration (BPA) were in progress in FY 1985. The studies included (1) a comparison of new energy-efficient homes with new standard construction homes, (2) monitoring of existing single family dwellings undergoing weatherization to reduce energy consumption, and (3) a survey of 38 commercial and institutional buildings. All buildings were located in and around the Oregon cities of Portland and Salem; Spokane, Washington; and Coeur D'Alene, Idaho. Because of regulatory pressures from the Pacific Northwest Electric Power Planning Act, BPA instituted recommendations for energy conservation that have included methods for reducing the amount of outside air entering buildings. The studies examine whether concentrations of some indoor pollutants increase in response to the reduced ventilation and cause greater health-related risks.

Accomplishments During FY 1985

New Energy-Efficient Homes

Model Conservation Standards (MCS) for the construction of new energy-efficient houses include specifications calling for air infiltration packages leading to infiltration rates as low as 0.1 ach. These homes have air-to-air heat exchangers installed to raise the ventilation above 0.5 ach. Twenty-nine MCS homes were monitored along with 32 new homes, built according to standard construction practices, that served as controls. The goals of the study include comparing pollutant concentrations and installed ventilation rates in the two groups of houses along with an evaluation of pollutant source strengths.

Beginning in February, 1985 technicians visited each house to collect data on the structural characteristics, conduct a leakage area measurement with a blower door, and deploy passive pollutant and ventilation monitors. Passive samplers for formaldehyde (HCHO), water vapor (H_2O), and nitrogen dioxide (NO_2) were placed at two to five interior locations at each house and one outdoor location for a period of approximately seven days. These devices sample air by establishing a pollutant selective concentration gradient within a tube of known dimensions. The pollutant diffuses to and is collected on an adsorbent or chemically treated disc(s) at the capped end.[26–28] Upon analysis they provide a measure of the average pollutant concentrations in the sampled space during the period they were uncapped. Type SF Track-Etch passive radon (Rn) monitors were placed both with the other pollutant samplers and also in crawlspace and basement locations. The radon samplers were exposed for periods of approximately three months. Ventilation measurements were made with a passive perfluorocarbon tracer (PFT) injection and sampling system developed at Brookhaven National Laboratory to provide a time averaged ventilation rate during pollutant sampling.[29] Two sets were used: one for the seven day sampling period, the other for the longer radon sampling period. During the seven day period, occupants were asked to complete a daily log of house activities that would affect air quality.

Indoor water vapor concentrations were quite uniform in all houses regardless of the type of house

or the geographical region (see Table 9). Since outdoor concentrations were quite different between the regions, some other explanation such as similarity of indoor sources or buffering by house materials may account for the uniformity. Because of the small sample size, the observed differences in radon concentration between MCS and control homes are not statistically significant. Indoor radon concentrations generally are dominated by source variations rather than ventilation rate variations. As a result, the source strength differences overwhelm any differences in ventilation between the two groups of houses. The results for formaldehyde show an unusual regional variation, with all Spokane area homes having a geometric mean (median) of 60 ppb and all Portland area homes a geometric mean of 93 ppb. These differences are statistically significant at the 1% level. However, the concentration differences between MCS and control homes are *not* statistically different. The regional variations could be due to differences in local building materials or the amount of particle board and plywood used. Concentrations were above 100 ppb in 18 homes and above 200 ppb in three homes (the highest being 343 ppb). These levels exceed guidelines of 100 ppb promulgated by the EPA and ASHRAE 62-81 and may cause reactions in moderately sensitive individuals. Nitrogen dioxide was not a problem inside these homes since only one house contained a combustion heating appliance. Indoor levels were usually below those measured outdoors. The normalized leakage area, specific leakage area (SLA), shows that the MCS homes generally are tighter than the control group. Because of an extreme outlier in the Portland MCS group (14.99 cm^2m^{-2}), a nonparametric rank statistical test was used and determined that the differences in SLA between *all* groupings was significant at the 1% level. Once again a regional difference is obvious with the Spokane area homes being tighter than their Portland area counterparts. This is expected since

Table 9. New home data summary.

	Spokane			Portland			All Homes	
	MCS	Control	Total	MCS	Control	Total	MCS	Control
Number of Homes:	12	14	26	17	18	35	29	32
Radon ($pCiL^{-1}$):								
Mean	4.1	4.7	4.4	1.8	1.2	1.4	2.7	2.8
GM	1.9	3.5	2.6	1.3	1.0	1.1	1.5	1.7
GSD	3.8	2.2	3.0	2.2	2.2	2.1	2.8	2.8
Outside	—	—	0.5	—	—	0.5	—	—
Water Vapor (gkg^{-1}):								
Mean	6.29	6.39	6.34	6.81	6.80	6.80	6.59	6.62
SD	1.00	1.32	1.16	1.16	0.77	0.97	1.11	1.05
Outside	—	—	3.72	—	—	5.54	—	—
Nitrogen Dioxide (ppb):								
highest-indoor	—	—	7	—	—	7	7 (all)	
outdoor	—	—	22	—	—	19	22 (all)	
In ÷ Out (>10 ppb out)	—	—	0.22	—	—	0.24	0.23	0.24
Formaldehyde (ppb):								
Mean	64	65	65	120	98	109	97	84
GM	60	59	60	103	84	93	83	72
GSD	1.5	1.6	1.5	1.7	1.8	1.8	1.7	1.8
200 ppb> # > 100 ppb	0	1	1	7	7	14	7	8
# > 200 ppb	0	0	1	2	1	3	2	1
Specific Leakage Area (cm^2m^{-2}):								
Mean	1.26	3.13	2.26	3.60	4.81	4.22	2.63	4.08
SD	0.49	1.34	1.39	3.14	1.41	2.45	2.67	1.60

the Spokane area experiences an average 6835 heating degree days while Portland accumulates only 4792 heating degree days annually (65°F base). Therefore, in order to meet the MCS guidelines of a certain ventilation rate, homes in Spokane must be tighter. The tightness of the houses in this study can be compared with typical SLA values of four to ten for conventional housing in the United States. Note that the measured leakage areas do not account for the additional ventilation in the MCS homes supplied by the air-to-air heat exchangers. At this point the data indicate that pollutant levels are very similar in the MCS and control homes. This tends to support the hypothesis that while indoor air quality problems may be exacerbated by low ventilation rates, problems do not occur without a robust pollutant source. However, we are waiting on the analysis of the PFT ventilation samplers to complete the investigation of the effect of ventilation in indoor pollutant levels.

Existing Homes

From October 1984 through January 1985 one hundred existing homes built prior to 1980 were tested and screened for HCHO, H_2O, and Rn using mailed passive samplers (described above). Sixteen other homes were screened only for radon during a 30 minute visit by a technician using a continuous radon monitor. Forty eight of these homes with measurable levels of HCHO or Rn were then selected for more intensive monitoring to evaluate the effects of house tightening weatherization retrofits on the concentrations of these indoor air pollutants.

In the Phase I screening sample, 45 homes were located in the Spokane, WA–Coeur D'Alene, ID area and 71 homes were located north of Portland in Vancouver, WA. The use of mailed passive samplers was both effective and economical. Only three percent of all samplers were rendered useless; the total cost of monitoring each house was approximately $150. The majority of these homes had pollutant levels below most currently recommended guidelines and standards. Nitrogen dioxide concentrations averaged 6 ppb, and ranged from below detection (5 ppb) to 45 ppb, with approximately 98% below 16 ppb. Few homes had combustion appliances that would elevate these levels. Only one newly remodeled home had HCHO concentrations above 100 ppb (136 ppb), while 98% of the homes were below 80 ppb and the total group had a mean of 36 ppb. A plot of HCHO concentration vs. building age for all new and existing homes (Fig. 17) shows that levels tend to be lower in older homes.

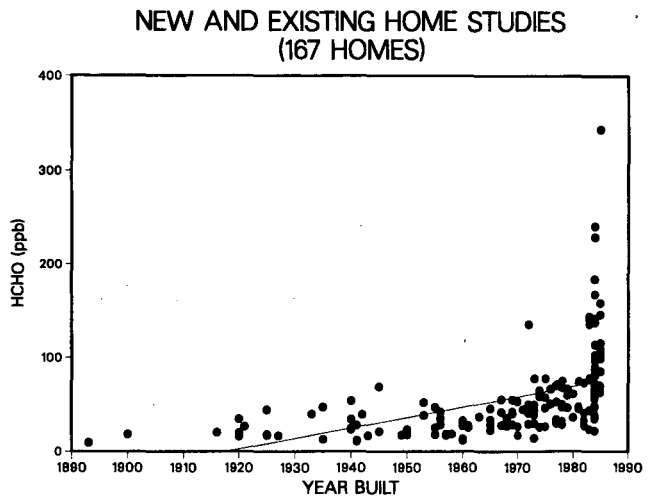


Figure 17. Indoor formaldehyde concentrations for 167 homes in the Pacific Northwest as a function of the age of the structures. Higher concentrations in newer homes could be due to a combination of greater use of UF-bonded wood products, higher outgassing rates for younger materials, and lower ventilation rates. (XBL 862-371)

Many factors could contribute to this: off-gassing of HCHO over time, less particle board and plywood in older buildings, and greater air leakage in older homes. The mean water vapor concentration was 6.15 gkg^{-1}, very similar to that measured in the new home study. Radon, however, appears to be a pollutant of concern in the Spokane River Valley area of Washington and Rathdrum Prairie of Idaho. While the average for a compilation of 552 U.S. residences is 1.6 $pCiL^{-1}$ and for 267 regional BPA employee homes is 1.4 $pCiL^{-1}$, the average heating season concentration for 46 new and existing homes in this area is 13.3 $pCiL^{-1}$.[15,30] Approximately 43% of these residences had concentrations above 8 $pCiL^{-1}$, the National Council on Radiation Protection and Measurements guideline. Concentrations were monitored in 14 of the 46 homes over the summer of 1985 using passive samplers and were observed to have declined by factors of up to 16 from heating season values. An examination of soils, domestic water supplies, and building materials strongly suggests that the high concentrations are due to the local subsurface soil composition and structure.

The more intensive monitoring of the 48 homes to be weatherized in Phase II began in December 1984. In each home, equipment was installed to monitor temperatures, windspeed and direction, and radon concentrations continuously. Passive monitors for pollutants and ventilation were also deployed along with instruments for making time-weighted average measurements of carbon monoxide

(CO) and respirable suspended particles (RSP). This equipment was operated for a 7–10 day period before and after each stage of weatherization, which could have included wall insulation and "house doctoring" along with caulking, weatherstripping and storm windows. Analysis of all data from this study continues and also waits on PFT ventilation rate measurements, so that effects of weatherization on infiltration and pollutant concentrations can be evaluated.

Figure 18 summarizes the preliminary findings of a separate four week controlled study of the interactive effects of air leakage reduction and conductive heat loss reduction on the pollutant levels generated by an unvented combustion heating source. Two identical units of a duplex in Oregon were used: one received staged weatherization of house-tightening followed by insulation, while the other was an unweatherized control. The figure shows the potential for reduced indoor air pollutant levels in homes with unvented combustion appliances resulting from increased R-values as a result of insulating during weatherization.

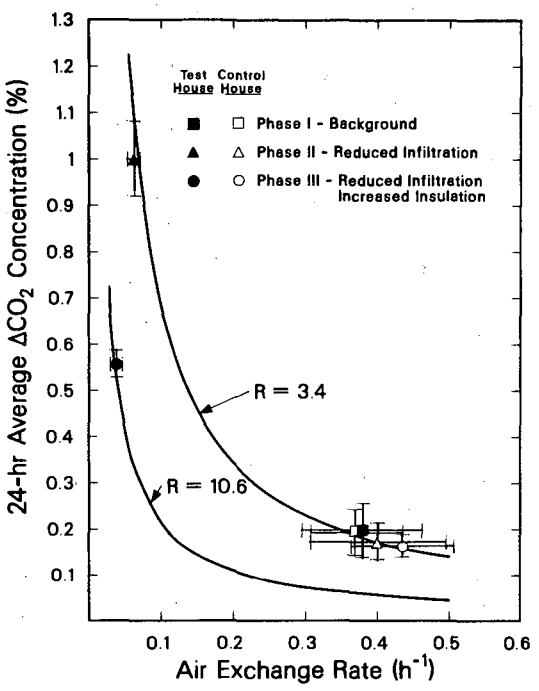


Figure 18. Effect of reduced infiltration house and reduced conductive losses resulting from house weatherization on indoor CO_2 concentrations in two dwellings with propane-fire space heaters. House tightening increases CO_2 concentrations while insulation retrofits reduces heating loads and therefore reduces CO_2 concentrations. (XCG 8411-13443)

Commercial and Institutional Buildings

A survey of 38 commercial and institutional buildings involved monitoring of ventilation rates and indoor air pollutant concentrations as detailed on Table 10. The objectives were to (1) inventory these parameters in non-residential, non-industrial facilities, (2) furnish data to assist in establishing energy conservation and ventilation guidelines and, (3) examine relationships between indoor air quality and ventilation rates. Field monitoring began in January, 1984 and continued into April, 1985. Two buildings were monitored twice for a total of 40 building assessments. Buildings ranged in age from 6 months to 90 years, in size from 9,300 to 369,000 sq. ft., and in occupancy from 25 to 2500 people. From 6 to 20 pollutant sampling sites were located in each building during the two week (10 working day) monitoring period. Sampling was started at the beginning of each working day and stopped at the end of occupancy for an accumulated minimum of 75 hours. Selected RSP filters were analyzed for up to 16 polycyclic aromatic hydrocarbons (PAH) including benzo(a)pyrene (BaP). Carbon dioxide (CO_2) was monitored at up to two locations for a one day period, while CO was sampled at up to seven locations for one 7–10 hour day. Twice daily observations of the ventilation system were recorded for use during a later tracer decay ventilation test. Data were also collected that describe building construction, materials, occupancy, smoking policies, and activities. Ventilation rates were measured in all buildings with a one time tracer dilution and decay test conducted over one 12-hour period during unoccupied hours. The ventilation systems were set up to mimic the conditions of the two week pollutant monitoring period, while a centrally located gas chromatograph with an electron capture detector monitored the decay of sulfur hexafluoride (SF_6) at up to nine building locations. The passive PFT system was also used to measure ventilation rates in 27 buildings. Samplers from this system were deployed along with the passive pollutant samplers for a three day period. Data from the analysis of these samplers are not yet available.

Table 11 presents a building average summary of all data collected. With the exception of RSP, most pollutant levels were quite low and often below the detection limits of our equipment. Formaldehyde reached the highest building average of 56 ppb in one six month old library. Individual site measurements ranged up to 75 ppb. Nitrogen dioxide averaged 18.1 ppb in all buildings and correlated most closely with outdoor concentrations whose source was primarily vehicular exhaust. Water vapor averaged 9.8 gkg^{-1} in one building, a level that could

Table 10. Air sampling instrumentation and analytical techniques.

Pollutant	Sampling Device	Analytical Techniques
HCHO	LBL Passive Diffusion Sampler	Spectrophotometric
H_2O	LBL Passive Diffusion Sampler	Gravimetric
Rn	Terradex Corp. Type SF Track Etch Sampler	Count number of alpha tracks on film, performed by Terradex Corp.
NO_2	Palmes' Passive Diffusion Sampler	Spectrophotometric
RSP	LBL Flow-Controlled Filtration Device with 3μ cut-point cyclone	Gravimetric
PAH	Same as RSP	HPLC, performed by McKesson Laboratory
CO_2	Horiba Model #APBA-210 CO_2 Detector	Non-dispersive Infrared Direct Reading
CO	LBL Constant-Flow Gas Collection Bag	General Electric Model 15EC53C01 Electrochemical Analyzer
Tracer	**Ventilation Measurement Device**	**Analytical Technique**
SF_6	Baseline Model 1030A Gas Chromatograph, Valco Electron Capture Detector Mod. 140B	Continuous Monitoring of Tracer Decay
Multiple	Source: Permeation Tubes	Brookhaven National Lab.
Perfluoro-carbons	Sampler: Passive Diffusion Adsorption Tubes	AIM System. Thermal Desorption and ECD/GC Analysis.

impair occupant comfort. Radon concentrations were elevated (7.8 $pCiL^{-1}$) in one building where air was drawn into the basement air handler through a three mile network of underground service tunnels. Otherwise, concentrations generally were low. Only six buildings averaged greater than the 2 ppm detection limit for CO. One individual site had an eight-hour average of 7 ppm, which is approaching the ASHRAE 62-1981 guideline of 9 ppm for a 10 hour average. At only one site, an elementary school classroom, did CO_2 exceed 1000 ppm (1300 ppm), while the average for all buildings was 499 ppm. RSP concentrations in smoking areas in 32 buildings had a geometric mean of 48 μgm^{-3} and ranged up to 308 μgm^{-3} at one site. In non-smoking areas, the geometric mean RSP was 16 μgm^{-3} and was lower than outdoor levels in 65% of the buildings. For comparison, the ASHRAE 62-1981 guideline is 75 μgm^{-3} for one year average exposure to total suspended particles (TSP). Both PAH and BaP were higher in smoking areas but were generally below a 2.2 ngm^{-3} average for BaP summarized from 121 United States ambient urban sites.[31] Building average ventilation rates ranged by a factor of 13 with a group average of 1.5 ach. Very poor correlation was noted between average building pollutant concentrations and measured outside air ventilation rates, implying that indoor air pollution in commercial buildings is dominated by factors other than ventilation (source strength, building volume, and other removal processes) (Fig. 19). Pollutant concentrations measured in two "problem" buildings with occupant complaints were below accepted guidelines. The cause of the complaints was not identified.

Table 11. Commercial and Institutional Building Summary.

	Mean	Standard Deviation	Range	Other/Comments
Building Use	—	—	—	6 schools 24 offices 3 libraries 5 multi-use
Age (yr)	23	—	0.5–90	—
Occupancy	526	—	25–2500	—
Height (stories)	5	—	underground-18	—
Area (ft^2)	94,250	—	9,300-369,000	—
No. HVAC Systems	5	—	0–32	—
HCHO (ppb)	below 36 ppb detection	—	BD-56	40[e]
$H_2O(gkg^{-1})$	6.6[a]	1.5	3.2–9.8	40[e]
NO_2 (ppb)	18.1[a]	8.4	BD (10)–43	33[e]
Rn ($pCiL^{-1}$)	0.8[b]	2.1	0.2–7.8	40[e]
CO (ppm)	below 2 ppm detection	—	BD–3.3	32[e]
CO_2 (ppm)	499[a]	102	337–840	39[e]
RSP (μg^{-3})	24[b]	2.0	BD[c]–67	40[e]
BaP (ng^{-3})	0.4[b]	2.7	BD[d]–4.90	29[e]
PAH (ng^{-3})	3.0[b]	3.9	BD[d]–45.49	29[e]
SF_6 Ventilation (ach)	1.5[a]	0.87	0.3–4.1	40[e]

[a]Arithmetic mean and standard deviation.

[b]Geometric mean and standard deviation.

[c]Detection limit based on minimum filter weight gain of 50 μg

[d]Detection limit based on analysis system sensitivities at time of analysis.

[e]Number of buildings included in summary.

Planned Activities for FY 1986

Analysis of the data from all three field studies will continue in FY 1986. Of primary importance is the necessity of integrating the perfluorocarbon tracer (PFT) ventilation results into the evaluation of the relationship between pollutant concentrations and ventilation rates.

In addition, 16 residences from this year's study identified as a having radon concentrations above 5.0 $pCiL^{-1}$ will be involved in a field evaluation of mitigation retrofits. Mitigation will be staged and includes sealing techniques, subsurface ventilation, house ventilation, and basement pressurization. Implementation, cost, and effectiveness will be investigated.

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. As various energy-conserving measures have been proposed and implemented (particularly those that reduce ventilation), there has been a growing awareness that such measures, when combined with the presence of pollutant sources, can adversely change the air quality in the affected buildings, causing health and comfort problems for the occupants. Towards the end of identifying the sources of these

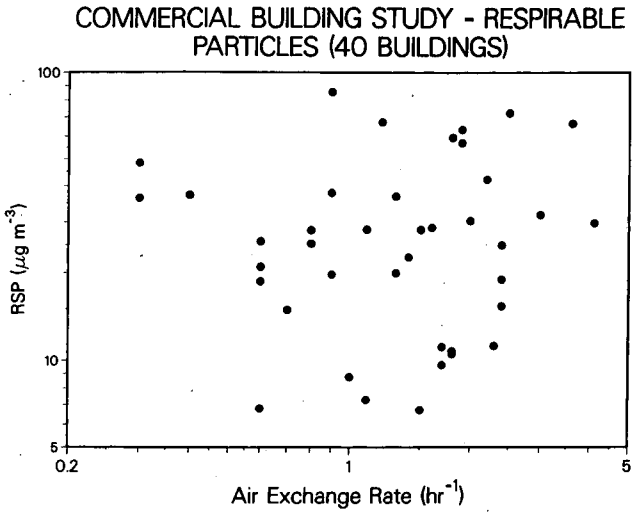


Figure 19. Scatter plot of average commercial indoor RSP concentrations and average building ventilation rates. Lack of observable correlation indicates that ventilation is not the most important parameter affecting indoor pollutant concentrations. (XBL 862-370)

problems and developing solutions to them, a significant amount of 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 of the results of this research have been published in journals or conference proceedings, some in internal reports, and some, for reasons of personnel shifts or program changes, have neither been formally collected nor published. The diversity of research sources and inaccessibility of some research results, combined with the rapid growth in the amount of research being carried out, has made it apparent that a centralized collection of these research results in an easily accessible form would greatly facilitate their exchange, evaluation, and analysis.

The goal of this project, therefore, is to create a computerized data base of those 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 which, together, comprise a data resource.) The Concentration of Indoor Pollutants data base (CIP data base) will contain research results, along with bibliographic references and information describing the experimental environment, and research procedures.

For a more detailed description of the CIP data base, see the 1984 Annual Report.

Accomplishments During FY 1985

The initial implementation of the CIP data base was completed in the Spring of 1985 and then reviewed by members of the project advisory committee and selected representatives of a number of gas and electric utilities. Each reviewer was asked to complete a questionnaire regarding the performance and usefulness of the data base. Based on this review process, modifications and enhancements to the CIP data base were carried out, and Version 2.0 of the Concentrations of Indoor Pollutants Data Base was released for general distribution in October. At that time the content of the bibliographic data base was 90% complete, with 192 entries, while the summary data base was 20% complete, with 20 entries. By the end of the year, both the bibliographic and summary data bases were 95% complete and current.

Planned Activities for FY 1986

During 1985 it became obvious that the data base needed to be converted from dBase II to dBase III for a number of reasons. Some of these were the increased power and flexibility of dBase III; the increasing number of potential users with dBase III; the decline in usage of 8-bit machines, which can't run dBase III; and the availability of a commercial compiler for dBase III to create a stand alone version of the CIP data base that would need neither dBase II or dBase III to run. Accordingly, work was begun on the conversion, and will be finished in the first quarter of 1986. There will then be a release of the new product as Version 3.0, along with the completed bibliographic and summary data bases.

The other major tasks for 1986 will be the continuing maintenance of the CIP data base and support of the user community. Maintaining the data base primarily consists of searching out and entering the results of new research. This includes monitoring the journals that publish research in indoor air quality, such as Environment International, Health Physics, the Journal of the Air Pollution Control Association, etc.; periodically searching the relevant electronic data bases, such as the Energy Data Base supported by the U.S. Department of Energy; and reviewing relevant conference proceedings. Periodically, updates containing the new entries to the CIP data base will be distributed to all users.

Support for the user community will consist of making the existence of the CIP data base known to as many potential users as possible; being available by phone and correspondence to aid users in utilizing the data base; and modifying the data base in response to user complaints and suggestions. A

newsletter will be distributed to all users on a regular basis, probably quarterly. It will address user needs, answer questions, and provide a communications medium for the user community.

The remote-access facility will become available in early 1986, allowing access to the CIP data base via the phone lines to remote users with a terminal and a modem. This facility will broaden the potential user community, and will be used as another communications medium with the user community.

RISK ASSESSMENT

The overall purpose of this work is to characterize indoor exposures to air pollutants and to examine their health implications. Considering the complexity of this question, the work has several manifestations. Exposure characterization and examination of health effects are the dominant part of the project. These efforts include 1) construction of an overall framework for examining exposures and health effects of indoor pollutants and 2) narrower studies of the three major pollutant classes to which the larger and broader efforts of LBL's Building Ventilation and Indoor Air Quality Program have been devoted: combustion products, radon and its decay products, and organic chemicals.

Accomplishments During FY 1985

Overall Framework for Assessing Exposures and Health Effects of Indoor Pollutants

Indoor pollutants fall into several pollutant classes, three of which—radon, combustion products, and organic compounds—can be characterized from similar scientific perspectives, in respect to both studying the behavior of the pollutants and estimating associated risks. However, in spite of these overall similarities, the nature of the exposures and health effects, as well as the character of the data that may be brought to bear on estimating these quantities, differ substantially. As a result, quantitative examination of a specific pollutant, pollutant class, or air pollution in general, requires careful attention to the specific behavior of pollutant(s) of interest and to the limited data that are available.

Considering our program's substantive experience with each of these pollutant classes, we have undertaken an effort to establish a consistent overall perspective for assessing the exposures and health risks of indoor pollutants. From the simplest point of view, of course, what is needed is information on pollutant concentrations during time spent indoors and on the risk factor expressing the relationship(s) between exposures and probability of associated health effects. The product of exposures and risk factors yield, the incidence or risk of the health effects induced. Unfortunately, the picture is complicated considerably by the need to consider multiple types of exposures and health effects and by the variable nature and reliability of the information available on both of these questions. The framework being developed will take this diversity into account, permitting an effective appreciation of the importance of indoor pollutants. This framework has already been applied to the case of lung cancer from ^{222}Rn decay products, where the exposure can be characterized by a relatively simple annual-average concentration and where the dose-response data for the health effect of interest is unusually strong.[15]

Related to the construction of this overall framework, we have also recently begun a logically subsidiary, but actually more substantial, effort developing a generalized approach for indoor exposure assessment *per se*, focusing for the present on exposures in homes. To some extent, the need for (and difficulty of) this effort would be circumvented by a large-scale national effort measuring all the pollutant concentrations (as well as influencing factors) in a statistical sample of U.S. homes. In the absence of results from such a survey, it is necessary to construct a surrogate that—within a consistent quantitative framework—makes the best possible use of presently available information. It is clear what the key elements in this surrogate are: 1) a data structure for describing U.S. housing and the associated factors that can influence indoor concentrations; 2) a capability for calculating indoor concentrations from the data contained in this structure; and 3) methods for sampling data in a way that is representative of the class of housing under consideration. The initial pollutant class for which the required computer programs will be developed is combustion products (see section on **Combustion Pollutant Exposures**). However, with the provision of analogous data for other pollutants, the same programs can treat classes of indoor pollutants. This exposure assessment framework will, we should note, not only provide improved understanding of exposures, but also indicate more clearly than heretofore possible what new or improved data are required and how survey efforts should be designed to obtain them.

Potential Risks from Exposure to Organic Carcinogens in Indoor Air

In FY 1985, progress was made in the area of assessing exposures of and potential risks from organic chemicals in indoor air. Increasing experi-

ence with so-called "complaint" or "sick" buildings suggests the occurrence of adverse effects on humans from exposure to organic chemicals in indoor air. However, except for a few cases involving such compounds as formaldehyde, chlordane, and pentachlorophenol, the complaints cannot be attributed with any certainty to individual chemicals. Furthermore, while the experience to date constitutes an important indicator of a potential problem, complaints are generally limited to acute or irritant effects, such as unpleasant odors, upper respiratory or eye irritation, or headaches. Thus complaints rarely serve as effective indicators of more life-threatening endpoints, such as cancer or reproductive effects, if only because individuals are not likely to be able to associate such toxic effects with the air inside the buildings they occupy.

These limitations on our experience with complaint buildings have so far precluded either: 1) assessment of the overall importance of organic chemicals indoors as a cause of any class of toxic effects or 2) identification of the most important contributors to such effects. Nonetheless, substantial data are available, primarily from other kinds of studies, on the toxic effects of many of the chemicals that occur indoors. Effective utilization of information from animal and human toxicology can help to narrow the focus of future studies by targeting high-risk chemicals and by identifying toxic effects to be examined in epidemiological studies. Such studies may include surveys in complaint (and control) buildings, as well as epidemiological studies designed to detect the association between particular chemicals and the more serious toxic effects, such as cancer and reproductive effects. Considering the many chemicals present in indoor air, at widely varying concentrations, and the limitations in sensitivity of epidemiological studies, success can only occur by targeting groups that are highly exposed to chemicals of particular concern. The full range of toxicological data should be brought to bear as a basis for indicating which chemicals (or chemical classes) are worthy of attention, as well as for indicating before hand the potential importance of various classes of effects.

In this study we have examined the current literature reporting concentrations of organic chemicals in indoor environments, and have constructed a nominal list of some 150 chemicals found indoors. We have then surveyed the known toxicological properties of these chemicals, relying primarily on results from animal studies. We have made rough estimates of the concentrations that might be expected to cause toxic effects in humans and have compared these to measured concentrations in indoor air as an approximate index of the significance of indoor exposures. The primary endpoints examined were carcinogenesis and reproductive effects, though some attention has also been given to other systemic toxic effects, and irritation.

As an example, for carcinogens we have calculated estimated risks from animal cancer test data and indoor air concentrations. The results of these calculations for 27 carcinogens found in indoor air are shown in Table 12. The values estimated for risk per unit exposure range over 4 orders of magnitude. This wide variation in the carcinogenic potential of carcinogens in indoor air is an important consideration underlying a study such as this. Thus, even though the evaluation of risks at indoor concentrations is complicated by fundamental limitations in the data on toxic effects, and by an incomplete framework within which to estimate the frequency or type of effects at low concentrations in humans relative to those at which toxicity is observed in animal experiments, the errors in the analysis are not likely to be as large as the very wide range of carcinogenic potency of the chemicals being evaluated. With such a wide range, even very rough approximations of risk may be useful.

As an example, consider the case of formaldehyde, which is commonly present in indoor air of non-complaint homes at concentrations averaging about 50 $\mu g/m^3$. Listed in Table 12 are three estimates of individual risk from lifetime exposure to this concentration. These estimates differ by a factor of 170. The higher estimates were calculated from risk estimates made by the Environmental Protection Agency (EPA) using a very conservative extrapolation model.[34] The lowest estimate was calculated from risk estimates made using an extrapolation model similar to the EPA's, but using less conservative assumptions and incorporating additional assumptions drawn from biological and pharmacological considerations, which result in considerably decreasing the estimated risk. Even though the difference in the lifetime risk estimates of these two models is roughly 150-fold, the fraction of total cancer risk attributed to formaldehyde is significant regardless of which model is used. Assessment of the importance of formaldehyde as an actual cause of human cancer will require the results of much more thorough investigations, but this simple analysis suggests that current emphasis on potential risks from chronic indoor exposures to formaldheyde is not inappropriate.

Inadequate data presently available on concentrations of chemicals in the indoor environment represent a major limitation of our analysis. For virtually no organic compounds (formaldehyde is to

Table 12. Estimates of carcinogenic risk from lifetime exposure to organic chemicals in indoor air.[a]

Chemical	Risk/Exposure[a] ($\mu g/m^3$) ($\times 10^{-5}$)	Exposure[b] ($\mu g/m^3$) MAX/MEAN or MEDIAN	Risk (Lifetime cancers per 10^5 people)
Aldrin	88	0.55/-	48/-
Benzene	>0.41	390/14	>160/>5.7
Benzo[a]pyrene	5.9	0.067/0.0071	0.4/0.042
Carbon tetrachloride	0.57	17/<1.4	9.7/<0.80
Chlordane	45	40/-	1800/-
Chloroform	1.4	47/<2.6	66/<3.6
Dibenz[a,h]anthracene	11	0.00050/0.00010	0.0055/0.0011
Dichlorvos	6.9[c]	10/-	69/-
Dieldrin	119	0.47/-	56/-
1,1,1-Trichloroethane	0.14[3]	1100/33	150/4.6
1,2-Dibromoethane	<13	<0.14/<0.14	<1.8/<1.8
1,1-Dichloroethane	0.059[d]	1.8/0.06	0.11/0.0035
1,2-Dichloroethane	<5.7	69/1.1	<390/<6.3
Ethanol	0.0035	390/130	1.4/0.46
Tetrachloroethylene	0.86	720/4.5	620/3.9
Trichloroethylene	0.16	180/<3.4	29<0.54
Formaldehyde	17[e](5.0) [~0.1][f]	125[7]/53[g]	2,100/900[5.3]
Heptachlor	<60	15/-	<900/-
Lindane	>5.4	50/0.18	>270/>0.97
Malathion	0.22[3]	2.0/-	0.44/-
Dichloromethane	(0.0180)	5000/<120	90/<2.2
Dimethylnitrosamine	278	0.8/-	222/-
N-Nitrosopyrrolidine	15	0.036/-	0.54/-
PCB's (Anrochlor 1260)	30	0.50/-	15/-
Di(2-ethylhexyl)phthalate	0.014[5]	230/60	3.2/0.84
Styrene	0.18	54/3.3	9.7/0.59
Vinylidene Chloride	3.0	420/2.7	1,300/8.1

[a]Estimates are based on the most potent TD50 reported by Gold, *et al.*[32] In parentheses are estimates from the Carcinogen Assessment Group at EPA (Anderson[33]). A "greater than" sign (>) indicates the TD50 was estimated from a dose-response that showed significant downward departure from linearity. A "less than" sign (<) indicates the TD50 was estimated from a dose-response that showed significant upward departure from linearity. All results were from experiments in either rats or mice.

[b]Data compiled from the published literature.

[c]The experiment used by Gold, *et al.*[32] to estimate the TD50 was classified negative by NCI/NTP or authors of a literature study.

[d]The experiment used by Gold, *et al.*[32] to estimate the TD50 was classified equivocal by the NCI/NTP.

[e]Gold, *et al.*[34]

[f]A much less conservative estimate than that of EPA, using the best estimate (instead of the upper 95% confidence limit value) and incorporating assumptions drawn from biochemical and pharmacological considerations (Starr[35]).

[g]At concentrations above 125 $\mu g/m^3$ the irritant effects of formaldehyde become noticeable to most people. We have, therefore, chosen this as the highest concentration that would be likely to occur chronically, even though much higher concentrations have been measured in non-complaint homes.

[h]In calculating a mean value, we have not included the relatively much higher concentrations reported in mobile homes.

some degree an exception) do we have sufficient direct information to state with much certainty what the frequency distribution of concentrations is, nor are we able to cite average exposures with any accuracy. Thus, in Table 12, risk from lifetime exposures to some carcinogens at high exposures (represented in the table by maximum values) may be quite significant (e.g., 10 carcinogens have lifetime risk values greater than 1 in a thousand cases of cancer). Though the absolute risk values shown represent only unlikely upper limits, since lifetime exposure to such high levels would not be expected to occur, this result does point out the importance of gaining a better understanding than we have now of the proportion of individuals exposed for extended periods to relatively high concentrations of these substances.

Other Pollutant-Specific Efforts

Part of the radon group's efforts over the past several years has involved examination of the aerial radiometric data accumulated as part of the National Uranium Resource Evaluation (NURE); the resulting information on surface radium concentrations may serve as a significant indicator of high indoor concentrations (see **Radon** section). Having obtained the entire NURE data set and loaded most of it into the LBL computer system, we have recently begun a collaboration with the Populations at Risk to Environmental Pollution project to examine potential correlations between the NURE data and U.S. health data that can be accessed through the LBL system. While the results of this examination may not provide unequivocal evidence on the relationship between (environmental) radon exposures and lung cancer rates, they would constitute the first systematic examination of such correlations, a substantial step beyond the limited and virtually anecdotal analyses performed to date.

In conjunction with the combustion emissions group, we have examined considerations in the design of field surveys to assess indoor exposures to combustion pollutants.[2] This represents a preliminary step in designing large scale assessments of indoor exposures to combustion pollutants via either field studies or modeling studies.

Planned Activities for FY 1986

We plan to continue our exposure and risk assessment efforts in combustion pollutant, radon and organic compounds. The new directions of this work will exemplify the type of analytical effort that is often neglected by the indoor air quality community, but without which we cannot hope to understand the significance of what we have done or choose effectively the path of future work.

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Windows and Daylighting*

(This article, except for the section on Aerogels, has been reprinted from the FY 1984 Annual Report.)

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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.

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

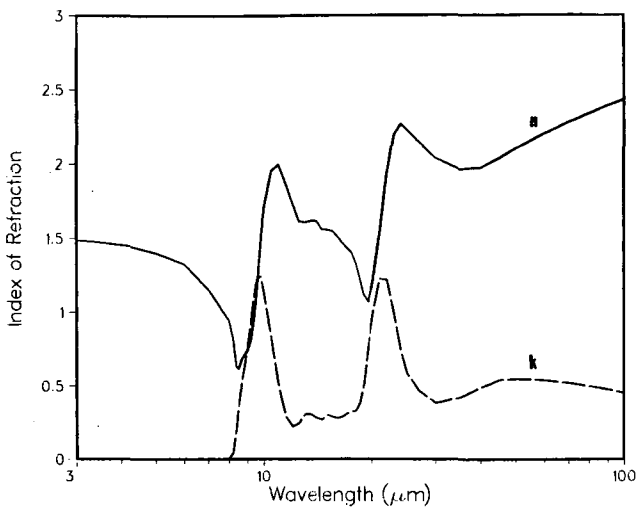

Figure 1. Real (n) and imaginary (k) parts of the complex index of refraction for soda-lime silica glass. (XBL 8412-5271)

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.

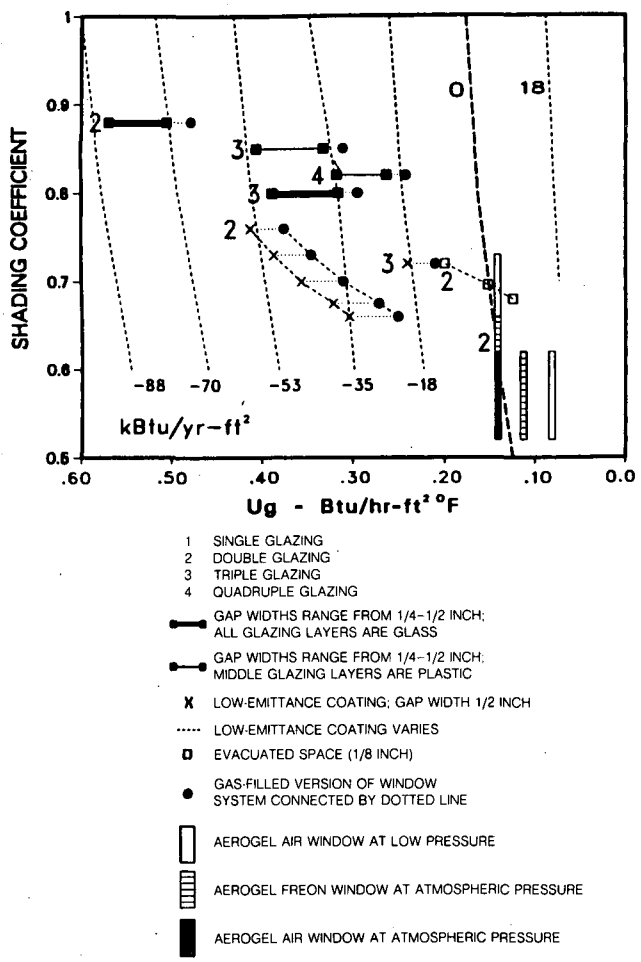

Figure 2. Simulation results for north-zone window, Madison, Wisconsin, showing net annual useful flux (primary window area = 66 ft^2). (XBL 856-2870)

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

Transparent silica aerogel is being developed at LBL because of its excellent thermal insulation properties for window glazing materials. It is an open cell porous solid containing a very high percentage of voids. Aerogel is transparent rather than translucent because the characteristic pore size is much smaller than the wavelength of light; therefore, it transmits

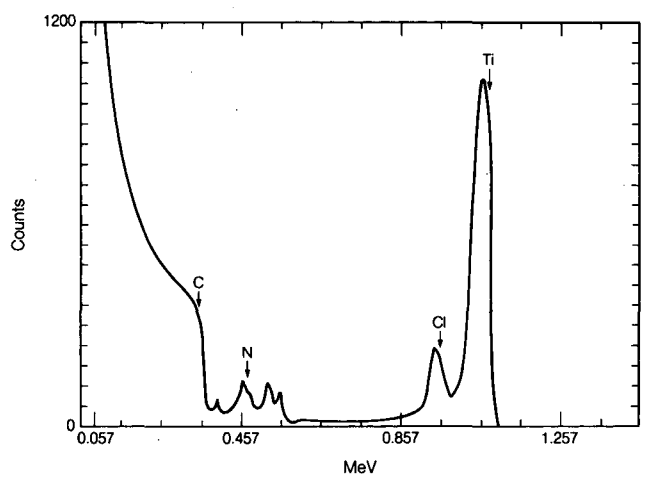

Figure 3. Rutherford backscattering spectrum for titanium oxynitride coating on glossy carbon substrate. (XBL 854-9799)

rather than scatters light. A 1-inch-thick aerogel window has an R value of about 7, which can be increased to nearly R-20 by removing 90% of the air from the aerogel. The goals of this research are to improve the optical and thermal properties of aerogel, discover less expensive synthesis methods, develop methods to protect it from the environment, and develop a technology base for production of transparent aerogels.

Aerogel is prepared by mixing a metal alkoxide with water and alcohol along with suitable catalysts. Water hydrolyzes the alkoxide compound to produce fine solid particles or polymers that link together to form alcogel, a transparent solid containing alcohol. To become useful as an insulator, the alcohol must be removed from the alcogel without damaging the silica matrix through the action of interfacial forces in the very fine pores. These interfacial forces can be eliminated by carrying out the solvent extraction under supercritical conditions. Researchers at LBL have been investigating both the preparation and drying of aerogel.

Accomplishments During FY 1985

Our efforts in 1985 have been concentrated on improving the two critical areas of synthesis of aerogels:

1. hydrolysis and condensation reaction of a less expensive alkoxide TEOS (tetraethylorthosilicate) than the toxic and expensive TMOS (tetramethylorthosilicate) normally used by others;
2. simplification of the drying process of the alcogels to achieve the aerogel without damage to the structure.

In addition, we have developed some unique techniques which allow us to study the microstructure of the gels by transmission electron microscopy and light scattering studies. They are discussed below. Progress in these three areas has significantly enhanced the prospects for large scale industrial preparation of aerogel for windows.

Alcogel Production from Low Toxicity Starting Material. Transparent silica aerogels for Cerenkov counters have been produced by hydrolysis and condensation of TMOS. Since TMOS is a very toxic starting material, the more desirable starting compound, TEOS, was used in the current work. Research in our laboratory led to the successful use of a base to catalyze TEOS.[2–4] Base catalysis of TEOS results in a more suitable material for window material than the acid catalysis method. We have improved the properties of the aerogel by exploring a wide range of process variables using the factorial design method.[2] Light scattering, optical transmission, and electron microscopy data were used to characterize the aerogels produced in our laboratory. Using these techniques we have established that the quality of the improved TEOS aerogels is comparable or better in transparency than those prepared from TMOS. The transmission spectrophotometer results confirming this are given in Fig. 4.

Ambient Temperature Supercritical Drying. Alcogel is a low density open pore material containing a high fraction of voids filled with alcohol. In conventional supercritical drying, the alcohol is removed from the alcogel by slowly releasing the pressure in an autoclave after it has been heated above its critical pressure and temperature. Under these conditions, the interfacial tensions in the alcogel drop to zero. Typical conditions for supercritical drying of alcohol are $\geqslant$ 270°C and 1800 psi. The necessity to cycle pressure vessels to these temperatures makes the drying process expensive and time consuming. We have developed a solvent substitution process[5] in which alcohol is replaced by liquid CO_2, which permits drying of alcogels at $\leqslant$ 40°C and 1200 psi. We have improved the substitution and drying process to minimize shrinkage and damage to the structure. The shrinkage can be controlled to $\leqslant$ 5% of the initial dimensions. The reproducibility of the process is good, and the drying is achieved in less time per batch than the 2–3 days required by the high temperature process. Further efforts are in progress to reduce the shrinkage.

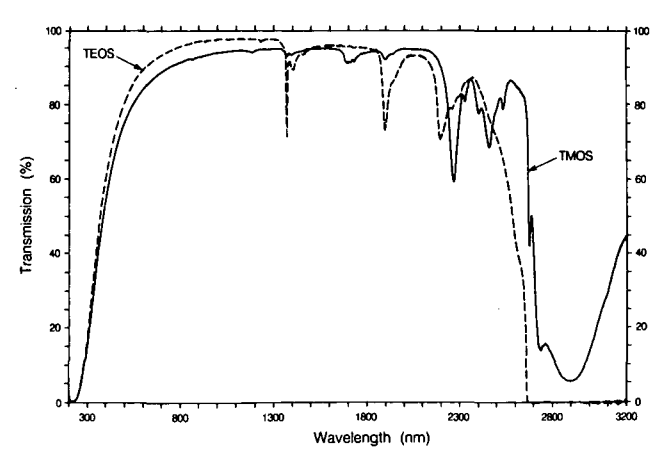

Figure 4. Transmission spectra of a 4-mm-thick sample of base catalyzed TMOS aerogel supercritically dried at 270°C and 110 bars (TMOS) and a 12-mm-thick base catalyzed TEOS aerogel sample supercritically dried by CO_2 but not heated to remove all adsorbed H_2O (TEOS). (XBL 859-8975)

Gel Microstructure. We have developed a variety of sample preparation methods to overcome difficulties in the study of aerogel with electron microscopy.[6] Transmission electron microscope studies using these methods have provided excellent evidence of the physical gelation mechanism. Micrographs show a cross linked chained structure similar to that conceptualized previously by various workers (Fig. 4a). These sample preparation techniques for TEM studies are excellent for studying the microstructural details of gels and aerogels at various stages in the sol-gel process.

We have performed light scattering studies of acid and base catalyzed sol-gel systems. By studying the time evolution of the scattering intensity, we can differentiate gelation mechanisms between the two gels. Information from these experiments is helpful in formulating and controlling the desired properties of complex sol-gel systems.

Planned Activities for FY 1986

In FY 1986 we will explore the substitution of Freon 116 for alcohol to further reduce the supercritical drying conditions to $\leqslant 20°C$ and 430 psi. If successful, this substitution will lower the processing cost below that of the CO_2 method. Treatment of the gels to render them hydrophobic will be studied to improve the chemical stability of aerogel against weathering and moisture. The adhesion of aerogel to glass plates of the window will be examined to improve the mechanical stability and resiliency of the aerogels.

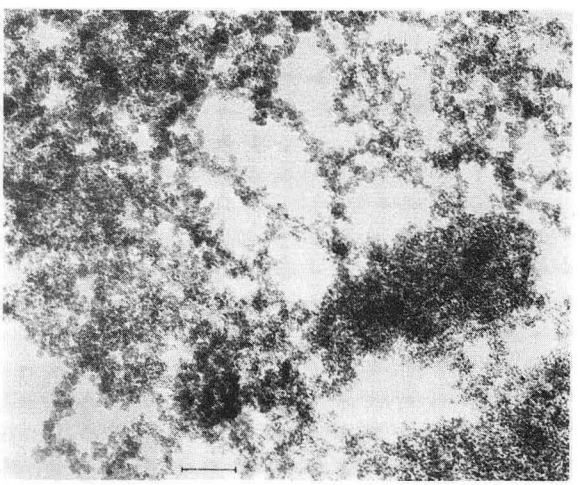

Figure 4a. Transmission electron micrograph of a base catalyzed TMOS aerogel flake after carbon coating. (XBB 859-7482)

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

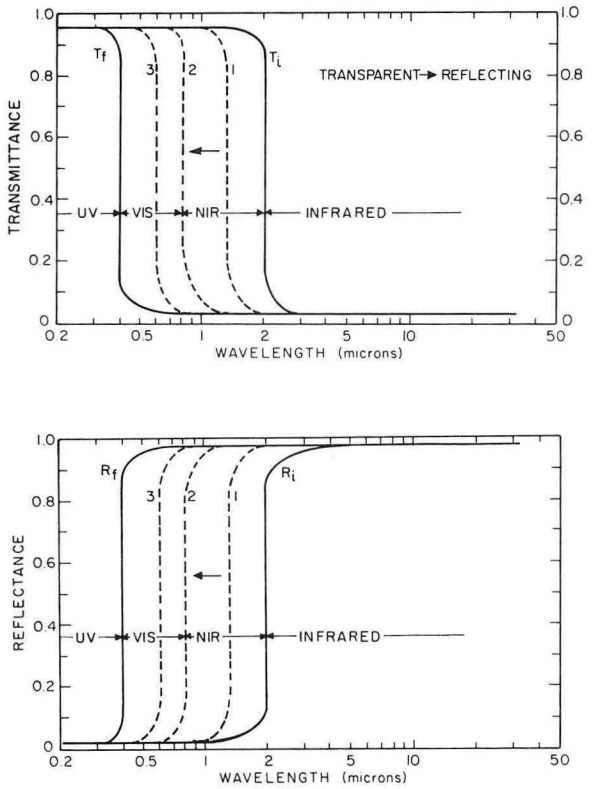

Figure 5. Idealized broadband spectral response for a solar optical shutter. This example ignores the effect of absorption and shows a highly transparent film transforming into a highly reflecting one. Such a shutter can control certain portions of the solar spectrum to provide or restrict both solar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

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.
(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.[7] 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.[7] 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[8] and the Department of Electrical

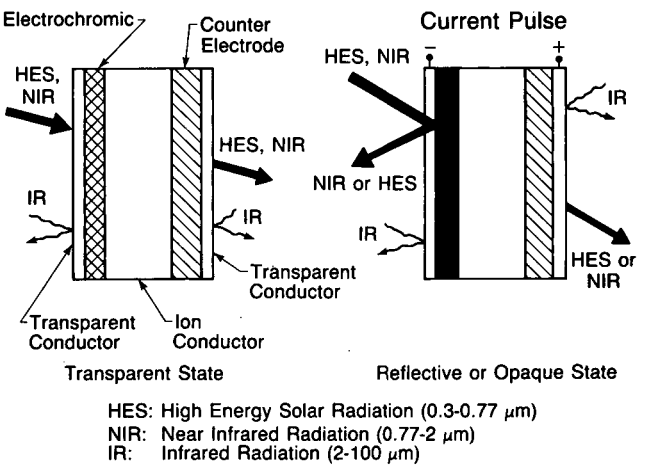

Figure 6. Schematic of an electrochromic optical switch shown in each of two states, transparent and colored. A current pulse causes an ion-based chemical reaction to take place in the electrochromic material. (XBL 842-10105)

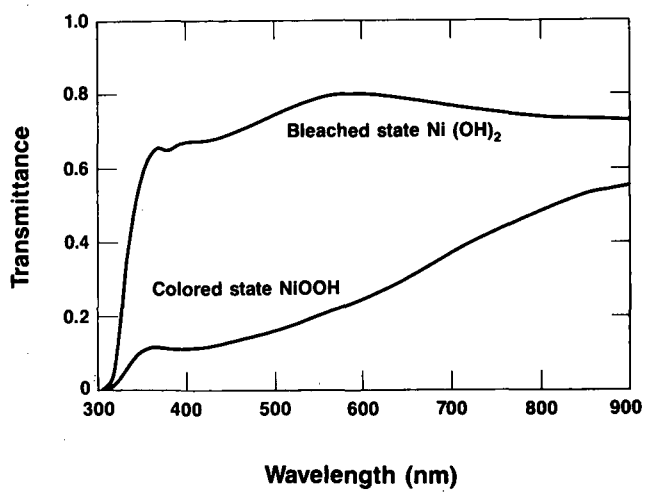

Figure 7. Transmission (near-normal) spectrum for nickel hydroxide in bleached and colored state. Conditions are IM-KOH electrolyte with 1 V applied potential. (XBL 852-6955)

Engineering at Tufts University.[9] Electrochromic near-infrared reflectance modulation was demonstrated in polycrystalline WO_3 material.[10] 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.[11]

Planned Activities for FY 1985

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

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. Con-

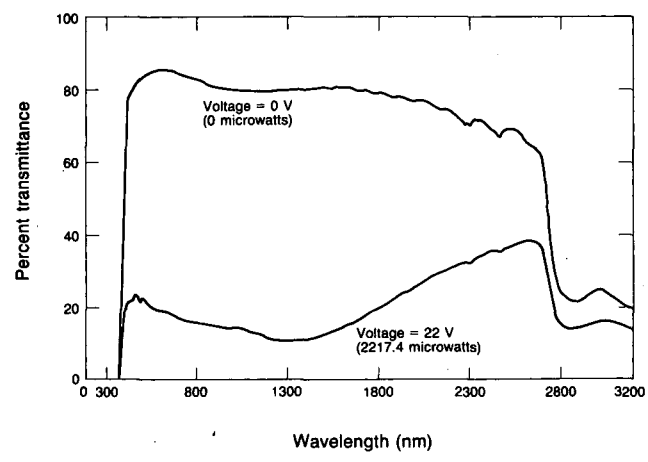

Figure 8. Spectral transmittance (near normal) for a dynamically scattering liquid crystal device. Response includes two glass cover plates and two transparent conductor electrode films. (XBL 852-7033)

ventional 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 transmission has acceptable values at moderate concentration angles. We also investigated the performance of plastic optical fibers and evaluated 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.

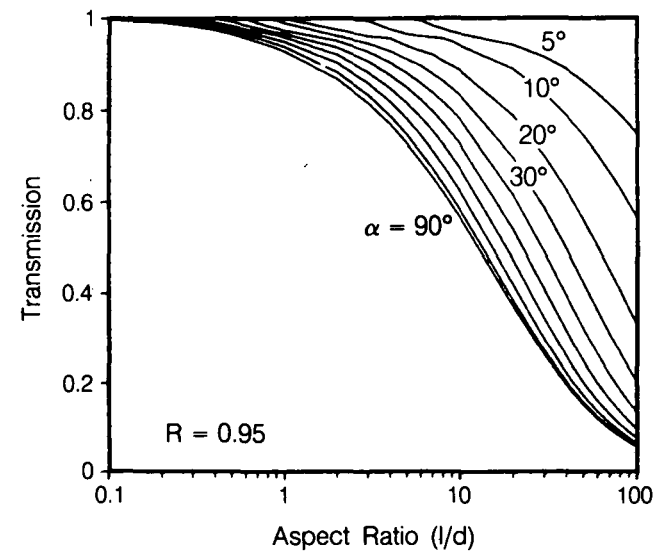

Figure 9. Transmission efficiency of a tubular light guide vs. aspect ratio (length/diameter). The parameter α is the half-angle of the concentrated sunlight. The inner surface reflectivity R is 0.95. (XBL 854-9798)

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 condi-

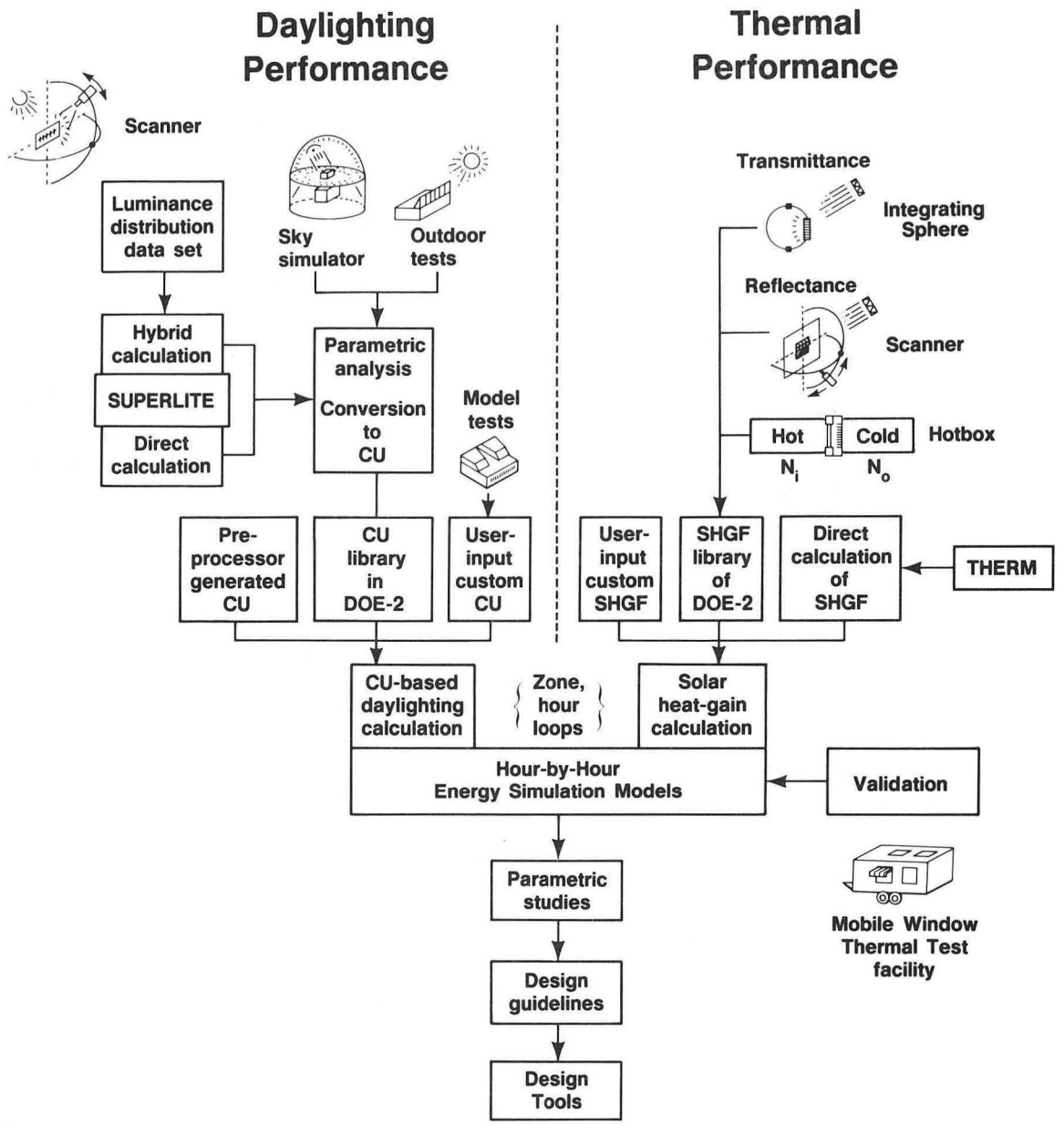

Figure 10. Schematic diagram of DOE-2.1 fenestration modeling capabilities under development. The new solar heat-gain model is shown on the right, the new illuminance model on the left. (XBL 8212-4972A)

tions. 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 Hand-

book 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 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)

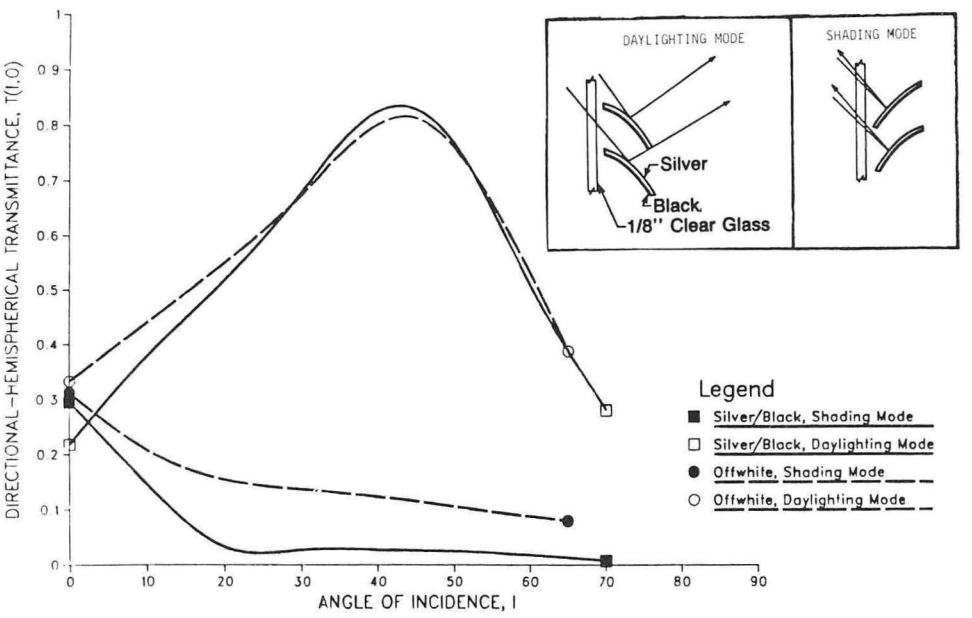

Figure 12. Measured transmittance of two venetian blinds with different surface treatments as a function of position and angle of incident light. (XBL 848-3341)

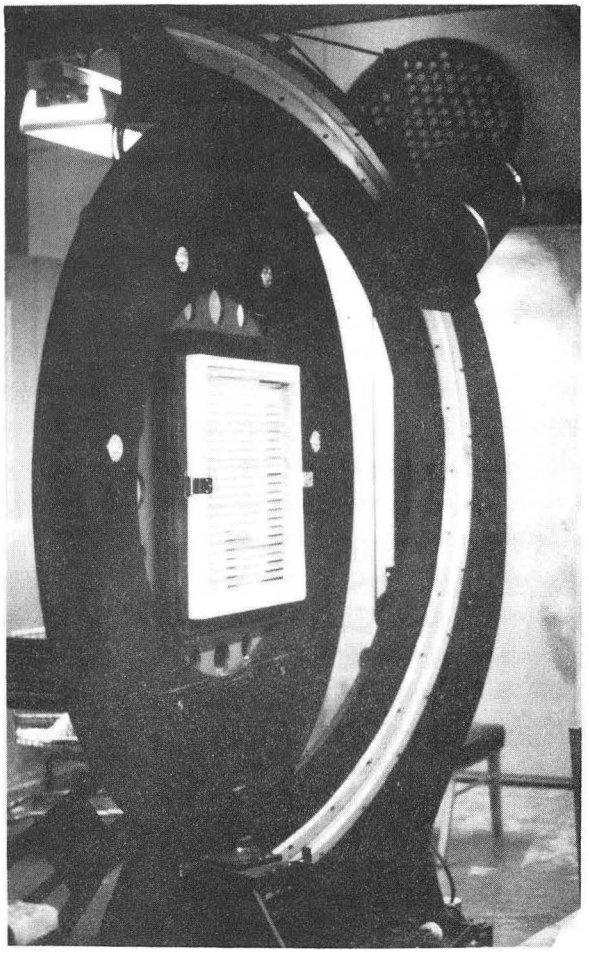

Figure 13. Scanning radiometer under construction. (CBB 852-1225)

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 daylight 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 gen-

erated 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.[12–14] 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.[15] (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

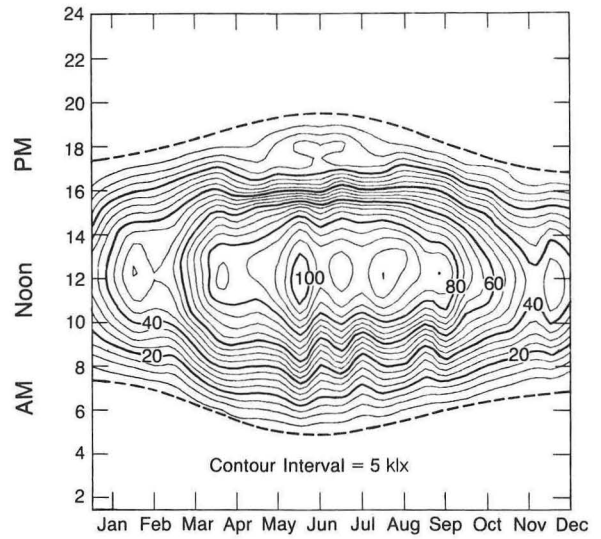

Figure 14. Isolux contours of global horizontal illuminance, based on four years of data measured in San Francisco. (XBL 845-10362)

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.

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 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.

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.

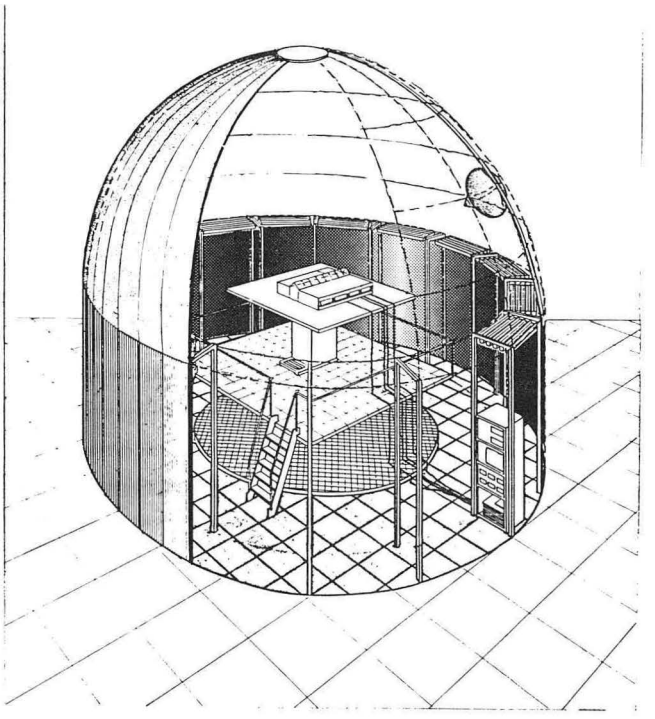

Figure 15. Schematic of 24-ft^2 diameter sky simulator with model on platform. (XBL 8412-5328)

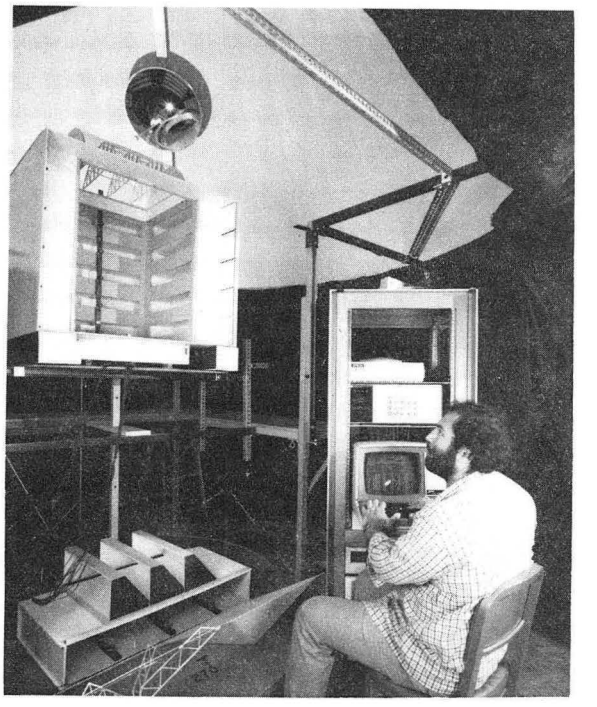

Figure 16. Interior of sky simulator showing reconfigurable scale model of a five-story atrium (with one side removed). (CBB 848-5926)

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 $\times$ 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 QUICK-LITE 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 more detail 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 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

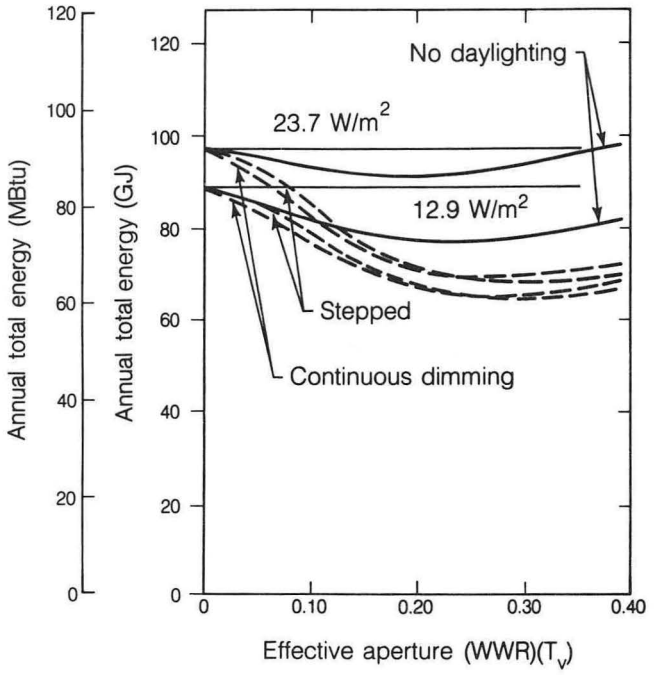

Figure 17. Energy consumption on the south zone of an office building in Madison, Wisconsin. The variation in annual energy use with window area and transmittance at two lighting power densities is shown for (1) an opaque exterior wall (thin horizontal lines), (2) a nondaylighted case, and (3) a daylighted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

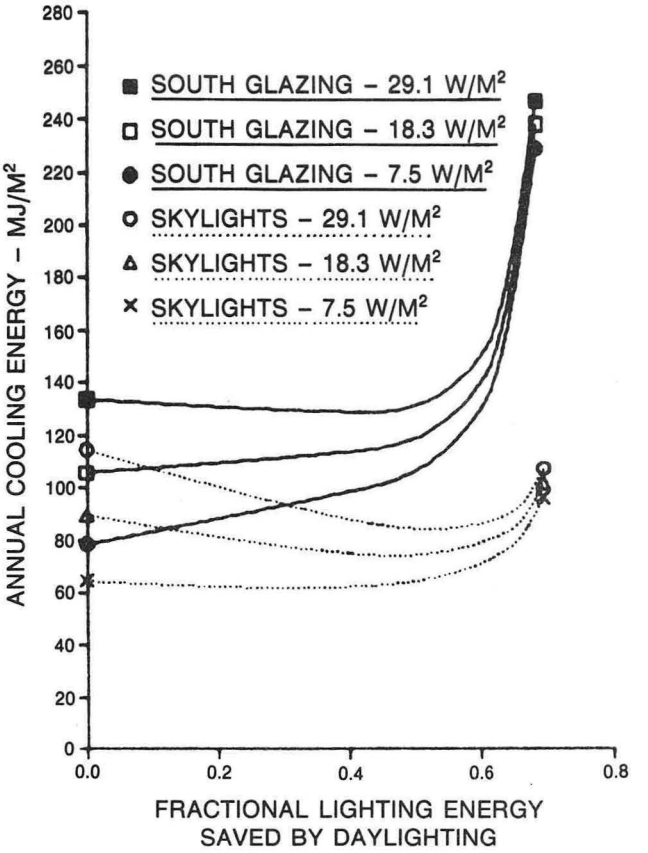

Figure 18. Cooling energy per unit floor area of daylighted space as a function of fractional electric lighting savings in Lake Charles, Louisiana. (XBL 856-2801)

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 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 radia-

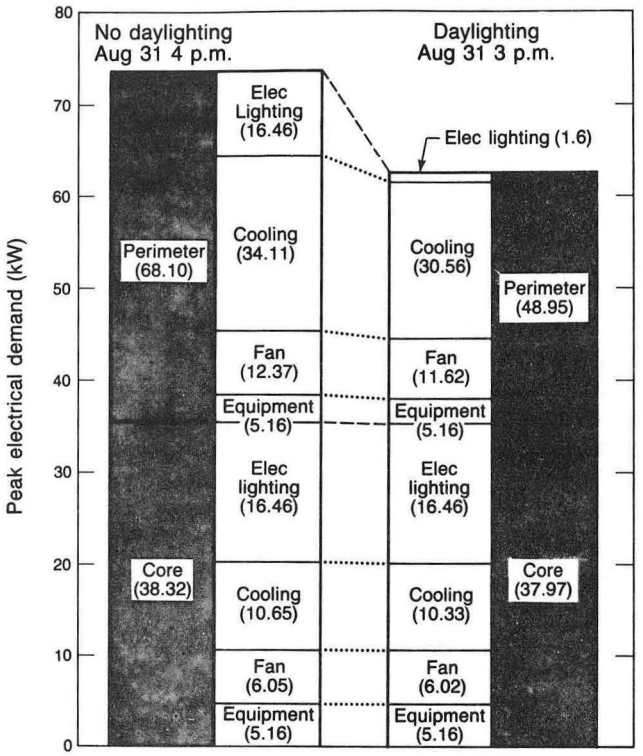

Figure 19. Peak electrical demand, broken down by end-use components, for an office building in Madison, Wisconsin. Nondaylighted (left) and daylighted cases are compared. Component breakdown is shown for the building's core (930 m^2) and perimeter (560 m^2) to reveal how daylighting can reduce peak 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)

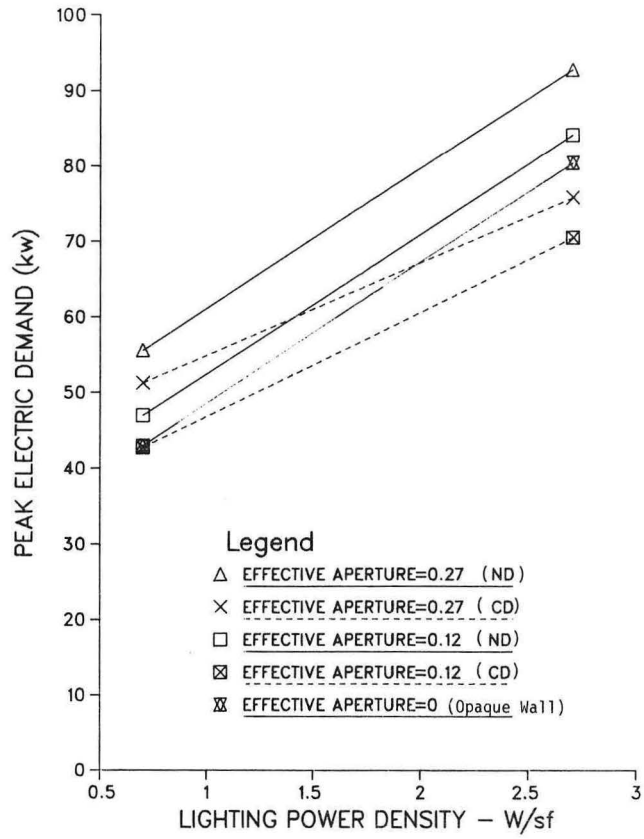

Figure 20. Peak electrical demand for an office module in Fresno as a function of installed electric lighting power density at two effective apertures in both daylighted (CD) and nondaylighted (ND) cases and an opaque wall. (XBL 856-2815)

tion, 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 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 materi-

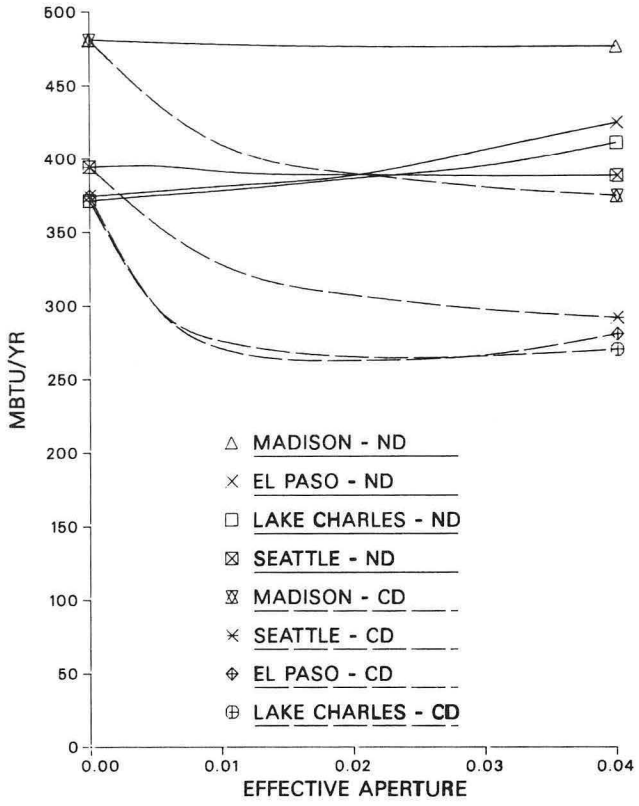

Figure 21. Energy consumption in a skylighted zone, showing variation in net annual consumption with effective aperture (skylight area and transmittance) for a non-daylighted (ND) and a continuously dimmed daylighted (CD) case in four climates. Installed lighting power density of 1.7 W/ft^2 provides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

als, the effects of fenestration performance on HVAC, and the effects of various HVAC options on fenestration performance. The cost implications of 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 constitutes 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).

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

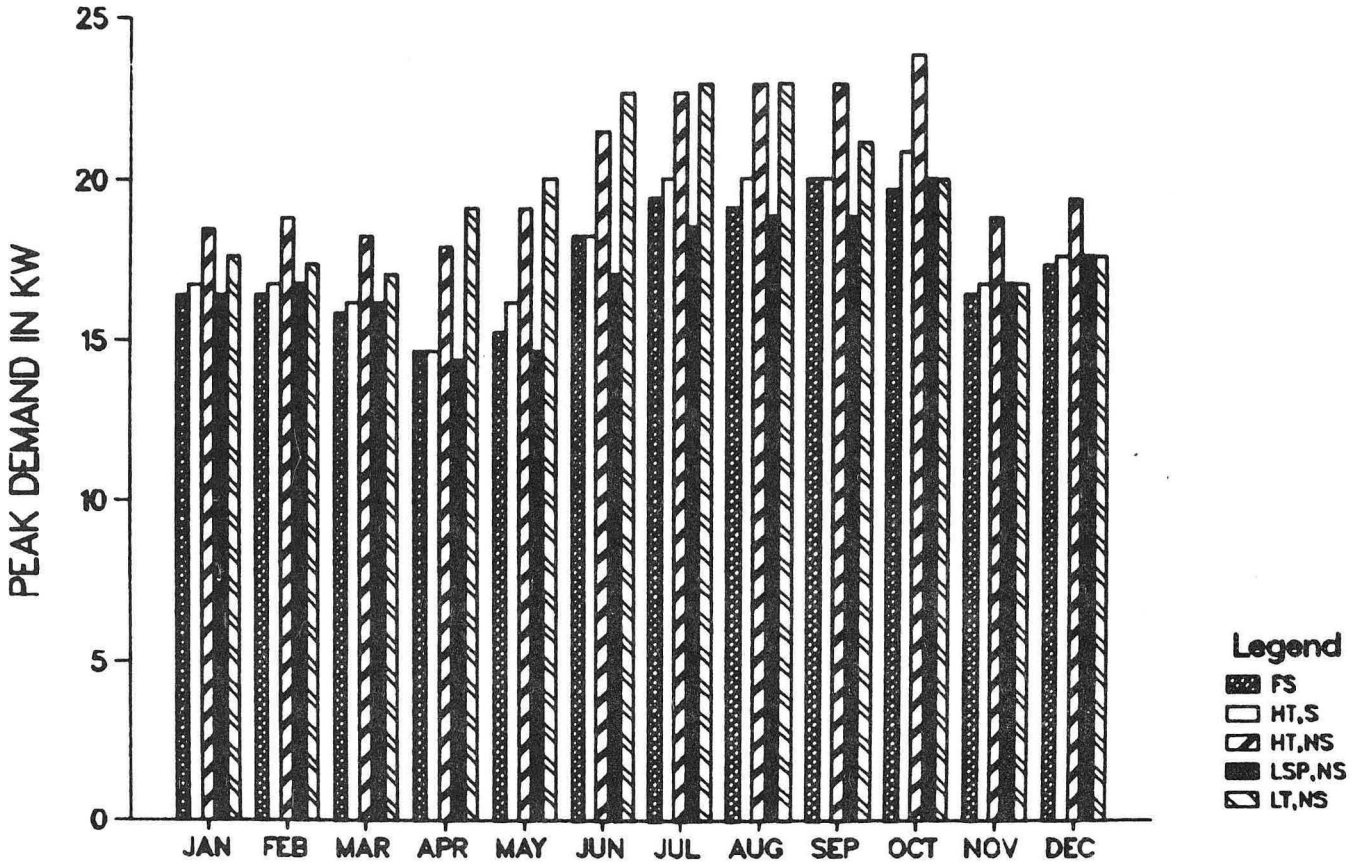

Figure 22. Monthly peak electric demand for an office building module in Madison, Wisconsin, comparing conventional glazings with two types of optical switching films. *FS*: electrochromic film with solar intensity control; *HT,S*: high-transmission glass with operable shading; *HT,NS*: high-transmittance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

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.

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:

- Tests of guard temperature-system capacity completed
- Guard air-handling system reconfigured to reduce air infiltration
- Air infiltration tests of both calorimeter chambers completed

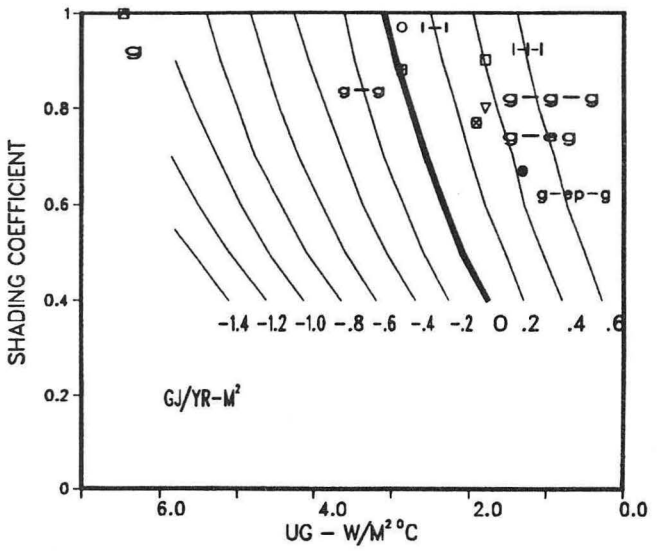

Figure 23. Net heating-season useful flux in Madison, Wisconsin, for a primary window area of 24.53 m^2 oriented due south. The performance of typical glazing systems is indicated in the table. (XBL 856-2800)

Glazing	U ($W/m^2{}^\circ C$)	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

- 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.

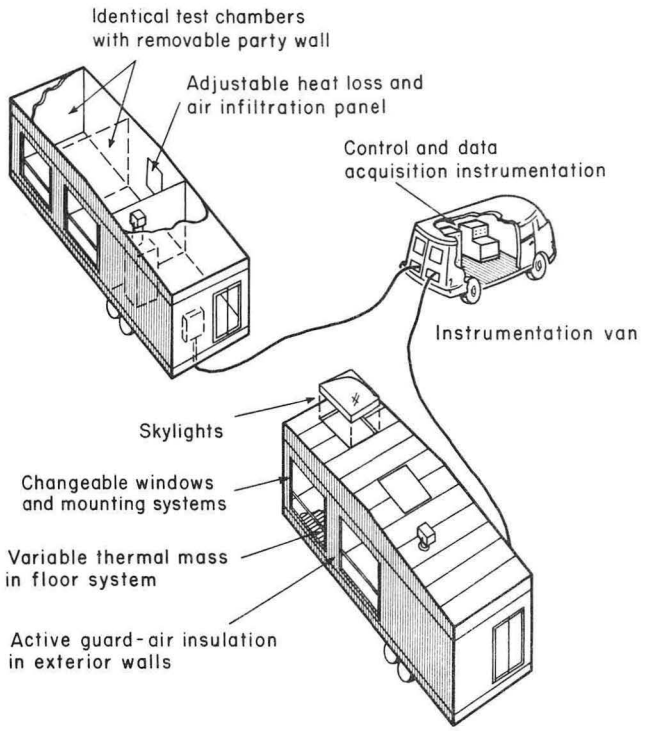

Figure 24. Schematic of Mobile Window Thermal Test (MoWiTT) Facility. One of the two double-module trailers has been built. (XBL 811-30)

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 under-

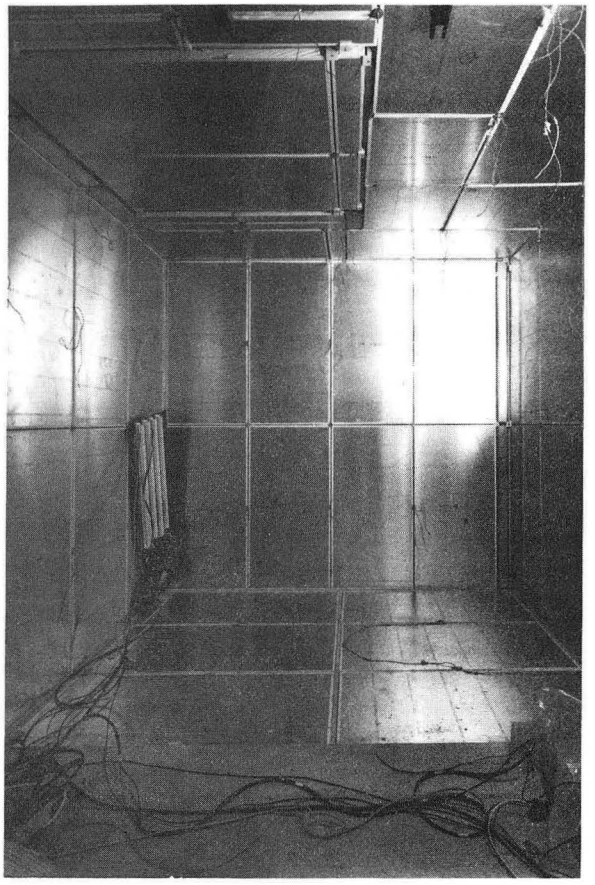

Figure 25. A MoWiTT calorimeter chamber completely instrumented with heat-flow sensors. Window will be mounted in far wall after calibration is complete. (CBB 838-7737)

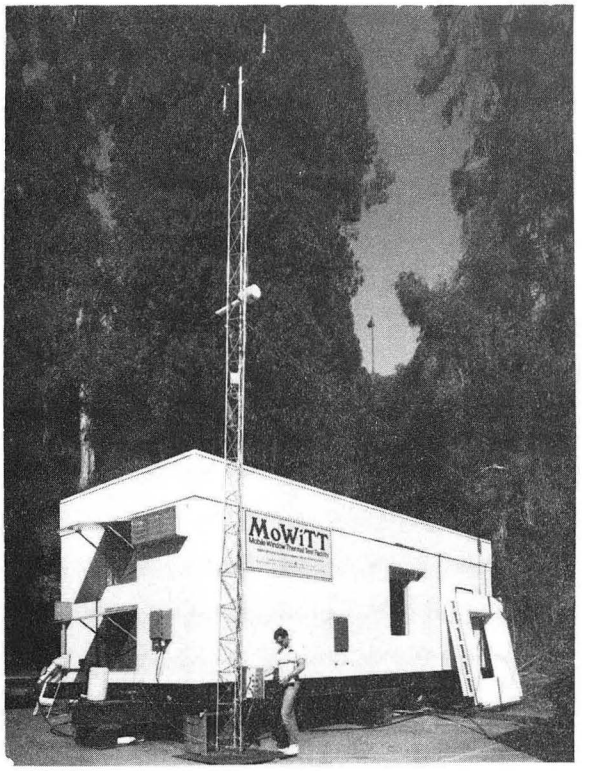

Figure 26. The MoWiTT Facility undergoing calibration and trial field test at LBL. Left chamber is fitted with a window; right chamber is undergoing a "sealed box" calibration test, after which it will be fitted with the frame system shown leaning against the wall. Left section of trailer contains chiller,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

stand 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 During 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.

Planned Activities for 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.

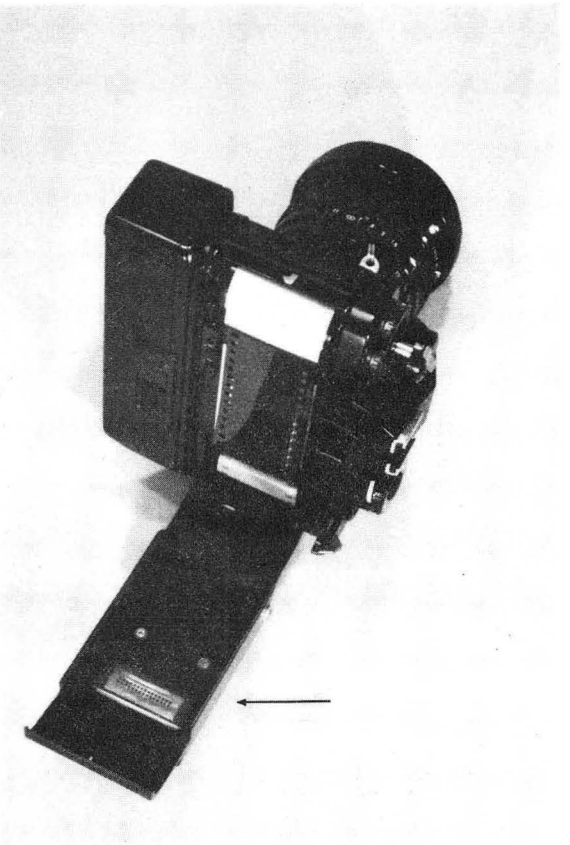

Figure 27. A prototype photographic luminance camera, with back opened to show panel for imprinting optical density scale (arrow). (CBB 857-5596)

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Lighting Systems Research*

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We estimate that 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.

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.

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Since its inception in 1976, the LBL Lighting Program has produced more than 105 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 1985 by each of our three major efforts—engineering science, building applications, and health impacts—and activities planned for FY 1986. 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 significant loss mechanisms have been isolated as targets of technical opportunity for achieving more efficient fluorescent lamps. The first application is to effect a reduction in the self-absorption of the ultraviolet (UV) radiation, a process 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 several ways of reducing the UV self-absorption. The first method is altering the isotopic composition of mercury. This element has seven stable isotopes, each with slightly different resonance UV emission spectra. Altering the naturally occurring isotopic composition can provide more escape channels for the resonance radiation, thereby reducing the probability of quenching collisions and increasing the amount of UV radiation reaching the phosphor. One possibility for isotope alteration—enrichment with ^{196}Hg—is being pursued in a joint effort by LBL and GTE Lighting. Should isotopic 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.

Another 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 6% to 10%. LBL and major firms in the lamp industry are studying practical ways to apply this technique.

To reduce the effects of energy loss in the phosphors requires altering 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.

A third mechanism developed at LBL uses a plasma excitation principle that allows for its excitation to be primarily near the inner lamp wall thereby reducing the UV transport distance and the likelihood of entrapment loss. This surface wave mode of operation occurs at high frequencies in the RF range between 100 and 1000 MHz and permits the lamp excitation without electrodes. This surface wave lamp shows better than 30% increased energy efficacy over fluorescents and operates without starting circuits and should be very long lasting because of the absence of electrode sputtering.

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.

To address the lack of data on the plasma discharges, a program on plasma diagnostics has been initiated to measure electron and ion distribution in optically thin and thick plasmas.

Accomplishments During FY 1985

Mercury Absorption Studies

The mercury isotope separation study was conducted using the laboratory-scale photoionization reactor. This technique achieved a 47-fold enrichment of ^{196}Hg with the continuous flow process. The next step is design and construction of a pilot plant to produce this Hg isotope in sufficient quantity for filling lamps.

A simpler procedure was developed for obtaining a weighed amount of ^{201}Hg isotope in a lamp. The ^{201}Hg was amalgamated on a gold foil and weighed before and after the Hg was removed by heating. The second method to determine the amount of ^{201}Hg, pumping the Hg between two "cold" spots at opposite ends of the lamp, was found to be more accurate if the cold spots were inside the lamp. External cold spots gave erratic results.

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)			
400-W high-pressure sodium		(CRI-25) 100	1984
400-W metal halide		(CRI-66) 80	1984
400-W mercury vapor		50	1984
Electrodeless/high-freq.			
1000-W lamps	10–15% improvement		1989
Low-W lamps	30% improvement		1989
New gases	20–25% improvement		1990
Color-constant/dimmable	20–25% improvement		1993

Magnetic Enhancement

A Helmholtz coil system was constructed to measure the enhanced efficacy of a low-pressure discharge lamp immersed in an axial magnetic field. Figure 1 is a photograph of the system. The gas-discharge lamp is placed in a temperature-controlled integrating cylinder, which is surrounded by the 18-in. water-cooled Helmholtz coils. A photometer on the right side of the integrating cylinder measures the total light flux from the lamp. The power input to the lamp is measured over a range of magnetic fields from zero to 1000 gauss. The measured increase in lamp efficacy is from 3% to 7% at 800 gauss.

Surface-Wave Lamp

A second-generation surface-wave launcher with impedance matcher was designed and built. This new system permits instant starting of the lamp and assures perfect impedance matching once the lamp is ignited, which means that all of the r.f. power is delivered to the plasma with no reflected component. This is a requirement for improved efficiency. Using the surface-wave launcher resulted in a better than 30% gain in efficacy in a standard F15, T-8 fluorescent lamp (15 watt, 1 in. diameter, 18 in. long), operated at normal power input at 60 Hz.

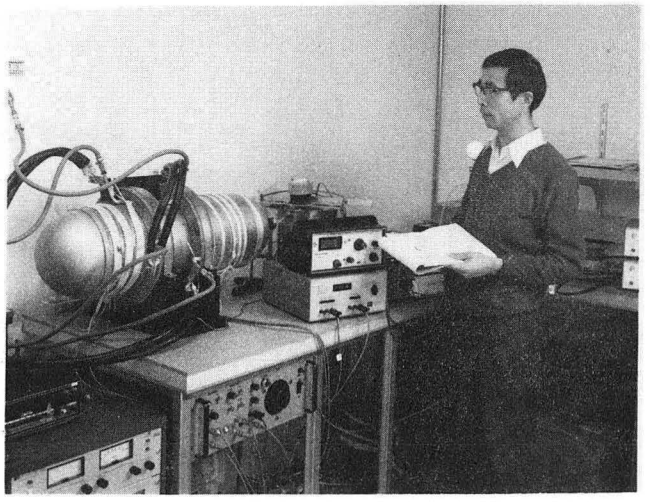

Figure 1. Photograph of the Helmholtz coil system (with test lamp in the integrating system) used to gather the total light flux of the lamp immersed in an axial magnetic field. (CBB 850-9876)

Electrodeless HID Lamp

Subcontractors have completed the first studies of the performance of new gases in electrodeless HID lamp systems. These gases could not be used in the past because of their corrosive interaction with the tungsten filament of lamps with electrodes. One lamp's efficacy was measured at 170 lumens per watt with a color rendering index (CRI) of 50. A lamp designed for optimum color rendition showed a CRI of 95 at an efficacy of 80 lumens per watt. These initial results indicate the vast improvements that can be realized with the electrodeless system. Notice in Table 1 that the 1000-watt high-pressure sodium lamp has an efficacy of 100 lumens per watt with a CRI of 25, while the metal-halide lamp with good color rendition has a CRI of 66 at 80 lm/W.

Diagnostics

To support the Lighting Program's lamp development efforts, we must characterize optically thick plasmas. We have set up spectroscopic equipment for measuring emission and absorption of the low- and high-pressure plasmas.

To study the metallic arc spectra, an electrodeless source assures the spectral purity of the plasma. The source can be operated at frequencies of 13.56 or 27.12 mHz at average power up to 1 kW.

The electrodeless light source can be filled with a variety of materials in the vacuum/filling/baking system.

Planned Activities for FY 1986

Mercury Absorption Studies

A lamp has been constructed and enriched with ^{201}Hg, increasing its concentration from its naturally occurring concentration of 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.

We are planning to complete detailed measurements of the ^{201}Hg-enriched low-pressure gas-discharge lamp. Measuring the amounts of Hg and isotope additions by two methods will assure the high degree of accuracy critical to selecting the Hg isotope for Hg isotope separation.

There are plans to consider an additional isotope separation process beyond the photochemical principles being worked on at GTE, which would utilize the AVLIS system at LLNL. The work in this area is dependent on the availability funds.

Magnetic Enhancement

LBL will systematically measure the lamps housed in the UV integrating cylinder to characterize the phenomenon of magnetic enhancement. The effect will be studied as a function of field intensity, lamp-wall temperature, gas fill, and input power. The angular distribution of the ultraviolet radiation will be examined to determine the extent of polarization. Finally, the change in the hyperfine structure will be studied with the high-resolution Jarrell-Ash spectrometer that has been put into commission.

Surface-Wave Lamp

The critical parameters influencing lamp efficacy including lamp diameter, length, and gas fill will be studied. We will continue investigating methods of screening lamps to contain the electromagnetic radiation. Initial measurements indicate that the levels a few feet from the lamps are negligible.

Electrodeless HID Lamp

The initial goal of this project was to develop a low-wattage, efficient HID lamp to replace the incandescent lamp. The effort to date has examined high-wattage, 400-watt lamps. A model of an electrodeless mercury-discharge HID lamp will be developed and used to determine the minimum wattage lamp feasible.

Diagnostics

The Lighting Program has described a technique to view and study slices of the plasma. The data can be analytically unfolded to determine the spatial distribution of mercury in the excited state through the plasma. A special precision-stepping motor mounted on an optical bench is required for scanning the plasma, and will be designed and constructed for conducting the measurements.

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 electromag-

netic compatibility of buildings, and the interaction of lighting with a building's HVAC systems.

Accomplishments During FY 1985

CONTROLITE

The CONTROLITE program was completed. This computer program is designed to be compatible with an IBM PC and to determine the most cost-effective lighting control strategy to implement for a particular space. A two-day workshop presented the program to 50 participants, including controls manufacturers, lighting consultants, and architects. Discs and the documentation were given to the participants. Several errors were subsequently found by these participants and the final corrected program was made available. Over 100 copies have been requested and it appears that CONTROLITE will be a standard lighting program.

Advanced Lighting Design

The luminaire and lamp/ballast thermal testing chambers have been constructed and debugged. Some initial data show several important thermal features and advantages of the air-handling fixtures. We have presented papers and some preliminary results at the IES and IEEE/IAS meetings, and are now prepared to test various generic-type fixtures for the energy-efficient lighting layouts and the NBS program.

Figure 2 is a photograph of the luminaire thermal test chamber. The luminaire is placed in position and the room temperature and air flows can be varied. The rate of air flow is measured by an orifice in the tube shown in the figure. Figure 3 shows the dramatic increase in the light output when the minimum lamp wall temperature is decreased from 55°C to 40°C by an air flow of 50 cfm through the fixture.

An external cold spot inducer was devised based on the Peltier effect. Cursory experiments showed that supplying less than 0.5 watt to the device could save 6 to 10 watts for a 4-ft, F-40, fluorescent lamp, operated at an elevated temperature, which represents many typical installations. A patent disclosure has been filed and legal counsel has recommended applying for a patent. In FY 1986 LBL will develop concepts for practical use of this invention. About 40% of all fluorescent lighting installations are operated in this elevated mode. If widely used this device has the potential of saving 80 billion kWh annually.

Planned Activities for FY 1986

CONTROLITE

To further the use of lighting controls, we are preparing to write a chapter for the new Illuminating Engineering Society (IES) Handbook. This is the first time that a section has been devoted to lighting controls.

Advanced Lighting Design

We will use both the lamp/ballast integrating chamber and the luminaire thermal chamber to measure the thermal performance of four types of fixtures: open air, enclosed, air-handling, and parabolic. The data will be presented to NBS to help

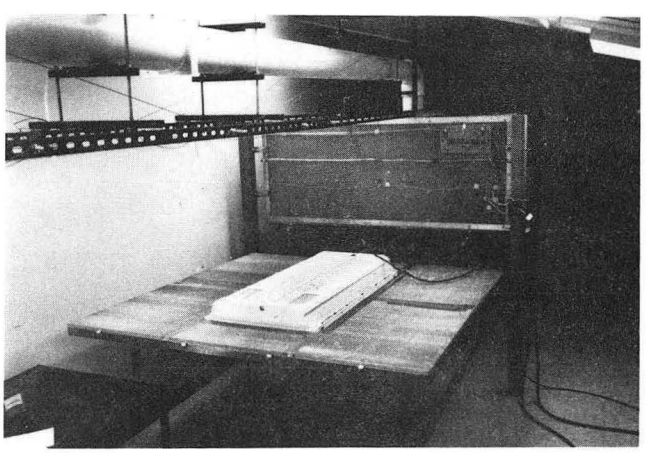

Figure 2. Photograph of the luminaire thermal test chamber for measuring thermal performance of fixtures. (CBB 855-4074)

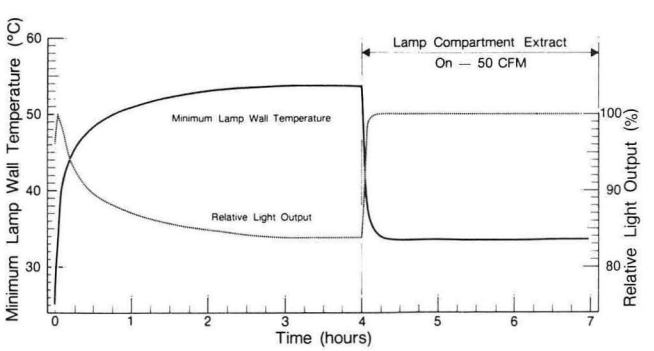

Figure 3. Plot of the minimum lamp-wall temperature (MLWT) and relative light output as a function of time for no air flow and a 50-cfm flow of air through the fixture. (XBL 858-3264)

their project determine the effect of lighting systems on the heating and cooling of spaces. In addition, we will present these techniques to NEMA to aid in setting up recommended testing standards, as well as establishing an explicit metric for the thermal performance of luminaires.

Optimization of Design Layouts

We are initiating our effort on dynamic lighting design. An open office space will be laid out and data from our luminaire test chamber and lamp/ballast integrating chamber will be input to determine the best energy-efficient system. The lighting will be evaluated with respect to economics as well as quality of illumination.

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) interactions between lighting and visual display terminal operation that affect productivity or comfort (carried out at the UC School of Optometry), and (3) analysis of the general relationship between lighting and visual performance.

In the first area 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 1985

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 if they did cause a response of the visual system.

Planned Activities for FY 1986

UCSF Program

The health impacts work will continue; plans will be made to convene the advisory group to review 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 refresh 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. Harris, A. Meier, H. Akbari, J. Busch, P. le Coniac, C. Conner, D. Connell, J. Eto, D. Flora, B. Gardiner, C. Goldman, K. Greely, S. Greenberg, M. Meal, E. Mills, A. Mitchell, O. de la Moriniere, M. Piette, R. Riley, A.H. Rosenfeld, D. Stein, A. Usibelli, and L. Wall

The Buildings Energy Data Group (BED) compiles, analyzes, and publishes *measured* energy performance data on efficient buildings and equipment. The group's goal is to improve energy efficiency in new and existing buildings by providing designers, owners, managers, policy-makers, and others with feedback on how well technical measures and operating strategies actually work to save energy or peak electric demand, and how this performance translates into net dollar savings. We provide information that will help these users make better-informed decisions on building design, operation, financing, energy demand forecasting, and public policy.

The core of BED's activity involves the development and updating of a data base series called BECA (Buildings Energy-Use Compilation and Analysis), and use of these data for comparative studies of measured building performance. BECA 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)
- Efficient appliances and water heating systems (BECA-D)
- Comparisons of predicted and measured performance (BECA-V)
- Load management and thermal storage systems (BECA-LM)

Each compilation is independent, but all rely on a computerized data base management system (DATATRIEVE). The data bases can be queried to produce statistics on sets of buildings with similar features, location, function, etc. Data are obtained from a variety of published and unpublished sources, often with the help of collaborators within the research community, private industry, and utilities. Each new entry is carefully reviewed for data quality and consistency. We calculate normalized performance indices and then "echo" the results to our data suppliers, both to verify accuracy of the data and to provide the contributor with some immediate feedback, in the form of results that can be compared with other BECA buildings (or with performance predictions, baseline values, or standards).

The Buildings Energy Data Group is also active in three areas that complement the core compilation effort: development of energy performance indicators, primary data collection and analysis, and studies of conservation potential.

Unlike the dynamometer tests of automobile fuel efficiency (miles-per-gallon), there is no equivalent for buildings that can directly measure and compare their overall energy performance under consistent, controlled conditions. Instead, we must collect detailed information about the building's energy consumption, physical characteristics, and operating schedule, and use these data to extract standardized energy performance indicators. Development of these standard performance parameters is an important research goal of the group.

We often provide informal advice and guidance to data collectors, and, increasingly, participate directly in the analysis of primary data. In special circumstances, where we have identified significant data gaps, BED initiates small pilot projects to directly measure equipment or building energy performance.

The data compilations also provide a valuable data base from which to estimate the future potential for conservation. Studies of conservation potential begin by characterizing the technical performance and costs of series of conservation measures. We then calculate costs of conserved energy, and aggregate these measure-specific data into "supply curves of conserved energy" (or reduced peak power).

THE BECA BUILDING ENERGY-USE COMPILATIONS

Accomplishments During FY 1985

New, Low-Energy Homes

The data compilation for new, low-energy homes (BECA-A) contains over 350 entries. Design strategies include superinsulated, double-envelope, active

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and passive solar, earth sheltered, and combinations of these. Each BECA-A entry includes a building description, occupancy patterns, and measured energy consumption. For a growing percentage of houses we have submetered energy data by end-use and other detailed results of on-site monitoring.

During FY 85, we continued to refine our computerized procedure ("SUBMET") for calculating standardized heating energy performance parameters.[1] We first adjust for variations in inside temperatures and internal gains—the two major occupant-controlled variables. We then use regression techniques to estimate a balance temperature, k-value (response of heating load to changes in outside temperature), and average-season heating loads, based on measured energy consumption and outside temperatures. Houses with significant sources of unmetered heat, such as wood stoves, are excluded from the compilation. This normalization technique permits a more realistic comparison of buildings, but still leaves a large variation in performance, even among houses with similar designs. Results are shown in Fig. 1.

Compared with a base-case (estimated heating loads for typical new U.S. homes), the BECA-A houses tend to require only about 30–50 percent of the heating energy. The best of these houses use less energy for space heat than for water heating or major appliances—under $100/year, even in cold areas of the U.S. and Canada.[2]

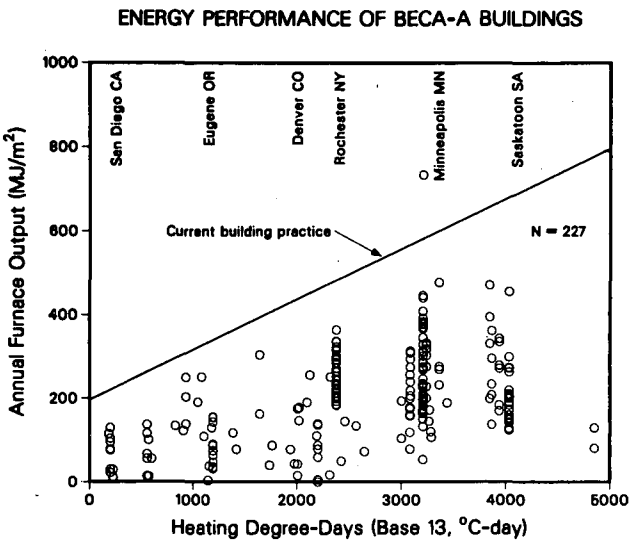

Figure 1. Thermal performance of 319 low-energy homes in the BECA-A compilation. Climate severity is approximated on the X-axis, in degree-days to base 13°C (rather than 18.3°C) to coincide with the average measured balance temperature. Energy consumption is expressed in terms of furnace output, as an indicator of building shell performance, without reflecting differences in heating system efficiency. The energy consumption plotted in the figure is based on the measured consumption, and then adjusted to standard operating conditions and system efficiencies. (XCG 848-13199)

In FY 85 we added about 50 data points to BECA-A, and began work on incorporating a large data set of well-monitored homes from the Pacific Northwest. The Bonneville Power Administration (BPA) selected our normalization technique for the analysis of data from the Residential Standards Demonstration Project.

Residential Retrofits

The compilation of measured energy savings from retrofits of residential buildings (BECA-B) now contains 90 single-family retrofit projects, representing over 50,000 homes, and 105 multifamily buildings, representing over 25,000 units. This year much of the data collection and analysis has focused on multifamily buildings, as summarized below.[3] We also participated in the data collection and analysis of five retrofitted public housing buildings in San Francisco.[4] Results on both single-family and multifamily retrofits are found in Ref. 5.

The most popular conservation measures in our sample of multifamily buildings involved HVAC system retrofits:

- heating system controls, such as outdoor resets, high-limit outdoor cutout, and aquastat,
- heating system equipment measures, such as new burners and vent dampers
- boiler replacements, and
- improved operations and maintenance practices.

The median cost of multifamily retrofits was $534/unit; costs were under $250/unit in 40 percent of the buildings. This suggests that many building owners confined their retrofit efforts to fairly low-cost measures, a pattern we find repeated in commercial (leased) buildings. For the multifamily sample, median annual energy savings were 11.7 MBtu/unit, or 16 percent of pre-retrofit energy use. Seventy percent of the projects saved between 10 and 30 percent.

Energy savings and cost-effectiveness are strongly influenced by the choice of retrofit strategies. We classified each building in the data base by retrofit strategy, and then calculated, for each group of projects, median values for energy savings, total cost, simple payback time, and internal rate of return (Table 1). Some interesting trends emerge when the

Table 1. Energy savings and cost-effectiveness of various retrofit strategies.[a]

Retrofit Strategy	Number of Projects [No. of Units]	Median Site Energy Savings [MBtu/unit-yr.]	Median Total Cost per Unit (1985 $)	Median SPT (years)	Median IRR (%)
Heating Controls	18 [5268]	6.5 ±2.6	48 ±58	1.2 ±0.5	95
System Packages[b]	13 [278]	20.3 ±4.9	177 ±146	1.9 ±1.0	47
System and Shell Packages	6 [138]	51.7 ±13.0	1141 ±358	2.2 ±1.6	50
EMCS[c]	4 [2858]	14.0 ±17.7	618 ±133	3.0 ±1.4	27
Shell Packages	14 [3397]	6.4 ±4.3	609 ±206	8.3 ±4.9	7
Distribution System Conversion[d]	7 [118]	23.7 ±12.5	780 ±1277	8.9 ±3.6	17
Window Measures	10 [11073]	11.0 ±1.2	1090 ±112	15.6 ±2.4	10
Solar DHW	6 [388]	2.3 ±3.6	568 ±21	36.5 ±57.0	0
Metering Conversion[e]	11 [2983]	10.6 ±4.4	228 ±5	1.4 ±0.3	57
Boiler Replacement & Controls	5 [568]	27.9 ±25.8	2191 ±1237	5.5 ±8.3	19
Boiler Replacement & Windows	7 [393]	21.0 ±5.3	2434 ±204	17.2 ±2.2	2

[a]Results given are median values plus standard error (se) of the sample median. Standard error of the sample median is computed from:

$$se[median(X)] = IQ(X)/N^{0.5}$$

where IQ is the interquartile range and N is the number of projects.

[b]"Packages" refers to sets of retrofit measures implemented at the same time, so that the savings attributable to individual retrofits cannot be determined. System packages are retrofits to space heat and hot water systems. Shell packages means that various envelope measures were implemented (e.g., insulation, caulking and weatherstripping, storm windows).

[c]EMCS refers to management control systems.

[d]At these projects, the heating distribution system was converted from steam to hot water.

[e]The category "Metering Conversion" includes conversion of electricity billing from master-metered to individual unit submetering and installation of tenant metering systems that divide total gas use in an apartment building on the basis of indicators that are proxies for the amount of heat delivered (e.g., number of hours that the thermostat calls for heat).

multifamily retrofit data are segmented in this fashion. For example, envelope measures (e.g., "shell" packages and window measures) tend to have much longer payback periods (over 8 years) than many of the heating system retrofits (under 2 years). Costs associated with HVAC system retrofits span a wide spectrum, ranging from $50 to $2400 per unit (high-cost HVAC retrofits typically include replacement of the existing heating plant). The most cost-effective retrofit strategies are not always those that produce the highest energy savings. For example, median energy savings were relatively small in buildings that installed heating system controls, although these measures proved to be exceptional investments, with a median payback time of just over one year.

Conversion to tenant submetering systems, although not strictly a technical efficiency measure, appeared economically attractive from the perspective of the building owner. Based on a sample of 10 low-rise Minnesota buildings, reduction in gas heating energy use (due to changes in occupant behavior) averaged 15–18 percent below pre-retrofit levels. Note that where submetering means that space heating costs are shifted from owner to tenant, this retrofit must be accompanied by a corresponding rent reduction to avoid significant increases in the tenants' total costs.

New, Energy-Efficient Commercial Buildings

The compilation of new, energy-efficient commercial buildings now includes 152 entries from the U.S. and abroad.[6] Most of the buildings are award winners, demonstration projects, or have been featured in case studies as energy-efficient buildings. About two-thirds of the buildings are offices. The average energy intensity for the BECA-CN offices is 66 kBtu/ft^2-yr (measured at the site), about half as much as the existing U.S. stock. A handful of the most efficient new buildings use only 20–30 kBtu/ft^2-yr (site).

We compare commercial building performance in terms of energy consumption, peak electric demand, operating conditions, energy costs, and building costs. These comparisons must consider services supplied by a building, such as computer centers, parking garages, and outdoor lights. Figure 2 shows the distribution of site energy use for office and school subsamples chosen to highlight such differences. For example, the offices with computer centers tend to have higher energy use than the other samples.

Over the past year we have placed increased emphasis on collecting and analyzing data on commercial building peak demand and electric load profiles; peak demand charges can represent 30–50 percent (or more) of total electricity costs for a large, new building. The "operating load factor" (OLF), or ratio of the average demand to the annual peak demand, represents a useful performance indicator. (Average demand is the annual electricity consumption (kWh/year) divided by 8760 hours/year.) Figure 3 shows the OLF for 32 all-electric offices in BECA-

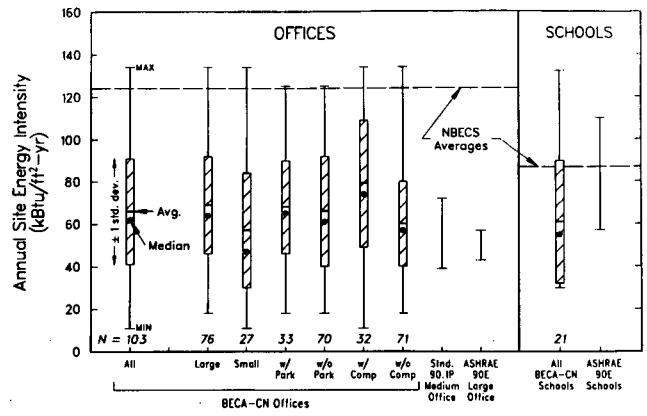

Figure 2. Annual site energy intensities for BECA-CN subsets. Maximum, minimum, average, and median values, and standard deviations are shown for 8 subsamples of BECA-CN offices and schools. ASHRAE Standard 90 simulation estimates, and NBECS averages for the U.S. stock (1979) are plotted for comparison. (XCG 861-7038)

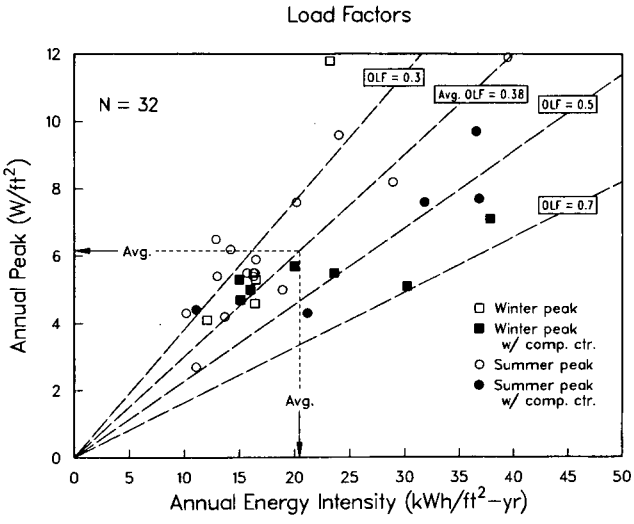

Figure 3. Operating load factor for all-electric buildings in BECA-CN. Operating load factor (OLF) is defined as the ratio between the buildings annual peak demand and electricity consumption. Lines of constant OLF, and the sample average (OLF = 0.38) are shown for comparison. Buildings with computer centers tend to have higher operating load factors. (XCG 8512-562)

CN. From a peak-shifting or shaving perspective, buildings with load management should have higher load factors. The buildings with computer centers have high load factors because of higher baseloads.

In 34 cases we have 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 lower estimates of miscellaneous loads such as receptacles, exterior lighting, and computers. In some cases, the actual building did not include special energy features originally considered in design studies; in others, poor performance or changing operational requirements rendered some features unusable. One example was a night-time cooling system that could not be used as planned because the building was occupied twenty-four hours per day rather than the ten hours assumed in the design. High ventilation rates needed to flush the building were inconsistent with nighttime occupancy.

Commercial Retrofits

The compilation of measured energy savings from retrofits in nonresidential buildings (BECA-CR) includes over three hundred entries.[7] 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 are measures that involve HVAC operations, maintenance, and lighting. The median retrofit cost is \$0.40/ft^2, resulting in a median payback time of only one year. We conclude that owners of many commercial buildings use very conservative investment criteria, and that actual investments seem to fall well short of the economic and technical potential. Table 2 shows the breakdown of median savings in the BECA-CR compilation, by building type.

Energy management in commercial buildings is often a continuing process, without clear "pre" and "post" periods. Our recent data collection has emphasized multi-year energy consumption records,

Table 2. BECA-CR summary. Summary of site energy savings from retrofits of commercial buildings that reduced energy use.[a]

Building Type	N	Savings (median)	Median Site Energy Savings (MJ/m^2-yr.)	(kBtu/ft^2-yr.)
Schools				
Elementary	82	27.7	345	30.4
Secondary	28	24.5	428	37.7
Colleges	13	44.5	1143	100.7
Offices				
Large	34	21.4	323	28.5
Small	13	20.8	370	32.6
Hospitals	6	26.4	1060	93.4
Retail	2	12.3	91	8.0
Hotels	5	14.4	480	42.3
Other				
Post Offices	92	24.0	318	28.0
Assembly	2	52.2	2141	188.6
Correctional	1	6.0	96	8.5
Other	14	23.6	268	23.6
TOTAL	292	24.6	350	30.8

[a]All averages are unweighted, i.e., each building's savings are weighted equally regardless of floorspace or energy usage.

in order to analyze long-term trends. Tracking buildings for several years can provide added insight into a building's energy performance, including the effects of successive retrofits or operational changes, the durability of savings, and the building's response to weather.

Residential Water Heating

In FY 85, we continued our compilation of measured energy performance of water heating systems (BECA-D). The compilation includes studies of new water heater performance (including heat pumps), retrofits (such as tank insulation), and baseline energy and water usage measurements. The compilation contains 75 entries, including measurements of over 11,000 water heaters.[8] In spite of the large number of water heating monitoring projects, few measured results include sufficient data on temperature, water usage, and heater/storage characteristics to make valid performance comparisons. Conclusions from the BECA-D data are summarized in Table 3.

Table 3. BECA-D summary. Measured energy performance data on residential water heating.

Item	Value[a]	Number of Households
Average Hot Water Use	17.7 gal/person-day (4.1)	273
Average Water Heating Electricity Use	4890 kWh/year (1483)	7115
Average Savings from Thermal Traps	340 kWh/year (158) 16 therms/year	74 1
Average Savings from Insulation Blankets	460 kWh/year (163) 11 therms/year (12)	79 25
Heat Pump Water Heater, Seasonal COP	1.98 (0.25)	500

[a]Numbers in parentheses are standard deviations.

Model Validation

The BECA-V compilation includes comparisons of building load predictions with measured energy performance. The data base contains over twenty-five studies, comprising about one hundred simulations of building energy use, performed with eighteen computer models. Complex or simplified methods of predicting building energy use play a central role not only in buildings research, but also in design and retrofit decisions, setting of efficiency standards, and the structuring of conservation programs. The success of these applications hinges to a large degree on the accuracy of model predictions. We find that prediction accuracy depends on several factors beyond the validity of the model's algorithms, most notably the quality of input data (or default assumptions) and the skills of model users.[9,10] With good quality data, many models can predict energy use of occupied buildings within 20% of the actual measured values.

Another aspect of model verification is inter-model comparisons. As part of a residential data analysis project funded by the Bonneville Power Administration, we compared results of three simplified heating load calculation methods with reference values produced by DOE-2, a state-of-the-art hourly simulation model.[11] We found that two of the models produced results reasonably consistent with DOE-2, except when modeling very tight, well-insulated houses. The third model consistently underestimated heating loads, compared with DOE-2. Inter-model comparisons of this sort can be a useful first step in planning (more costly) verification studies of predictions vs. measured data. They may also provide guidance in design of monitoring projects, concerning the choice of analytical models and the level of detail, accuracy, and duration for on-site data collection.

Planned Activities for FY 1986

Data collection and analysis for the BECA compilations will continue during FY 86, with special emphasis on detailed, submetered data; case studies of multiyear performance; refinement and validation of techniques for occupancy- and weather-normalization (particularly in larger, complex buildings); and more outreach and direct contacts with current and potential users of measured BECA data. The focus of activities will vary with the compilation.

For new, low energy homes (BECA-A), we will continue to investigate the performance contributions of specific components (glazing, reduced infiltration, efficient heating equipment), based on submetered data that will be available from the Pacific Northwest and other regions. The analysis of measured data on cooling will begin with the testing of performance parameters, first using "synthetic" (simulated) data. Economic analyses will focus on the incremental cost data from low-energy homes in the Pacific Northwest, plus an improved baseline analysis using national stock survey data. The data on low-energy buildings outside of the U.S. and Canada will be significantly expanded, as we obtain the results of several dozen monitored demonstration sites in France, Denmark, Sweden, and other European countries. Finally, we hope to expand our collection of performance data on "production" housing built for resale, but designed with energy-saving features—as opposed to custom-designed low-energy houses, or special demonstration projects. This will probably mean using whole-building data (perhaps supplemented with simplified, short-term test data), but aggregated across several houses of the same design in the same subdivision.

The residential retrofit data base (BECA-B) will continue to concentrate on multifamily buildings in FY 86, based on the more detailed data that will become available from the multifamily component of DOE's Buildings Energy Retrofit Research project. We will extend the savings calculation methods to accommodate end-use submetered data, indoor temperatures, and other changes in operating conditions. Over one hundred multifamily retrofits from Europe will be added to the compilation this coming year.

Up to now, the commercial buildings compilations (BECA-CN and BECA-CR) have depended largely on information which can be extracted from billing data. We believe that more detailed energy performance studies of occupied commercial buildings are needed. Monitoring of commercial buildings is already ten years behind the residential sector; only in 1984 did extensive submetering projects begin. As these data become available, future BECA efforts will focus on more detailed analyses of submetered data, for fewer buildings. As discussed below, we are currently testing techniques that are "intermediate" between billing data and continuous, multi-channel monitoring, especially the use of data that can be extracted from energy management systems already in place.

Our present compilations have shown that internal loads represent a major unknown factor in commercial buildings.[12] We will continue to investigate actual energy use for these loads, especially computers and electronic equipment. Detailed data of this sort will contribute to a better understanding of differences between predicted and measured energy use (or retrofit savings).

Even without more detailed data, cross-sectional comparison at the utility bill level should be of interest for buildings with standardized designs and similar functions, but located at different sites. We plan to assemble and analyze such data for efficient or retrofitted retail chains, banks, restaurants, etc. We are also collaborating with ASHRAE on a series of detailed, multiyear case studies of previous Energy Award winners.

Beginning with simulated data from the DOE-2 computer model, we are examining the weather-responsiveness of various commercial building types, in order to develop guidelines for weather-adjusting the energy use of these larger buildings. This is related to our continuing project with the Building Owners and Managers Association (BOMA), to refine and expand the energy section of their annual survey. Our participation consists of a series of investigations, principally with DOE-2 simulation data, to determine the key factors influencing commercial building energy consumption.

Given the importance of peak electric load management in commercial buildings, we will continue the BECA-LM compilation begun in FY 85. The emphasis will be on measured performance of thermal storage and energy management systems. Depending on data availability and staff resources, we hope to begin a new data compilation on retrofits and efficient new designs of industrial buildings (BECA-I).

Analysis of several multifamily retrofit projects will also contribute data on savings from water heating measures. We will continue to seek out measured data that permit comparisons of appliance performance in the field with laboratory test results.

PRIMARY DATA AND ANALYSIS

Accomplishments During FY 1985 and Planned Activities for FY 1986

The BECA compilations often reveal gaps in the data on measured performance of buildings and equipment, or a need to systematize methods of data collection, analysis, or comparison. In response, we occasionally undertake small, pilot monitoring projects to begin filling these data gaps and to test new approaches to data collection and analysis. Finally,

we work with other groups at LBL to develop standard measurement and analysis protocols, and informally advise people about to undertake a field monitoring project.

In past years we conducted small monitoring experiments on commercial, reach-in refrigerators and drinking water coolers, two end-uses that have been largely neglected in previous studies of commercial sector energy use and potential savings.[13,14] Even our limited monitoring suggested that, on a national basis, these two end-uses consume significant amounts of electricity—equivalent to 2.5 times the output of a 1000-MW baseload power plant. We found that both appliances could be designed to use thirty percent less electricity, with only small additional investments. This year we will participate in a BPA-sponsored study to test, in the laboratory and in actual homes, the performance of high-efficiency imported Japanese refrigerators. We will continue, at a low level, monitoring and data compilation on other poorly-documented appliances and equipment, including furnace accessories, refrigerated vending machines, and computer workstations.

A major new area of activity involves the use of in-place energy management systems (EMS) as sources of relatively low-cost performance monitoring data.[15] Compared with whole-building utility billing data, these systems in many cases can provide far more useful information on performance of building subsystems, energy consumption by end-use, and load profiles. Compared with a dedicated, on-site monitoring and data-logging system, extracting data from an existing EMS can be far more cost-effective. Use of an EMS offers two added advantages: the possibility of long-term tracking of building performance, and more direct feedback to help the building operator optimize control settings, maintenance schedules, and make other energy-related management decisions based on actual building conditions and responses. In FY 86 we will conduct a series of pilot studies to obtain practical experience with EMS-derived performance data at several commercial facilities.

CONSERVATION TECHNOLOGIES DATA AND POTENTIALS

Accomplishments During FY 1985

We have participated in several studies of the estimated technical and economic potential for conservation in the buildings sector.[16–21] In the past, such estimates were often based on engineering calculations or computer model predictions. Future studies will increasingly rely on measured data, as documented in the BECA data bases. For electricity end-uses, there will also be increased emphasis on peak demand savings and on load profile impacts in general, to make such "conservation technical potentials" studies more directly relevant to utility system "least-cost" energy planning decisions.[22]

In one recent study, we examined the maximum technically feasible potential for conservation in the residential sector of BPA's service area.[18] Over three hundred conservation measures were evaluated, using the LBL computer program, CPS 2.0. Each measure was ranked according to its "cost of conserved energy," and aggregated in the form of "supply curves of conserved energy." An example of a conservation supply curve is shown in Fig. 4. Our study found a technical potential for saving over 2800 billion kWh by the year 2000, a 42 percent reduction compared with BPA's "conventional" demand forecast.

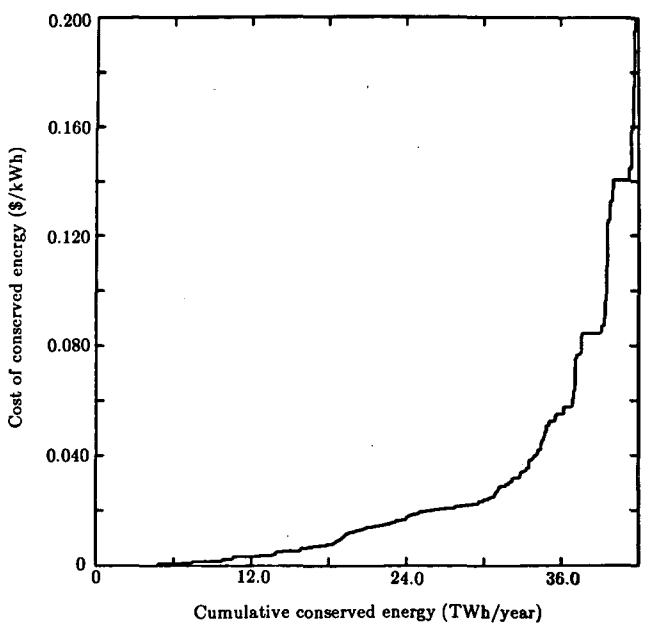

Figure 4. A supply curve of conserved energy for the residential sector in the Pacific Northwest, composed of many individual "steps." Each step represents a conservation measure applied to a subset of similar houses. The height of the step indicates the measure's cost-of-conserved-energy; the width represents the technical potential for savings if that measure were applied wherever feasible, throughout the stock. A measure is cost-effective if its cost-of-conserved-energy is less than a reference price (i.e., marginal or average cost). This supply curve shows that by the year 2000 there is a potential for saving 41.5 billion kWh at a cost of less than $0.15/kWh. This represents 42 percent of the forecasted residential electricity use in the region. (XBL 866-2322)

In another study we examined conservation technologies for new and existing commercial buildings in California.[18] The study analyzed technical performance, costs, and applicability of efficient technologies for air conditioning (including coolth storage), ventilation, refrigeration, motor efficiency, electric lighting, and daylighting. The study demonstrated that both existing and emerging technologies could significantly reduce energy use and peak power in California commercial buildings. However, we also concluded that installation of hardware does not, by itself, necessarily guarantee either energy savings or peak load reductions; a sustained effort at good building operation and management is also crucial. Indeed, carefully managed buildings **without** exceptional energy efficiency features will sometimes outperform those with "state-of-the-art" design but less continuing attention from the operator. We also found a number of areas with inadequate or poorly documented information, especially in terms of a technology's impact on electric load profiles. This again underscores the need for more detailed performance monitoring and analysis of occupied commercial buildings. The findings from this study were designed to be used not only by utility program planners and forecasters, but also by energy auditors in the field.

Planned Activities for FY 1986

The analysis of conservation and load-shaping potential will continue in FY 86, under a new Congressionally-mandated program to assist utilities and state regulatory agencies in developing data and analytical tools for "least-cost" energy services planning. Our efforts will focus on three areas:

- Updating the data base on residential and commercial technologies, with an emphasis on measured as opposed to calculated savings.
- Developing and testing the next generation of the CPS computer model for calculating conservation supply curves, to include a simplified micro-computer version, and capabilities for evaluating electric load-shaping impacts;
- Cooperative projects with selected utilities and states to apply these common models and data bases, using baseline stock and energy use data for specific utility service areas.

Several states have already indicated an interest in collaborating on least-cost studies, or have initiated projects of their own that can be enhanced by the national program through sharing of experience and data.

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Building Energy Simulation*

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The goal of the Building Energy Simulation Group (BESG) 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, the current generation of which is known as DOE-2, 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]

The BESG is also undertaking projects that are designed to lead to the production of the next generation of building performance simulation programs. The main efforts in the advanced simulation area at this time are the creation of a simulation "kernel" system and organization of the simulation development community to enhance collaboration. The kernel system has three main components: software primitives, including a component model library and simulation tools; software harness to facilitate the construction of simulation programs by allowing general linkage of component models and support models; and a knowledge base, which will contain the rules of simulation development and use so as to allow, at a future time, the construction of expert systems for building performance simulation. These three aspects of the kernel system will provide the basic tools and information to allow the BESG and other groups to develop the simulation programs of the future. They will also provide a mechanism to facilitate exchange of research results and technology advances, and a basis for integrating performance simulation into CAD and expert system software.

ACCOMPLISHMENTS DURING FY 1985

The BESG maintains a research effort that continues to develop new versions of DOE-2. 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, which is the latest version completed and released to the public in 1985, are described below.

Functions

The DOE-2 simulation program consists of 9 modules with about 73000 lines of FORTRAN source code. Although, with regular BDL input a user can describe many simulation tasks, there are cases when standard capabilities are not enough. Examples of these might be: (1) treatment of building components such as windows with special properties; (2) use of different algorithms for some types of calculation; (3) computation of coefficients or intermediate values that are used in the regular simulation algorithms; (4) input of values that are not allowed by the standard BDL rules; (5) output of values that are intermediate results or are a combination of calculated values; or (6) quickly testing certain algorithms without modifying and recompiling the BDL and simulation programs. In order to allow these broader simulation capabilities we have implemented the "functions" feature in the DOE-2.1C LOADS program.

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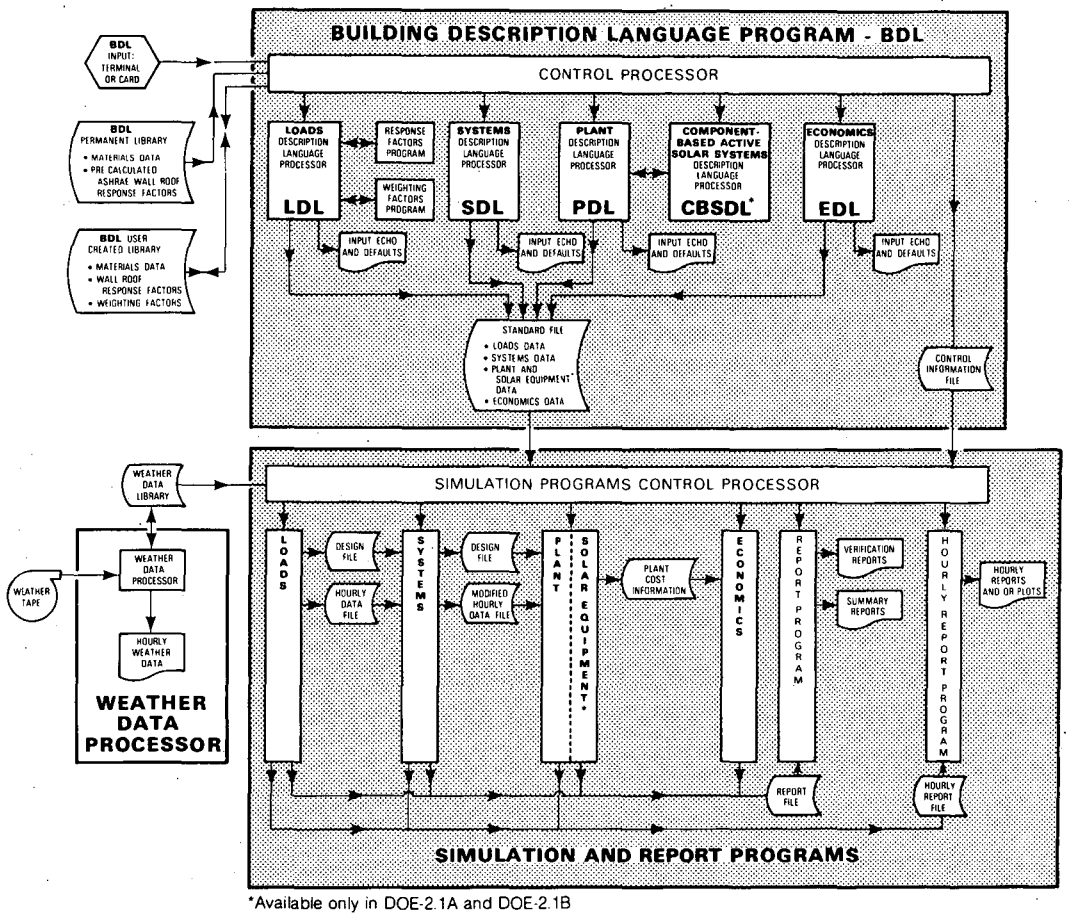

Figure 1. DOE-2 computer program configuration. (XBL 8010-2210B)

Using BDL, one writes in a subset of the FORTRAN language a subroutine that is similar to the ones in the LOADS simulation program. This subroutine has the capability of accessing and modifying all the variables that are used in the regular simulation modules. This newly added subroutine is triggered by BDL keywords in each component of the LOADS input. For example, if in the WINDOW command we say FUNCTION = (*FUNC1*, *FUNC2*), in the simulation phase every time the window calculations are done for that window the function FUNC1 will be triggered before the standard DOE-2 window computation, and FUNC2 will be triggered after the standard DOE-2 window computation. FUNC1 may be used to preset some of the constants and variables that are used in the regular DOE-2 algorithms. FUNC2 may be used to modify or completely recalculate the results that are computed by the regular DOE-2 algorithms.

The specifications of FUNC1 and FUNC2 follow the usual LOADS input. They start by using the ASSIGN statement to associate the simulation variables (that the function will use or alter) with the local function variables. This stage looks redundant, but is needed because some variables that are used in the simulation are pseudo-FORTRAN variables that may be more than 6 characters in length, and may contain embedded dashes. The ASSIGN statement also causes BDL to produce the necessary information to access these variables. Any variable inside the DOE-2 calculations can be accessed by an offset with respect to the beginning location of a labelled common block, or by a constant offset plus a base pointer with respect to the blank common block. With the ASSIGN statement, the local variable that will be used inside the function gets this access information.

Inside the computation section of the function, the local variables mentioned in the ASSIGN statement can be used in algebraic or logical expressions, or in I/O statements, just as in FORTRAN. These expressions are converted into sequential instruc-

tions to be evaluated at simulation time. The instructions are operator-operand pairs that include arithmetic, logical, I/O, and go to operations that are used in a general purpose computer.

In the simulation phase, whenever the FUNCTION keyword is used the following events take place. The appropriate function description block is accessed. By looking at the variables table, and using the access information in it, the values to be used in the function module are fetched from the DOE-2 simulation data structure into the local variables mentioned in the function. The next step involves the step by step execution of the instructions that define the arithmetic, logical, and I/O statements of the user input. After this, and before returning to the regular DOE-2 simulation stream, the values that were changed by the function are returned back to the DOE-2 simulation data-structure, again using the access information belonging to this function's variables table.

An example of an application of FUNCTIONS is given is Ref. 17, in which DOE-2 analyses are performed to evaluate innovative windows which use optical switching materials like electrochromics and photochromics for sun control.

Sunspace/Atrium Model

In a collaboration with the RAMSES group at the University of Paris-South, new capabilities have been added to DOE-2.1C to allow simulation of residential sunspaces (such as attached greenhouses) and commercial atria. This work was stimulated by the fact that sunspaces and atria are currently very popular architectural elements, and, being quite complex from a thermal point of view, require an accurate energy analysis to produce a design which is energy efficient and comfortable year-round.

The new algorithms allow simulation of different forms of heat transfer between the sunspace (or atrium) and adjacent rooms which could not be calculated with DOE-2.1B (see Fig. 2).

The calculation of beam solar radiation which passes through the sunspace into adjacent rooms is done by using the DOE-2 shadow routines to project the hourly-varying solar image of each exterior window onto the different interior surfaces in the sunspace. In this calculation external obstructions (such as overhangs and neighboring buildings) and internal obstructions are accounted for. Diffuse solar radiation incident on the interior surfaces of the sunspace is also calculated. This radiation, which is assumed to be uniformly distributed throughout the sunspace, originates by transmission through the exterior windows or by internal reflection of beam radiation.

The user can specify any of several different forms of convection between the sunspace and adjacent rooms. These include fan-forced or buoyancy-driven air circulation 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 into the sunspace, where, after mixing with the sunspace air, it is either exhausted or transferred back to the central air handling system.

The program makes available several mechanisms for controlling heat gain and loss from the sunspace and heat exchange with adjacent rooms: (1) Air flow between sunspace and adjacent rooms can be turned on and off via a time-clock schedule or by a controller which acts on the the sunspace-to-room temperature difference. (2) A venting algorithm allows outside air to be circulated through the sunspace to prevent overheating. The venting can either be fan-forced or natural. If forced, a fixed air-change rate is used. If natural, the program calculates the air-change rate from windspeed and inside-outside temperature difference using user-specified correlation coefficients. (3) For sun control, fixed obstructions such as fins and overhangs can be modeled, or movable shading devices can be deployed on exterior or interior glazing according to a time-of-year/time-of-day schedule. Alternatively, shades can be deployed whenever transmitted solar radiation exceeds a user-specified threshold value (which may vary seasonally or by time of day). More complex

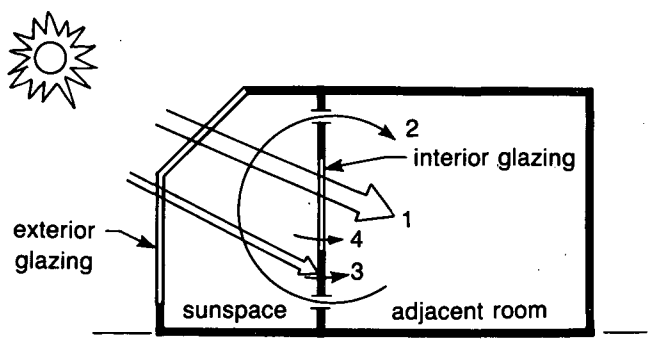

Figure 2. Cross section showing different forms of heat transfer between a sunspace and an adjacent room: (1) solar radiation passing from sunspace to room through interior glazing; (2) natural convection by thermocirculation through upper and lower vents; (3) delayed conduction through interior wall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

dynamic controls are possible with functional input (see previous section). (4) Conductive heat loss can be reduced by using movable insulation on sunspace exterior or interior windows. The insulation can be deployed according to a schedule or deployed whenever the outside temperature falls below a threshold value.

In order to track the large temperature swings that can occur in sunspaces, the venting and inter-zone convection calculation is done in small timesteps, ranging from 0.6 to 3 minutes depending on the sunspace heat capacity and load in a given hour. The conventional one-hour timestep used in DOE-2 was found to give unstable or unphysical results for the convection calculations, particularly when the temperature difference between sunspace and adjacent room was large at the beginning of an hour.

The interior walls in a sunspace are often fairly massive, so that the delay in the heat transfer by conduction through the wall can be important. The DOE-2.1B program was modified so that interior wall response factors are used in the SYSTEMS program to calculate delayed conduction taking into account time-varying space temperatures. This calculation also considers the interior sol-air effect, i.e., the effect of solar radiation absorbed on the sunspace side of an interior wall.

DOE-2 has a built-in routines which allow daylight illuminance levels in a sunspace to be calculated, although, due to the geometric complexity involved, the program cannot directly calculate illuminance levels in adjacent rooms due to daylight originating in the sunspace. However, functional input allows users to enter daylight factors, obtained from scale model measurements, which give room/sunspace illuminance ratios as a function of sky conditions. The program will then use these factors to determine hourly illuminance values and the corresponding reduction in electric lighting power for rooms with lighting control systems.

An important limitation of the sunspace model is that it does not account for air temperature stratification or in-room convective flows. We therefore caution against its use for multi-story atria unless the atrium air is well-mixed by the distribution system.

The French RAMSES group will validate the sunspace model against measurements of insulation, temperature, and inter-zone air flow for attached sunspaces on an apartment building near Paris. The program has been extensively tested in an energy analysis of the Pacific Museum of Flight in Seattle.[15] This building, which is currently under construction, contains a 48000 sq ft exhibition gallery with a 100% glazed roof through which sunlight can pass to adjacent rooms.

Sample results of the sunspace simulation are shown in Fig. 3, which is based on SYSTEMS hourly reports from the residential sunspace example in the DOE-2.1C Sample Run Book.[5]

Powered Induction Unit

The DOE-2 SYSTEMS program simulates a wide variety of secondary systems. Periodically new configurations appear on the market and are added to the DOE-2 simulation capabilities. The powered induction unit (PIU) has gained popularity in recent years, as designers have attempted to mitigate some of the perceived deficiencies of variable air volume (VAV) systems, and in addition to conserve energy by recovering excess heat from the building core. Consequently a model of the PIU system has been added to the DOE-2.1C SYSTEMS program.

The PIU system resembles the traditional VAV system with the addition, to the VAV terminal box, of a small fan or blower, which induces some amount of air from the plenum. The fan has two functions.

(1) Warm return air from the building core is sent into the plenum. The PIU fans draw this air from the plenum into the exterior zones requiring heat, thus conserving energy.

(2) The fan provides increased air movement when the VAV damper decreases primary air to the minimum, providing increased occupant comfort. In addition, primary air may be decreased below levels normally allowed in standard VAV systems, saving additional energy.

DOE-2 models two types of PIU boxes—series and parallel. In the series unit (Fig. 4) the fan draws air from both the primary (central system) and the secondary (plenum) air streams. The proportion of primary to secondary air is controlled by the VAV damper. The amount of secondary plus primary air is constant, and the fan runs all the time (when the central fan is on) at constant speed. In the parallel unit (Fig. 5) the fan draws air from the secondary air stream only. In addition, the operation of the fan is VAU intermittent—a thermostat set point regulates turning the fan on and off. When cooling is required, the fan is generally off, and the unit operates as a normal VAV. When the primary air damper is at minimum, the fan is on, and the operation is constant volume ventilating/heating. Thus

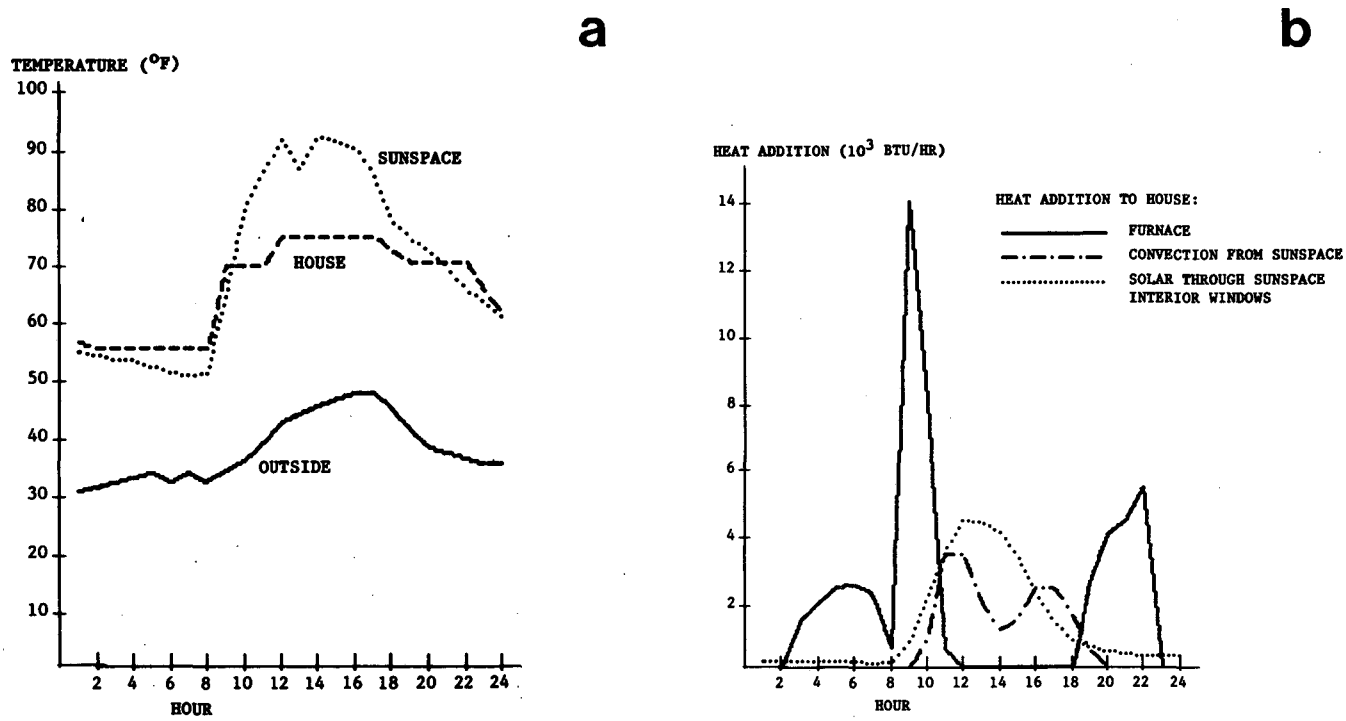

Figure 3. Sample hourly output for a clear January day in Chicago from a DOE-2.1C simulation of a house with a south-facing attached sunspace. The heating setpoint of the house is 70°F during the day and 55°F at night. Warm air from the sunspace is circulated to the house at 200 CFM whenever the sunspace-house 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]

the parallel unit does not supply a fixed air quantity to the zone under all conditions.

The capabilities of the PIU model are fairly broad. As in all DOE-2 system descriptions, the user gives a list of zones belonging to the system. In addition, for the PIU, one zone (the "induced-air-zone," usually the core zone) is denoted as a supplier of secondary air to the rest of the zones in the system. For each zone, the user can select the terminal unit as being constant volume, VAV, series PIU, or parallel PIU. The system can be simulated with any combination of terminal boxes in each zone. Reheat coils are also optional in each zone. When PIU boxes are selected, the user generally sizes the blowers. For parallel terminal units, the user supplies a set point temperature for the blower (which can be scheduled, to allow for setback). Normally the PIU fans operate in conjunction with the main

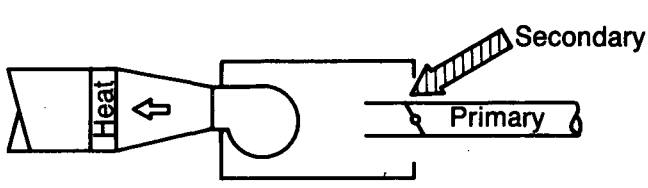

Figure 4. (XBL 843-10166)

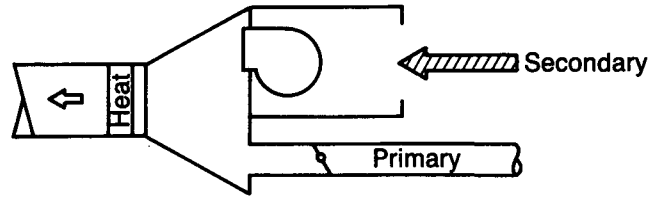

Figure 5. (XBL 843-10164)

system fan, but the user can decide to run the PIU fans independently at night and use the reheat coils to maintain a minimum temperature.

Two features of the PIU system have required changes in the DOE-2 simulation methods: the coupling of the "induced-air-zone" to the other zones, and the intermittent operation of the parallel PIU fan.

Normally DOE-2 models zones as being convectively independent, in order to avoid solving for all zone temperatures and extraction rates simultaneously. The exception has been plenums; air can be supplied from or returned through a plenum. In the case of a PIU system, however, air can be taken from one conditioned zone and supplied to other zones in the system. Since the zone temperatures and extraction rates are then strongly coupled, this situation would normally require iteration. DOE-2 avoids this by: (1) allowing only one zone to supply air; (2) simulating this zone first in each time step. Thus the temperature of the air coming from the induced-air-zone is known, and the rest of the zones are simulated independently. For each zone the program must keep track of the amount of primary air and secondary air required by each zone, and the amount of secondary air available from the induced-air-zone. If more secondary air is required than is available from the induced-air-zone, the additional air is assumed to come from the actual zone being simulated.

For each zone DOE-2 obtains the zone temperature and extraction rate by simultaneously solving the temperature deviation equation

$$\sum_{i=0}^{2} p_i \, (ER_{t-i\Delta} - \dot{Q}_{t-i\Delta}) = \sum_{i=0}^{3} g_i \, \Delta T_{t-i\Delta}$$

and the thermostat equation

$$ER_t = f(T_t) \; .$$

Here p and g are the coefficients of the room transfer functions, ER is the extraction rate, $\dot{Q}$ is the cooling load at constant temperature, ΔT is the difference between the constant temperature and the real room temperature, T_t. Normally $f(T_t)$ is assumed to be a piecewise linear function—the pieces being simply the heating action band, the dead band, and the cooling action band. The fan setpoint for parallel PIU's adds complexity by dividing either the cooling band or the dead band into two pieces (Fig. 6). If $f(T_t)$ were simply linear, ER_t and T_t could be obtained trivially. Since $f(T_t)$ is piecewise linear, and since the limits of each band (the capacities) are temperature

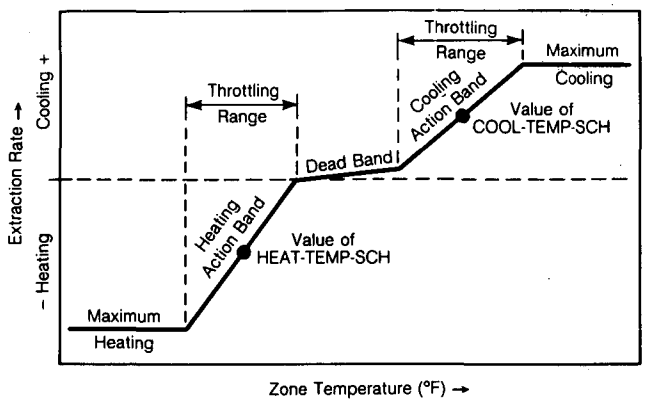

Figure 6. (XBL 825-600A)

dependent, DOE-2 employs a bracketing technique. An extraction rate (at the top or bottom of one of the bands) is assumed, and the temperature response is calculated. Depending on the temperature response, the endpoints are adjusted, the correct band is chosen, and the actual extraction rate and zone temperature are solved for. For the parallel PIU, extraction rates are also assumed for the fan on and for the fan off. Depending on the temperature response, the fan is assigned to be on, off, or a combination of the two for the time step.

Advanced Cogeneration Capabilities

Since its inception, the DOE-2 PLANT program has offered users the ability to study the performance of on-site electrical generation and cogeneration as part of a building's central plant. Recent changes in Federal and State laws, however, have granted small power producers and cogenerators additional flexibility in the operation of dispersed electrical generation facilities (PURPA). These changes permit easier access to electric utility grids for additional support on-site and, in addition, provide a regulated market for the sale of excess electrical energy. No longer must installations be sized to meet electrical peak demands, including the specification of redundant capacity, as in the days of the Total Energy Systems. Electricity may be both freely sold to and bought from the local grid.

The DOE-2.1C version of PLANT acknowledges these regulatory changes with an entirely reworked concept of electricity generators, and heat- and electricity-driven chillers, when operated in a cogeneration mode. When applied to reciprocating internal combustion engines (diesel and spark-ignition) and gas turbines, cogeneration refers to the sequential generation of electricity and the recovery of heat

for use in satisfying building thermal energy demands (heating and cooling). The new features have been used to study the economies of cogeneration in commercial buildings.[14]

The essence of the new concept is the explicit recognition of the energy value of both the cogeneration process-heat and electricity. Previously, the user was only permitted to schedule operation based on the electrical output of the prime movers. The associated heat recovered could only be used to the extent that a demand existed for thermal energy; any excess would be wasted. Now that the availability of a utility grid has loosened the requirement that operation be based solely on the on-site electrical needs, operation can be scheduled to eliminate wasted recovered thermal energy.

The user can now specify a cogeneration mode of operation that is based on either electrical or thermal loads. These features have been integrated with the existing command structure of PLANT to allow operation to be scheduled in either mode, during the course of a given day or on the basis of the magnitude of the load to be served. Thus the user can specify a cogeneration system that will track the thermal loads of a building, where these loads may consist of heating or cooling loads (if a heat-driven absorption chiller is available to accept recovered heat from the prime movers). In a thermal tracking mode with interconnection to a utility, both outputs of the prime movers will be fully used resulting in the most efficient use of energy from the electricity conversion process. At other times, when utility rates for purchase are high, operation can be scheduled for the full output of the generators in order to maximize sales of electricity to the utility. When utility rates for sale are high, operation can be scheduled to follow electrical loads, to minimize purchases from the utility. In addition, when both heat- and electricity-driven chillers are available to meet cooling loads, the output of the prime mover can be specified to balance loads between the two chillers. For example, increased electrical output will be accompanied by increased recovered thermal energy output. Both outputs can be used to satisfy cooling demands, and the loads on the two chillers will be allocated accordingly.

The implementation of these new cogeneration capabilities has required modifications to two aspects of the PLANT program: (a) equipment simulations; and (b) load allocations.

The equipment simulations for the prime movers (reciprocating internal combustion engine and gas turbine) and the chillers (absorption, centrifugal, reciprocating, and double-bundle) have been rewritten. The inputs and outputs of each type of equipment are now described with simple quadratic transfer functions. The coefficients to these equations remain user-definable, as before. The use of quadratic equations permits rapid determination of input values from output values, and vice versa, via the solution of the quadratic equation. This feature forms the cornerstone of the logic underlying the revised load allocation algorithms. Basically, these types of equipment are now no more than black boxes described by a handful of quadratic transfer functions.

The load allocation routines required several levels of modification. First, the original specification of prime mover equipment capacities had to be modified to include a rating for thermal output, as well as electrical output. Next, the user-input load allocation instructions for prime mover operation had to be similarly modified to permit load allocation on the basis of either thermal or electric loads. The allocation logic remains the same; only the nature of the loads being allocated has changed.

The major modification to the load allocation routines took place in the default allocation algorithms, which are used in conjunction with or in place of user-specified operation. The design of the PLANT program allows for varying levels of user-specified and default-optimized operation. For example, prime mover operation may be user specified on a daily/hourly basis, while chiller operation will be determined by the program. At an even higher level of generality, only a cogeneration mode (e.g., track thermal loads) need be specified by the user. The user-specified inputs for operation provide boundaries or constraints for the program's internal logic, which attempts to optimize the equipment operation. Generally the quadratic transfer functions are used to find the optimal operating point for each piece of equipment, and no iterations needed. For one situation, however—the determination of prime mover output when both heat- and electricity-driven chillers are present and a cooling load exists—an iterative solution was necessary.

Expanded Treatment of Energy Costs

The DOE-2.1C version of DOE-2 features greatly expanded capabilities for the treatment of energy costs. In the past decade, novel approaches for the billing of energy (electricity, in particular) have gained wide acceptance. Time-of-day prices, demand ratchets, and lifeline blocks are all increasingly familiar features of current and prospective rate schedules for energy. For dispersed producers of electricity,

Federal law permits several valuation options for the sale of electricity to the electric grid. All of these developments have been incorporated into DOE-2.1C.

The changes are symbolized by the movement of the energy cost commands from the PLANT program to the ECONOMICS program. In previous versions of DOE-2, energy costs were calculated by PLANT and life cycle costs by ECONOMICS. The energy cost calculations in PLANT could handle some simple block rate structures, but could not deal with time-of-day charges, demand ratchets, or complex block structures. In DOE-2.1C an hourly file containing plant loads, fuel demands, and generation is passed to ECONOMICS, allowing ECONOMICS to do all of the energy cost calculations, as well as the life cycle costs.

Rate structures of a number of utilities were analyzed and the structures were reduced to four basic components. These components correspond to four DOE-2 commands, each with its associated keywords and codewords. This discussion focuses on the concepts involved rather than the DOE-2 inputs.

The first component (corresponding to the ENERGY-COST command in DOE-2) identifies the type of energy being valued (fuel type and billing units) and describes the components of a monthly bill (minimum charges, fixed charges, and rate limitations). The first component also contains features for simplified rate structures (all consumption valued at one rate) and provides links to two of the other three components for more sophisticated rate structures.

The second component (SCHEDULE, DAY-CHARGE-SCHEDULE) describes how energy used in the hours of the monthly billing period is allocated into different billing categories. This component is used primarily to specify time-of-day rate structures (e.g., on-, off-, and shoulder-peak periods) and rates that vary by season (e.g., Winter versus Summer). This component is optional; the default is that all consumption during the month falls into the same billing category.

The third component (CHARGE-ASSIGNMENT) describes how the energy in a given billing category is actually billed. This component primarily describes block rate structures; many rate structures provide for successive tiers of use, each of which has a specific rate (dollars per unit of consumption) associated with it. Included in this category are lifeline rates, as well as declining block rates. In addition, some rate structures define the tier boundaries endogenously, based on demand (e.g., kWh/kW).

The fourth component (COST-PARAMETERS) is used only to describe features of electricity tariffs. These features include the specification of demand ratchets, and the PURPA mandated options for the sale of electricity to utilities. Demand ratchets are essentially hurdle levels of demand, which the demand charge can not fall below. They are typically based on a previously recorded level of demand, but can also appear as an average of previous high demands. In addition, the duration of demand ratchet can vary from 12 months down to 1 month, or can be restricted by season. The PURPA-mandated options permit sellers of electricity to choose one of two accounting conventions for the valuation of electricity sales. The first, called Net Sale, offsets purchases of electricity on-site and sells the excess at the utility's avoided cost rates. The second, called Simultaneous Buy/Sell, values all electricity generation at avoided cost, but bills on-site consumption at standard utility rates.

Advanced Simulation

The Building Energy Simulation Group, in collaboration with other institutions [(University of Strathclyde, Scotland; California State University, Fullerton, U.S.A.; University of Paris-South (CNRS), France; Chinese Academy of Sciences, Beijing, China; Centre Scientifique et Technique, France; and the Universite de Liege, Belgium] formulated a proposal for creating the software tools essential for the next generation of building energy simulation models. The intention of this project is not to develop a single new model but, instead, to provide a kernel system of highly-portable software modules and linking protocols which will enable groups in the public and private sectors to construct a variety of customized programs. The work plan has been developed in the context of the following guiding principles: (1) Researchers developing building performance simulation techniques can no longer afford to work as independent groups creating non-interchangeable software. Some mechanism must be found to give all developers access to the developments of others while retaining the flexibility to tailor a simulation system to individual needs. (2) As many energy sources become more expensive, and as improved efficiency technologies become more complex, designers of the future will be required to focus more critically on the intimate relationship between design and performance. This will require a quantum jump in the capability and accuracy of the energy simulation techniques now available. (3) The private sector of architectural and

engineering firms, HVAC equipment manufacturers, and CAD (Computer Aided Design) system vendors does not necessarily support the development of large public domain simulation codes. However, they *will* support developments of the kind proposed, which seek to create and order the building blocks of energy simulation. Private and public sector organizations can then use the resulting kernel system to construct customized simulation systems which embody an appropriate level of detail, offer wide ranging application potential, and use the most up-to-date techniques. (4) Increasingly, energy simulation models will form part of a building's operating system, allowing controls to be optimized in real time before being applied to the building. (5) The building design profession will increasingly rely on advanced CAD software packages. As systems possessing a drafting function proliferate, a demand will grow for explicit performance appraisal software. Designers will then come to rely on simulation techniques to test alternative hypotheses throughout the design stages and post occupancy. Indeed, CAD system integration is perhaps the most effective mechanism for market penetration of advanced energy analysis systems. (6) It is likely that, with the advent of powerful, integrated CAD systems, the design profession will seek to refine the building model and associated performance database beyond the construction phase. One possible scenario is that a client of the future will expect delivery of a computer-based model and performance database, in addition to the building itself. The information regarding building performance is then readily available for inspection. And, of course, the model can be used at any time as the basis for HVAC system maintenance, trouble shooting, and retrofits.

Each of these factors calls for the existence of a modular approach to energy simulation and, it could be argued, would be badly served if only free-standing, monolithic programs continue to be developed.

Existing simulation systems suffer to some extent from one or more of the following:

- The software structure is often extremely inflexible and unyielding. The program may have been conceived in a now-outdated machine environment—possibly batch oriented with card input. This means that the structure is monolithic, imposing extreme management and updating difficulties.
- To date it has not been possible to formulate a common approach to the simulation problem. Funding policy and the ever-present competition within and between the private and public sectors have served only to stifle inter-organization collaboration. The result is that each system has customized I/O procedures and unique internal structure. Physical models are different in each code, as are linking protocols, network representations, theoretical emphasis, and so on. This situation is obviously divisive and generates little confidence in the developments taking place.
- Often system authors are energy specialists, but have little formal training in modern software design and implementation techniques. The resulting software structure is inelegant, with the application knowledge inextricably bound to the source code. Contemporary software engineering favors the separation of the problem-specific knowledge from the basic software structure. This is a fundamental prerequisite of software system design which, if disregarded, can become a serious barrier to software evolution. For example, with existing systems it is often difficult to upgrade algorithms since this may require the detailed knowledge of data structures, internal memory, and possible side effects of one change on the rest of the software package. More elaborate modifications, such as substituting one numerical integration scheme for another, are at present intractable problems.
- In many of the currently available systems, the real world flowpaths have been oversimplified or omitted entirely and simultaneity of processes has not been addressed. An unsuspecting user is then left to struggle with the inadequacies of a model which has unacceptably degraded the all-important temporal and spatial couplings. These issues will certainly raise doubts about accuracy and flexibility and are the main focus in any validation exercise.
- And finally, among the research groups, there exists no clear statement on long term development objectives and task sharing required to accomplish these goals. As a result, many existing systems are not well tailored since each author organization has been forced to address every element of the problem: I/O, heat transfer theory, database design and management, solution techniques, software structure,

validation, documentation, etc. It is clear that no single organization can possess the necessary expertise in all areas. Each system is then promoted in a manner which implicitly undermines the development effort expended on its contemporaries. This is clearly an intolerable situation and one which serves only to fragment an already small development community.

Proposed Workplan

A model-creation system is proposed which consists of three main elements: (1) a public-domain library of *software primitives*; (2) a *software harness*, i.e. executive software for controlling how the primitives are linked into a modelling system, and (3) a *knowledge base*, which contains the rules for model construction. The characteristics of these elements and the tasks required to construct them are as follows.

(1) Software Primitives. Many useful models and techniques already exist within contemporary modeling systems, and much additional software continues to emerge as existing codes are extended or new developments pursued. The first task is to divide the useful, existing software into small, logically independent units called software primitives and place them within a central, public-domain library. Each library entry is then a small software module which performs a single task. The library entries will be independent in the sense that each primitive will have no "knowledge" of any overall data structure. The primitives will obtain data and return results in a standard way, by invoking special primitives which will fetch data from and return data to a central storage area. There will be no attempt to prescribe an overall modeling technology; instead, we hope to allow the free evolution of useful *software tools* for those concerned with developments in building energy simulation. Naturally, portability will be a necessary attribute for all of these tools.

The library will certainly have different types of entries: first principle, governing equation generators for building and system components; self-contained algorithmic approaches; data manipulators, software development and management tools, and simulation support modules. By accepting a high level of pluralism it is likely that a rich modeling base can be formed, entirely free of application assumptions. Many precedents already exist: the NAG, SLATEC, and SPSS libraries in the statistics and numerical analysis fields, GKS for computer graphics, the UNIX operating system and its software tools, and numerous other mathematical and structural (finite element) libraries.

Maintenance of the library will require some support software. Extracting, altering, and adding primitives to the library will require a simple database management system, for instance. It will be necessary to keep track of the history of the library—when a primitive was added or altered, and what the alteration was. This support software will be kept as simple as possible, and existing software will be used whenever possible.

Tasks:

- The required primitives must be identified and agreed upon.
- The standards for constructing a primitive must be considered and clearly defined.
- A proforma (or submittal form) must be drafted and tested to allow different groups to submit algorithms, theories, and procedures for transformation into a useful primitive.
- From the submitted proformas, the corresponding software tools must be generated, documented, and tested.
- The coordination of a regular publication is also necessary to inform the modeling community of the availability of new primitives as they emerge.

(2) Software Harness. The second stage addresses the development of harness or executive software which will allow primitives extracted from the library to be combined into an actual modeling system. This software will consist of a *data manager* used to define and control data traffic among the modules (primitives) and a *simulation controller* to control the sequence in which the modules (or groups of modules) will be executed. Creation of the software harness is analagous to the development of a computer operating system, such as UNIX, where the problems of concurrent processes and communication among processes have already been addressed. Using techniques from this field will facilitate the use of parallel processing at some future point in time. It will also permit the construction of any modeling approach (so long as the necessary software primitives exist), from the establishment and integration of matrix equations representing energy and fluid flow within buildings and their systems, to more pragmatic models which apply simplifications appropriate to the problem in hand.

It is important to note that the harness software is designed for use by model *developers* not by model users. It is an efficient way of building appropriate

models which can be easily improved as the underlying techniques are refined. Users would continue to use prescribed programs, the only difference being that their architecture would be highly modular and so easy to change.

Tasks:

- Supporting software must be created to allow the insertion of new primitives as free-standing entities.
- Data management routines must be devised to control information flow among software primitives.
- Simulation control routines will be developed to receive the flow-graph template and to trigger the operational primitives.
- Whole-building simulation systems must be devised, employing the software primitives and using existing programs as examples.
- Tests of the harness will be constructed and carried out at both the component and whole-building level.

(3) Knowledge Base. The third important stage consists of setting down the rules which govern model construction and use in a design, educational, or research context. This is essential if it is desired to move to so-called "expert" systems.

Concerning model construction, it would seem appropriate to set down the rules employed by some contemporary programs as a first step template. This would include those rules commonly applied to component models, as well as those applicable to overall solving strategies. Normal academic interchange would then serve to modify these templates or to create alternative approaches. Each participant can have his/her say, allowing the more effective templates to become prominent with time.

Model use is a different problem. A proper debate on the role of simulation in the building design process is long overdue. The intention here is to explain how existing and planned energy simulation systems work. This knowledge is required by those future developers who will construct expert systems in this application area. It is proposed not to develop decision-making software, but simply to organize a database of information in this one area.

Tasks:

- By inviting inputs from groups active in the field, it should be possible to create the software templates for some of the existing programs.
- National and/or international workshops would seem to be the appropriate mechanism to enable potential model users to set down their expectations of design appraisal by simulation.
- Additionally, the group of successful, seasoned users of existing software represents a source of knowledge that could be used for an expert system-based user interface.

The primitives library and software harness described above are illustrated schematically in Fig. 7.

International Association

To enhance collaboration and information exchange among individuals and organizations interested in building energy performance simulation, it is proposed that a new professional society be formed, tentatively called the International Association for Building Performance Simulation (IABPS). It is also the mission of IABPS to assist in the advancement of the field of building energy performance simulation by coordinating and conducting research which benefits model system developers or users and, specifically, to act as a repository and distribution point for the proposed prototype kernel system for the next generation of building energy simulation software.

During FY 1985, efforts were undertaken to organize the simulation community to form the above-mentioned association, as well as to begin work on the kernel system. The BESG also undertook specific technical projects to lay the groundwork

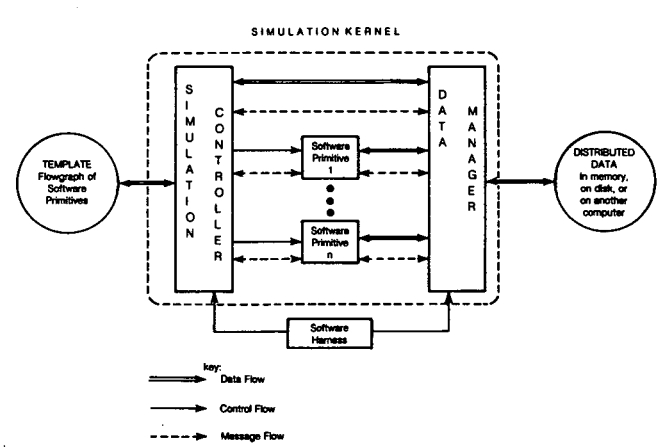

Figure 7. Proposed kernel system for creating building energy simulation models. (XBL 862-10304)

for the next generation of software. The major accomplishments during this period included:

(1) Numerous collaboration meetings were held, leading to the proposal for the next generation of building energy simulation software.

(2) Several current state-of-the-art building energy simulation programs were implemented on the BESG's ELXSI computer and a critical evaluation of the capabilities of these programs and their solution techniques and component algorithms was begun. The programs implemented include the following:

- ESP, which uses finite differencing to obtain a simultaneous solution of the coupled envelope and HVAC system heat flows. The implementation was done at LBL by J. A. Clarke, the program author, on leave from the ABACUS unit of the University of Strathclyde, Scotland. Also implemented were the ABACUS 3-D display programs BIBLE and VISTA.
- ASTEC, a program widely used in France for electric network analysis. Studies were done by J. Sornay of CSTB, France, while visiting LBL during FY1985.
- SPICE, an electric network analysis program developed at U.C. Berkeley.
- TRNSYS, the component-based system simulation program developed at the University of Wisconsin.
- HVACSIM+, a component-based system simulation program (recently developed by NBS) which uses variable-time-step, variable-order Gear algorithms for integrating systems of stiff, coupled differential equations.

(3) Lan-Chieh Huang, a mathematician on leave from the Chinese Academy of Sciences, began work on a new method for calculating unsteady, multi-dimensional natural convection in enclosures. The method, which is based on the Boussinesq approximation to the Navier-Stokes equations, uses exponentials to model the rapidly-varying flow in the boundary layer. This allows the heat flux at the walls to be calculated without using very fine gridding (and, therefore, large amounts of computer time) in the finite-difference solution.

(4) Work began on the use of ESP as a test-bed for the implementation and evaluation of advanced simulation methods. The first technique to be investigated will be a "timestep controller" which will improve the accuracy of an energy calculation by dynamically changing the simulation timestep in response to variations in climatic variables, such as outside temperature or solar radiation, or building control variables such as thermostat setpoints.

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 Building Energy Simulation Group gathers the information necessary to ensure this relevancy and usefulness.

A study[16] 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 completed in FY 1985. The results indicate that DOE-2 and BLAST give similar results, and that DOE-2 agrees within a reasonable tolerance ($\pm 20\%$) with measured hourly data from test cells.

PLANNED ACTIVITIES FOR FY 1986

The 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.

During FY 1986, if, as expected, the developer and user communities agree, IABPS will be formed and begin to operate. It is expected that the "kernel" system concept will also be generally accepted and work will be contributed by many organizations. The BESG will begin work formulating methods of component model representation to allow convenient mathematical presentation of component

models and model reduction techniques; this will allow complex networks to be reduced to their minimum set of equations and solved in an optimum way. Work will also begin on design of the data structure and control flow for the software harness. The BESG will continue existing collaborations and continue efforts to form meaningful new collaborations.

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- *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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